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Structure of residual oil as a function of wettability using pore-network modelling

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ABSTRACT

In the water flooding of mixed-wet porous media, oil may drain down to relatively low residual oil saturations (S_{or}). Various studies have indicated that such low saturations can only be reached when oil layers in pore corners are included in the pore-scale modelling. These processes within a macroscopic porous medium can be modelled at the pore-scale by incorporating the fundamental physics of capillary dominated displacement within idealised pore network models. Recently, the authors have developed thermodynamic criteria for oil layer existence in pores with non-uniform wettability which takes as input geometrically and topologically representative networks, to calculate realistic S_{or} values for mixed-wet and oil-wet sandstones [16, 21]. This previous work is developed in this paper to include (i) the visualisation of the 3D structure of this residual oil, and (ii) a statistical analysis of this "residual/remaining" oil. Both the visualisation and the statistical analysis are done under a wide range of wettability conditions, which is reported for the first time in this paper.

The structure of residual oil for strongly water wet systems is well known (where residual = remaining oil) and our model agrees with this but this structure changes radically for mixed wet systems (where residual ≠ remaining) and this has not yet been visualised experimentally. We find that for more water-wet systems high final residual oil saturations are reached at relatively small amounts of water injected and this oil is present in the pores as bulk oil. On the other hand, for more oil-wet systems we find a slow decrease of the amount of remaining oil with increasing amounts of injected water. During the process, the remaining connectivity of the oil phase is increasingly provided by oil layers only, hence the slow drainage. The final residual oil saturation, only reached in the theoretical limit of an infinite amount of injected water, is almost entirely contained in large number of (relatively low volume) oil layers, which are present in pores of most radius sizes.

1. Introduction and model description

The aim of all Enhanced Oil Recovery (EOR) methods is to mobilize oil trapped either locally by capillary forces and/or by large scale bypassing during waterflooding. It is the more local "residual/remaining" oil that we focus on in this paper and the prediction of this residual oil saturation (S_{or}) after waterflooding is very important before carrying out any EOR process. The mechanism through which a particular EOR method, such as gas displacement or low salinity waterflooding, actually works to reduce residual oil depends in turn on precisely *how* that oil is trapped at the pore-scale. Likewise, in aquifer remediation to remove low saturations of NAPL or DNAPL, the structure of this oil distribution at the pore-scale is important. Pore-scale network modelling can be used to estimate both the nature of the trapped residual oil and the relevant flow parameters in its subsequent mobilization, if the correct physics of oil displacement are properly included. It is noted here, that very frequently the precise meaning of "residual oil" is not absolutely clear when it is used in the literature and the *four* meanings of "S_{or}" as used in this work are defined in Section 1.2 below. In addition, when we refer to the "structure" of S_{or}, we mean the volume distribution across the pore space and its related correlation statistics. This is important since it will certainly affect the detailed physics of any EOR process used to mobilise this "residual" oil e.g. by gas injection, water-alternating-gas (WAG) or chemical injection, as in surfactant flooding.

1.2. Pore network modelling

Pore-scale network modelling is a well-established approach for calculating the small scale petrophysical functions of two- and three-phase flow through porous media, such as capillary pressure and relative permeabilities [2–7]. Recently, it has been possible to construct direct models of the actual pore space, either numerically or by micro-CT (Computed Tomography) scanning,

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Nomenclature

BL Buckley–Leverett theory of 1D water/oil displacement;
BO, BW, OL Bulk Oil in network model (BO – red), Bulk Water (BW – blue), Oil Layers (OL – yellow);
BT Break though of water in a water-oil displacement (w → o), in this paper;
CT, micro-CT X-ray Computed Tomography and mico-Computed Tomography which has a much finer pore-scale resolution;
EOR Enhanced Oil Recovery which is often applied as Chemical or Gas EOR to reduce the "residual oil";
I_{ow} the Amott–Harvey index which is a measure of the wettability of the porous medium based on water and oil imbibition into a mixed wet core sample;
I_n a description of the commonly used "I_n" pore body (PB) filling mechanisms in imbition, where n refers to the number of adjacent bonds containing the water phase – see references [5,13–15];
IM, PD the two-phase displacement processes of Imbibition (IM – i.e. water displacing oil in this case) and Primary Drainage (PD – i.e. oil injection into a strongly water wet system at $S_w = 1$);
k_{rw}, k_{rw}, k_r Relative permeability to water (k_{rw}) and oil (k_{ro}); k_r is used to generically denote the set of both relative permeability curves (k_{rw} and k_{ro});
MW, MWL, FW Descriptions of wettability; Mixed Wet (MW) and Mixed Wet Large (MWL) where the larger pores in the network are preferentially oil wet [1,16,23,25]. By contrast, FW refers to a Fractionally-Wet system. MW and FW are defined in Section 1.3;
NAPL, DNAPL An "oil like" Non Aqueous Phase Liquid (NAPL) and a Dense NAPL (DNAPL);
N01, N09, N11, N14 The 4 network model cases with varying wettability as specified in Table 1;
NMR, T_1/T_2 Nuclear Magnetic Resonance (NMR) specifically referring here to the measurement of the spin–lattice (T_1) and the spin-spin (T_2) relaxations time distributions [29];
o → w, w → o Pore scale two-phase displacement processes involving oil displacing water (o→ w; a drainage process) and water displacing oil (w → o; an imbibition process);
P_c, P_{cf} the Capillary Pressure (P_c) and a specific Final Capillary Pressure (P_{cf}) at which an imbibition process is terminated to achieve the corresponding "residual oil";
PB Pore Body or "node" in a network model which, if present, has volume; included in the "with PB" network model cases reported here and contrasted with the "no PB" cases where all the volume of the network in entirely in the "bonds";
PBF the Pore Body Filling process where water displaces oil from a PB (if present) – generally described by the I_n mechanism in network modelling (see above);
PV Pore Volume – of the core or network model;
RF Recovery Factor – in oil recovery it is usually the fraction of the total oil recovered in a waterflooding or EOR process;
S_w, S_o the Water Saturation (S_w) or Oil Saturation (S_o) in a network model or a core;
S_{wi} the Initial Water Saturation (S_{wi}) at which a waterflood commences to displace oil;
S_{or} the "Residual Oil" (S_{or}) commonly (imprecisely) referred to as the oil remaining after a waterflood; *four* more precise definitions of S_{or} are given in Section 1.2;
WAG Water-Alternating-Gas is an EOR process in which cycles of gas and water are injected to displace remaining/residual oil;
1D, 3D 1 and 3 Dimensional, respectively;
θ_a The (water) advancing oil/water contact angle – a measure of the surface wettability.

from which more idealised geometric pore networks can be extracted, as shown in Fig. 1 [8–12,30–33]. These network models can then be used in physics-based calculations which model the pore-scale displacement events, e.g. piston-like displacements, snap-off, layer formation/collapse etc.

Also in common with existing models, we represent the "pore throats" or "bonds" as straight (angular) tubes, but we have two options for modeling the pore bodies (PB) or "nodes". In the first option, like several existing models, the pore bodies are included in the model explicitly and they contain most of the pore volume and are involved in displacement processes (denoted "with PB"). In the second option, we distribute the pore body volume between the bonds connected to that pore body and ignore any displacements related to it (denoted "no PB"). In the "no PB" case, the connected network is made up of bond which we describe as "pore elements", represented in the final network calculation as idealized geometries. However, even for the "with PB" case, we simply use an (effective) throat conductance, which is the harmonic mean of the throat and adjoining body conductances [13]. In addition, if pore bodies are included in the network model, we must include the appropriate physics of pore body filling (PBF) through the well known co-operative PB filling I_n- mechanisms [5,13–15]. Although the first option (with PB) may appear to be more realistic, the second option has 2 specific advantages in that (i) the "no PB" case is much faster due to a more efficient phase clustering algorithm, and (ii) this case also avoids some of the uncertain aspects of the I_n- PBF mechanism. However, results are presented here for both "with PB" and "no PB" cases in this paper and some comparative comments are made on how this affects the resulting oil distributions at S_{or}. Fig. 1(b) shows the extracted network used in the "with PB" case in this work in which both PB ("nodes") and pore throats ("bonds") joining them are shown.

Table 1
Details of the 4 cases N01, N09, N11 and N14 in Fig. 5(c); I_{ow} values and residual oil (S_{or}) values at various PV throughputs.

	N01	N09	N11	N14
I_{ow}	−0.47	0.13	0.31	0.59
BT	51.9%	28.8%	28.6%	28.5%
3PV	40.0%	22.5%	22.0%	24.7%
20PV	28.2%	15.9%	15.6%	24.7%
infPV	2.0%	4.1%	8.4%	24.7%

1.3. The waterflooding cycle and the calculation of residual oil saturation, S_{or}

The two phase flooding cycle is modelled in a pore network model from primary drainage (PD) to a water saturation value denoted S_{wi} followed by "ageing" (to alter wettability to some specified state). S_{wi} is the *initial* water saturation for the subsequent imbibition (IM) process, after which we reach a value of "residual