Best paper award: second honorable mention

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CORE WETTABILITY : SHOULD I_{AH} EQUAL I_{USBM} ?

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ABSTRACT

The wettability of a crude oil/brine/rock system is of central importance in determining the oil recovery efficiency of water displacement processes in oil reservoirs. Wettability of a rock sample has traditionally been measured using one of two experimental techniques, *viz*. the United States Bureau of Mines and Amott tests. The former gives the USBM index, I_{USBM}, and the latter yields the Amott-Harvey index, I_{AH}. As there is no well-established theoretical basis for either test, the relationship between the two, if any, is unclear.

Analytical relationships between I_{AH} and I_{USBM} for mixed-wet and fractionally-wet media have been derived assuming uniform pore size distribution and ignoring the effects of pore connectivity. This simple approach provides some guidelines regarding the influence of the distribution of oil-wet surfaces on I_{AH} and I_{USBM}. More detailed insight into the relationship between I_{AH} and I_{USBM} is provided by modelling the pore-scale displacement processes in a network of interconnected pores. The effects of pore size distribution, interconnectivity, displacement mechanisms, distribution of volume and of oil-wet pores within the pore space have all been investigated by means of the network model.

The results of these analytical calculations and network simulations show, as expected, that I_{AH} and I_{USBM} need not be identical. The calculated indices and the relationship between them suggest explanations for some of the trends that appear in experimental data when both I_{USBM} and I_{AH} have been reported in the literature for tests with comparable fluids and solids. Such calculations should help with the design of more informative wettability tests in the future.

INTRODUCTION

It is now well established that the wetting characteristics of a reservoir crude oil/brine/rock (COBR) system strongly influence water-oil displacement processes in petroleum reservoirs (Cuiec, 1991; Morrow, 1990; Jadhunandan and Morrow, 1995). Wettability is a surface phenomenon, classically defined using the concept of contact angle. No such direct test of wettability in porous media is available, however. The most widely used empirical wettability

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[#] Present Address : Edinburgh Petroleum Services Ltd., Research Park, Riccarton, Edinburgh, Scotland, UK measurements for reservoir cores, including Amott (Amott, 1959; Boneau and Clampitt, 1977), USBM (Donaldson *et al*., 1969) and combined Amott/USBM methods (Sharma and Wunderlich, 1985), are based on displacement studies.

I_{AH} and I_{USBM} are used almost interchangeably within the oil industry as indicators of rock wetting, although there are obvious differences. I_{AH}, by definition, must fall between –1 and +1, a restriction which does not apply to I_{USBM}; numerical discrepancies for strongly-wetted conditions are thus expected. Of more importance are comparisons over the wide range of weakly-wetted and intermediate conditions between these two extremes. Since I_{AH} reflects spontaneous imbibition, whereas I_{USBM} is derived from drainage capillary pressure curves, it is not immediately evident what the relationship between these two measures should be.

In cases where data for both measures are available, comparisons show significant scatter (Buckley, 1996). At most only qualitative agreement between the two is observed, as shown in Figs. 1a and 1b, where I_{USBM} vs. I_{AH} is plotted for experimental data from many sources in the literature. In Fig. 1a, some of the scatter can probably be attributed to real differences between samples, since different pieces of core were used to measure I_{USBM} and I_{AH}. Figure 1b shows measurements made by the combined Amott/USBM technique (Sharma and Wunderlich, 1985) in which both indices are measured for the same piece of core in the course of a series of imbibition and drainage displacements. Consistency is better within any one set of data, but there are noticeable differences from one data set to another. Again, some of the discrepancies may represent real differences between the different sets of cores. In addition, however, while there is general agreement on the essentials of the Amott and USBM tests, important modifications have been introduced (e.g. Cuiec, 1975; Longeron *et al*., 1994) and techniques can vary significantly from one laboratory to another.

For future reference, the four quadrants in Fig. 1a are designated **A** ($I_{USBM} > 0$; $I_{AH} > 0$), **B** ($I_{USBM} >0$; $I_{AH} < 0$), **C** ($I_{USBM} < 0$; $I_{AH} < 0$) and **D** ($I_{USBM} < 0$; $I_{AH} > 0$). Some trends can be observed immediately: (a) most points fall in quadrant A; (b) across the range from $I_{AH} = -1$ to $I_{AH} = +1$, there appears to be a systematic tendency for most points to lie *above* the I $I_{USBM} = I_{AH}$ line; (c) there is an (almost) empty quarter, *viz*. quadrant D, and (d) there are a fair number of points that fall in quadrant C where the USBM test indicates a preferential wetting by water whereas the AH test suggests predominantly oil-wet behaviour.

In this work, our central objectives are (a) to explore the relationship between the AH and USBM wettability indices using analytical and pore-scale network modelling, and (b) to use predicted correlations between I_{AH} and I_{USBM} to reexamine and interpret existing experimental data.

ANALYTICAL RESULTS

It is shown elsewhere that, for a uniform pore size distribution (PSD), there are analytical relationships between I_{USBM} and I_{AH} for various wetting scenarios (Dixit *et al.*, 1998b). In these calculations we distinguish *wettability types* that are based on the fraction of *oil-wet* pores, α, and their distribution within the pore space in the following ways:

- *fractionally-wet* where the oil-wet pores are uncorrelated to pore size (denoted FW);
- *mixed-wet* where the largest pores are oil-wet (denoted MWL); or
- *mixed-wet* where the smallest pores are oil-wet (denoted MWS).

Although not discussed in detail here, there are physical reasons why either the larger or smaller pores may become preferentially more *oil-wet* on ageing after primary drainage leading to the MWL and MWS cases. Simple pore filling sequences are assumed within the water-wet and oil-wet pore clusters and accessibility issues are neglected in these analytical calculations. The analytical relationships derived between I_{USBM} and I_{AH} for these three wettability types are given in equations 1-3.

Fractionally-wet (FW) case :

$$I_{USBM} = \log_{10}\left(\frac{1+I_{AH}}{1-I_{AH}}\right) \tag{1}$$

Mixed-wet case with *large* pores being oil-wet (MWL) :

$$I_{USBM} = \log_{10}\left(\frac{\left[\dfrac{I_{AH}(R_{\max}^{n+1} - R_{\min}^{n+1}) + (R_{\max}^{n+1} + R_{\min}^{n+1})}{2}\right]^{\frac{n}{n+1}} - R_{\min}^{n}}{R_{\max}^{n} - \left[\dfrac{I_{AH}(R_{\max}^{n+1} - R_{\min}^{n+1}) + (R_{\max}^{n+1} + R_{\min}^{n+1})}{2}\right]^{\frac{n}{n+1}}}\right) \tag{2}$$

Mixed-wet case with *small* pores being oil-wet (MWS) :

$$I_{USBM} = \log_{10}\left(\frac{R_{\max}^{n} - \left[\dfrac{(R_{\max}^{n+1} + R_{\min}^{n+1}) - I_{AH}(R_{\max}^{n+1} - R_{\min}^{n+1})}{2}\right]^{\frac{n}{n+1}}}{\left[\dfrac{(R_{\max}^{n+1} + R_{\min}^{n+1}) - I_{AH}(R_{\max}^{n+1} - R_{\min}^{n+1})}{2}\right]^{\frac{n}{n+1}} - R_{\min}^{n}}\right) \tag{3}$$

where R_{min} and R_{max} are the uniform PSD limits and ν is the volume exponent (Dixit *et al.*, 1996). Fig. 2 shows the relationships between I_{AH} and I_{USBM} predicted by this simple analytical approach. The FW case is linear over the range $-0.5 < I_{AH} < 0.5$, following the $I_{USBM} = I_{AH}$ line. For a strictly FW system, there is a symmetric relationship between the wetting indices which is independent of the type or range of PSD or volume exponent, ν. Clearly, for either type of *mixed-wet* system—MWL or MWS—both the PSD limits (R_{min} and R_{max}) and ν do affect the relationship between the two indices.

The calculated I_{USBM} vs. I_{AH} relationships are clearly distinguished for mixed-wet conditions, with MWL systems predicted to lie *above* and the MWS systems predicted to lie *below* the $I_{AH} = I_{USBM}$ line in quadrant A. If current views of mixed-wet systems are broadly correct (i.e. that wetting is altered in the *larger* pores), then most experimental data points should lie above the $I_{AH} = I_{USBM}$ line. In Fig. 1b, most of the data sets, with the exception of Yan *et al.* (1993), do indeed lie above the line. Wetting alteration in the experiments of Yan *et al.* was caused by exposure to oil-based drilling muds; perhaps in that case it is predominantly the *smaller* pores that become oil-wet.

PORE SCALE NETWORK MODELLING RESULTS

The analytical calculations above incorporated a number of simplifying assumptions:

- a uniform PSD was selected,
- accessibility functions were not considered (Heiba *et al.*, 1982, 1983; Stauffer and Aharony, 1994), and
- single contact angles (0° in the water-wet and 180° in the oil-wet pores) were assumed.

Recently network models have been developed which take into account a number of realistic pore-level flow phenomena, including wettability alterations after primary drainage (Dixit *et al.*, 1996; Blunt, 1997). The effects of wettability alterations on oil-water capillary pressure curves and the application of the *capillarity surface* concept to predict phase distributions have been discussed in McDougall *et al*. (1997). Using the same simulator, we have also studied waterflood recovery trends in fractionally-wet and mixed-wet systems and, based on these results, a *Regime* based framework has been proposed for wettability classification (Dixit *et al.*, 1996). A typical Regime diagram is shown in Fig. 3. The three main Regimes (I, II and III) are defined by the value of α, the fraction of oil-wet pores in the pore network. An important boundary exists between Regimes I and II at $\alpha = \alpha_{crit}$ where α_{crit} is the critical fraction of pores that must be *oil-wet* in order to form an oil-wet spanning cluster across the network. From percolation theory (Stauffer and Aharony, 1994) this quantity is given by, $\alpha_{crit} = D/[z \bullet (D-1)]$ for an uncorrelated network of dimension D and coordination number z. The network approach has also been used to explore hysteresis trends in water-wet and mixed-wet consolidated and unconsolidated media (Dixit *et al.*, 1997, 1998a). Numerous, apparently conflicting waterflood recovery results and relative permeability hysteresis trends have been interpreted with the help of the simulator.

Here the network simulator and Regime-based approach are applied in networks of 20x20x20 or 25x25x25 pores to evaluate the complex displacement processes that were not considered in the analytical approach above. The parameters tested for their impact on I_{USBM} and I_{AH} are summarized in Table 1. Complete results from this series of simulations are presented elsewhere (Dixit *et al.*, 1998b). Here we present selected results for comparison with the analytical predictions and with existing experimental data.

Table 1. Parameters varied in network simulations

Parameters		Ranges tested
Topology	Pore size distribution (PSD)	Rayleigh (RAY), log uniform (LU), cubic (CU)
	R_{min} and R_{max}	(0.1,25)μm, (0.1,50)μm, and (0.1,100)μm,
	Coordination number (z)	4 and 6
	Volume exponent (ν)	1 - 3
Displacement mechanisms	Water-wet clusters	Snap-off (θ=0°), piston-like (θ=60-89°), & both (θ=0-89°)
	Oil-wet clusters	Piston-like only (θ=91-120°)
Wettability distribution	Fractional wetting (FW)	α = 0.187, 0.375, & 0.567
	Mixed with oil-wet large pores (MWL)	
	Mixed with oil-wet small pores (MWS)	

Effect of Imbibition Mechanism in the Water-wet Region: The effect of the pore-scale imbibition mechanism in the water-wet region (i.e. snap-off or piston-like displacements) upon calculated wettability indices is shown in Fig. 4 for a fractionally wetted system. (For explanation of simulations involving different displacement mechanisms, see the discussion in Dixit *et al.*, 1997.) It is assumed that the displacements in the oil-wet region are mainly governed by piston-like displacements. The wettability Regime is varied by changing α over the range from 0.187 to 0.567 which shifts both I_{AH} and I_{USBM} from higher to lower values.

When piston-like displacements are selected for water imbibition in the FW simulations, I_{USBM} almost equals I_{AH}, in agreement with the analytical prediction. With the change in imbibition mechanism from piston-like to snap-off in the water-wet pores, however, the USBM index increases significantly whereas the AH index remains practically unchanged. This trend is almost independent of the wettability Regime and overall coordination number of the network.

Simulations in which both mechanisms were allowed resulted in I_{USBM} values that were almost as high as in the case with snap-off alone.
The effect of coordination number is small, except in the intermediate wetting cases (α=0.375) where changing z shifts the system from the borderline between Regimes I and II (z=4, α_{crit}=0.375) to Regime II (z=6, α_{crit}=0.25). Other simulations have shown that an increase in the volume exponent ν shifts both indices to lower values, preserving the differences between them. If snap-off is allowed, the USBM indices are consistently higher than the corresponding AH values, regardless of the value of ν.

Imbibition without Snap-off: In previous simulation studies, we have shown that the characteristic relative permeability hysteresis trends of poorly consolidated porous media could be reproduced by incorporating piston-like displacements in both wettability regions and by using a relatively high volume exponent and low conductivity exponent (Dixit *et al.*, 1997, 1998a). Variations in I_{USBM} and I_{AH} with this combination of parameters—which is often associated with "poorly consolidated" porous media—are shown in Fig. 5.

For poorly consolidated, fractionally-wet systems, the correlation between the I_{AH} and I_{USBM} is excellent. This trend is quite insensitive to pore geometry and topological parameters, in agreement with the prediction of the simple analytical model. A similar result was shown in Fig. 4, for parameters more representative of consolidated porous media, when only piston-like displacement was allowed (as expected for weakly-wet conditions). The agreement between the full network model and the analytical prediction reflects the symmetry between the analytical assumptions and the full network calculation for a random distribution of wetting (FW) and piston-like displacement mechanisms regardless of wettability.

Asymmetry is introduced when we hypothesize that some of the large pores (MWL) or some of the small pores (MWS) become oil-wet, even if the mechanism continues to be restricted to piston-like displacement. As shown in Fig. 5, the MWL points lie above the $I_{USBM} = I_{AH}$ line and the MWS points lie below, as predicted by the analytical calculations. The MWS case is a particularly interesting result since this is the only one which gives points that lie below the $I_{USBM} = I_{AH}$ line, suggesting that measurements in which $I_{USBM} < I_{AH}$ might represent porous media in which it is the small pores that are oil-wet.

COMPARISON OF PREDICTIONS WITH EXPERIMENTAL DATA

Figure 6 summarizes all of the simulations testing sensitivities to pore size distribution, pore size range, pore volume exponent, imbibition mechanism and coordination number. Referring back to Fig. 1b, the sequential measurements of I_{USBM} and I_{AH} on a a single piece of core, some interesting comparisons emerge.

(a) There is a broad but scattered correlation between the USBM and AH indices for both the experimental results and the theoretical calculations.

(b) Most points in the I_{USBM} vs. I_{AH} correlation results fall in quadrant A in both the theoretical and experimental results. Clearly, in the theoretical calculations, this could be changed trivially by simply taking more oil-wet network calculations. However, because of the assumption that the water-filled pores at the end of the primary drainage remain water-wet, we tend to bias the system toward more water-wet conditions (as indeed occurs experimentally).

(c) Across the range from $I_{AH} = -1$ to $I_{AH} = +1$, there is a systematic tendency for the USBM test to indicate more water-wet behaviour than does the Amott test, with most points *above* the $I_{USBM} = I_{AH}$ line in both the theoretical calculations and the experimental results. This is particularly true in experimental results with $I_{AH} < 0$. This feature is captured by the numerical network simulations. The analytical result which predicts this behaviour suggests that this is due to the more common occurrence of the MWL wettability type (where larger pores tend to be oil-wet) in reservoir cores and to the influence of the snap-off mechanism in water-wet pores.

(d) Quadrant D is an almost empty quarter in both the simulations and in the experimental results. In the simulations, this may be partly a simple corollary of trend (b) above (since all points are moved upwards on the figure).

(e) A significant minority of points on the I_{USBM} vs. I_{AH} diagram lie in quadrant A but *below* the $I_{USBM} = I_{AH}$ line. Both the analytical results and the network simulations suggest that these points are due to small pores being oil-wet (the MWS wetting scenario) and piston-like displacement in both water-wet and oil-wet pore clusters.

Thus, encouraging agreement is seen between the experimental USBM and Amott wettability test results and the theoretical simulations. However, although most broad experimental trends are satisfactorily reproduced, further work is required to ensure that this is being done for the correct reasons in terms of the pore-scale physics. The analytical and network calculations provide some testable predictions, that—if confirmed experimentally—could extend the usefulness of the combination of AH and USBM indices in diagnosing the wetting conditions of porous media. For example, fractionally-wet media can be constructed by mixing grains of different wetting. Our calculations predict that I_{AH} should equal I_{USBM} for such systems if they are weakly wetted or poorly consolidated (i.e., if snap-off is suppressed). The prediction that $I_{USBM} < I_{AH}$ occurs only if the smaller pores are the more oil-wet (again, with snap-off suppressed) might also be tested. It should be possible to determine, perhaps by tagging the imbibing fluids and examining their distribution after imbibition, to verify whether, in such a case, it really is the smallest pores that are oil-wet.

SHOULD $I_{AH} = I_{USBM}$?

Although these two empirical measures of wetting are clearly related, both the analytical study and network simulation suggest that only for weakly-wetted media with randomly distributed water-wet and oil-wet pores (the FW case) should the same numerical values be expected from the USBM and Amott-Harvey tests. For identical fractions of oil-wet pores, both indices are shifted by changing assumptions about the distribution and sizes of pores and the volume associated with each pore. If the larger pores are assumed to become oil-wet, the USBM index indicates more water-wet conditions than does the AH (i.e., $I_{USBM} > I_{AH}$). Snap-off in the water-wet pores also shifts USBM calculations to more water-wet values without affecting the Amott-Harvey results. Only if snap-off is suppressed and the smaller pores are the more oil-wet is the opposite trend, $I_{USBM} < I_{AH}$, predicted.

NOMENCLATURE

CU	cubic PSD
COBR	crude oil/brine/rock
D	dimension of the network, D = 3 in all cases in this paper.
f(r)	pore size distribution; *number* density of pores of capillary entry radius, r
FW	fractionally wet
I_{AH}	Amott Harvey wettability index, $I_{AH} = I_O + I_W$
I_o	Amott oil index
I_{USBM}	United States Bureau of Mines wettability index
I_w	Amott water index
LU	log-normal PSD
MWL	mixed-wet, large pores are oil-wet
MWS	mixed-wet, small pores are oil-wet
OW	oil-wet
PSD	pore size distribution, f(r)
r	pore entry radius
RAY	modified Rayleigh PSD
R_{max}	maximum pore radius in PSD
R_{min}	minimum pore radius in PSD
WW	water-wet
z	coordination number
α	fraction of oil-wet pores in the network
α_{crit}	critical fraction of oil-wet pores in the network, percolation threshold
ν	volume exponent where volume of pore, $v(r) \sim r^{\nu}$

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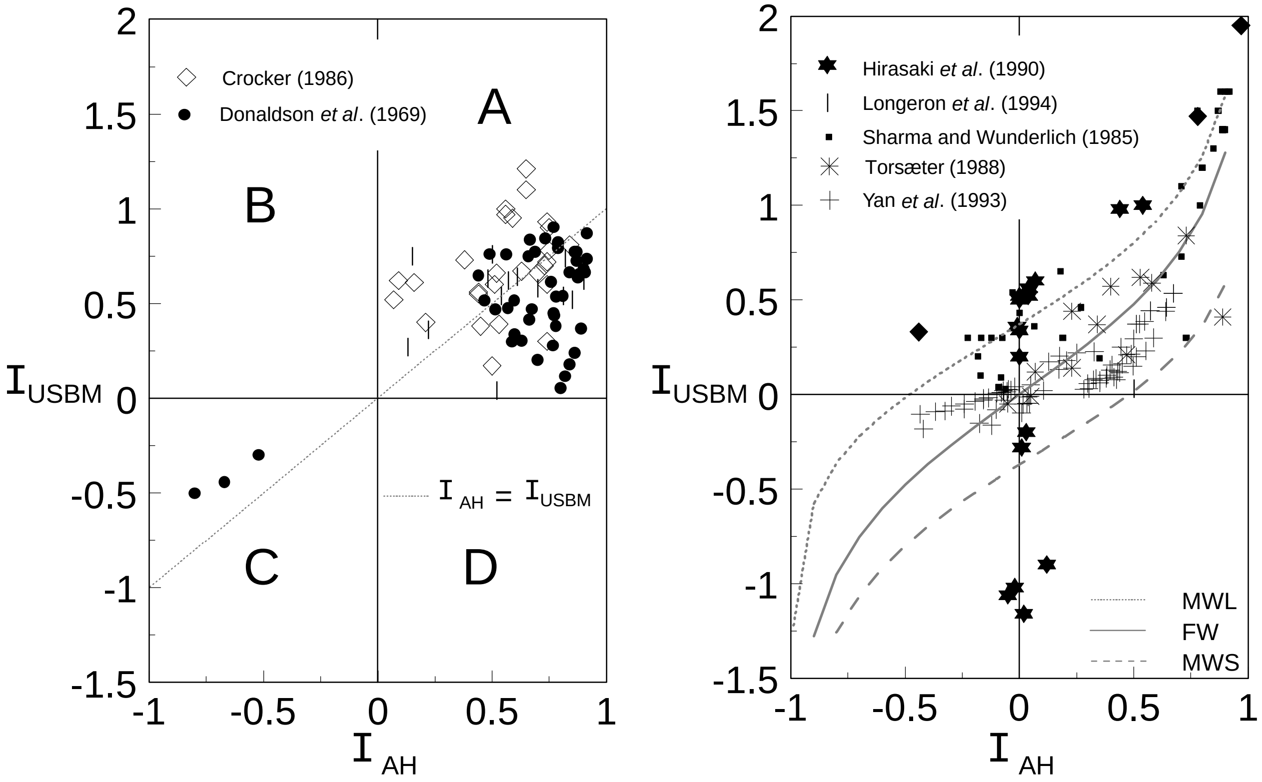


(a) separate measurements of I_{USBM} and I_{AH} (b) combined measurements of I_{USBM} and I_{AH}

Figure 1. Comparison of Amott-Harvey and USBM indices measured in (a) separate experiments with duplicate core plugs or (b) in a combined sequence of measurements with a single core plug (data from various literature sources, as indicated).

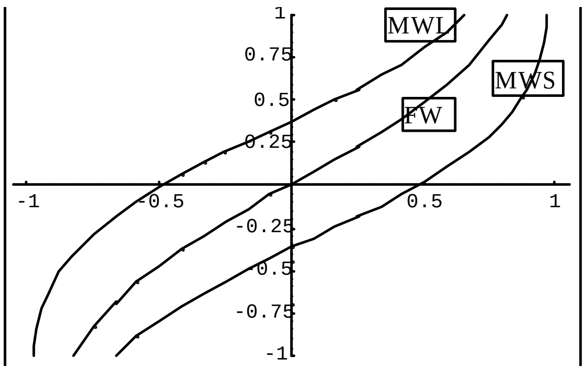


Figure 2. I_{USBM} vs. I_{AH} relationships for the simple analytical model with FW, MWL and MWS wettability types, uniform PSD, (1,50)μm pore size range, volume exponent ν=1.

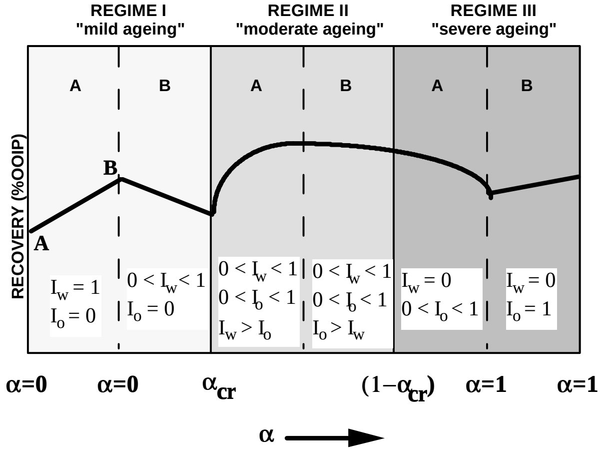
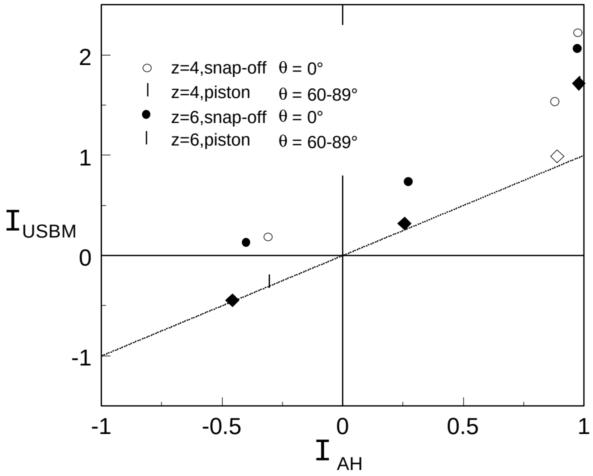
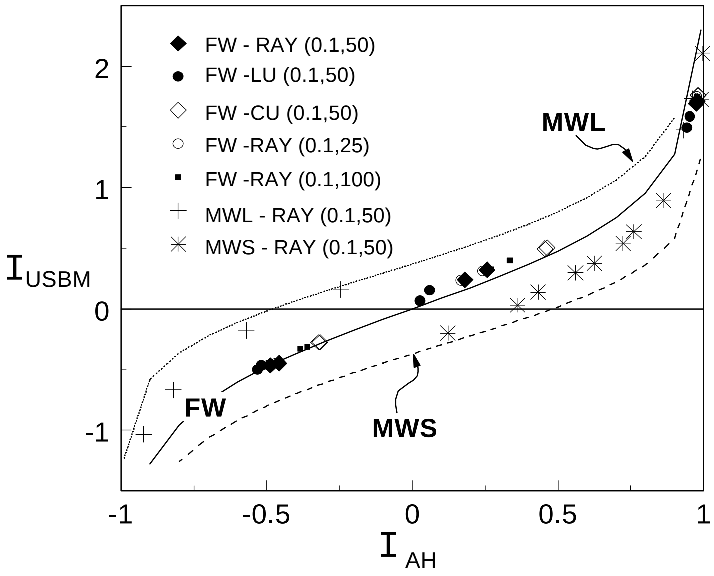


Figure 3. Schematic representation of *Regime*-based wettability framework relating wettability to waterflood recovery (from Dixit *et al.*, 1996).



network size z=4	25x25x5	**PSD**	modivied RAY	**mechanism OW**	piston θ=91-120°
z=6	20x20x20		(0.1,50)μm; ν = 2	**WW**	as shown°
z	as shown	**α**	0.187, 0.375, 0.567	**wettability type**	FW

Figure 4. Effect of the pore-scale displacement mechanism in the water-wet region (assuming piston-like displacement in OW regions) on I_{USBM} and I_{AH} wettability indices.



network size	20x20x20	**PSD**	as shown	**mechanism OW**	piston θ=91-120°
			ν = 3	**WW**	piston θ=60-89°
z	6	**α**	0.187, 0.375, 0.567	**wettability type**	as shown

Figure 5. Simulated I_{USBM} and I_{AH} wettability indices for “poorly consolidated” porous media.

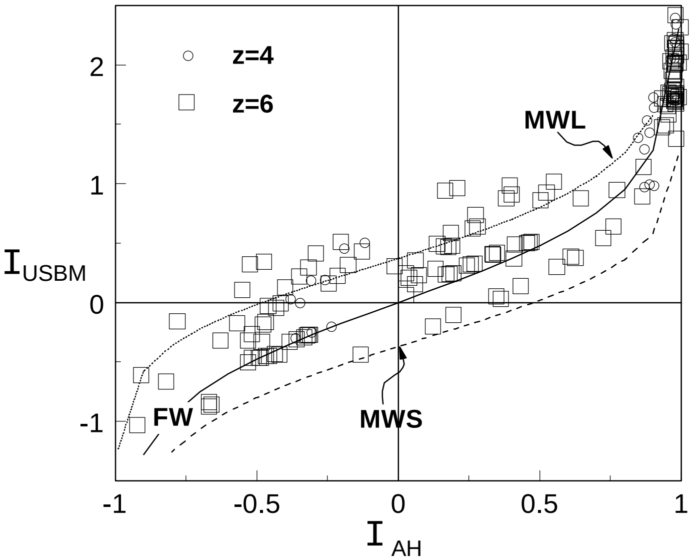


Figure 6. Simulated I_{USBM} vs I_{AH} trend for a wide range of sensitivities. See Table 1 for conditions tested.