INFLUENCE OF WETTABILITY ON RESISTIVITY OF SEDIMENTARY ROCKS

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ABSTRACT

Measurements of electrical resistivity are commonly used in well-logging to estimate petrophysical properties of oil reservoirs. However, the basis for these estimates is essentially empirical, due to the fact that pore level mechanisms that control electrical properties of sedimentary rocks are not considered. The empiricism complicates log interpretation when mud filtrate invasion has altered formation saturations and when the wettability of the formation is not known. In this work we present a methodology for *a priori* prediction of resistivity index for different wettability conditions and for both drainage and imbibition. The approach is based on the mechanistic modeling of capillarity-controlled displacement and DC current flow at the grain scale in a simple but physically representative class of model rocks. The method allows computing pore-level fluid configurations, which, in turn, makes possible *a priori* predictions of macroscopic electrical properties. Meniscus motion at the grain scale is entirely mechanistic, so the method accounts for hysteresis automatically. Wettability is handled via contact angle with the interface and thus governs the shape of meniscus. Hysteresis during the fluid displacement cycle (drainage then imbibition of the wetting phase) has a significant effect on resistivity index. We demonstrate the influence of uniform wettability with simulations for strongly and weakly wetted conditions. The conducting phase may be wetting or nonwetting; we illustrate both cases. The results for electrical properties are also presented as electrical efficiency, which was developed specifically to account for the effects of pore-level geometry. The predictions made in this paper are compared with existing experimental data and found to be consistent with them.

INTRODUCTION

Macroscopic electrical properties of rocks, such as resistivity index, are frequently used to estimate water content of oil reservoirs and therefore are fundamental to formation evaluation. In this work we present a technique for *a priori* predictions of electrical properties of rocks during displacement processes (primary drainage followed by imbibition). The results are presented as resistivity index and electrical efficiency (Herrick and Kennedy [13]) that allows quantifying the effect of pore space geometry on electrical properties of porous media.

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The methodology used in this work is based upon the mechanistic modeling of the movement of fluid interfaces during displacement processes in a physically representative model porous medium. This allows obtaining realistic fluid configurations at the pore-level. The model porous medium is an experimental dense random packing of equal spheres, for which the coordinates of the centers have been measured (*Finney pack*, [9]). Knowledge of the coordinates determines the grain space and the void space in the packing, thereby overcoming a long-standing difficulty for theoretical approaches.

Despite the simplicity of the model porous medium, it is a powerful tool for investigation of the processes which occur in sedimentary rocks. In particular it allows *a priori* predictions of macroscopic behavior that have been validated by experimental data. Knowledge of the pore space geometry and wettability conditions (the value of the contact angle) allows computing accurate configuration of liquid phases in porous media. Then drainage and imbibition of a wetting phase in this model porous medium are simulated. The conductivity of the packing is computed simultaneously with the saturation at any stage of drainage or imbibition, which allows predicting hysteresis in electrical properties. This in turn provides a quantitative understanding of how electrical properties depend on the physical (i.e. wettability) features of porous media.

The basis for use of the Finney pack as a physically representative model porous medium has been established [15, 17]. The methodology for modeling displacement processes in these model rocks was suggested by Bryant and Blunt [3] and Mason and Mellor [16] and subsequently developed by Bryant and Johnson [8] (drainage) and by Gladkikh and Bryant [11] (imbibition) with rigorous computations of the geometry of fluid interfaces within the packing. The methodology for the modeling of electric current flow used in this paper is based on the technique suggested by Bryant and Blunt [3] and Bryant *et al* [4 – 6] for fluid flow and by Bryant and Pallatt [7] for electric current flow. We apply this approach for imbibition as well as drainage.

PHYSICALLY REPRESENTATIVE MODEL POROUS MEDIA

The power of using a dense random packing of equal spheres with complete geometrical description as a model porous medium was first recognized by Mason [15]. To perform numerical modeling of pore-level processes in the Finney pack, Mellor [17] suggested using Delaunay tessellation of sphere centers. Applied to points in n–dimensional space, Delaunay tessellation finds sets of $n+1$ nearest neighbors. Thus it subdivides the volume of the Finney packing into tetrahedral cells which provide a natural means of identifying pore bodies and the pore throats that connect them. The details can be found in [9, 15 – 17]. Further, it is desirable to create simple models of sedimentary rocks from the model sediment (Finney pack). Bryant *et al* [4 – 6] simulated results of geological processes, such as compaction and cementation, in the Finney pack, and predicted trends of permeability decreasing with decrease in porosity. In this work we follow their approach in modeling results of isopachous cementation, which occurs as uniform layers upon the surfaces of grains. No surface roughness is modeled, so the surfaces of grains remain smooth after cementation as well.

MODEL OF FLUID DISPLACEMENT

We simulate a physical experiment: primary drainage of a W (wetting) phase from the model porous medium and subsequent imbibition (displacement of the NW (non-wetting) phase by the W phase). To do this, we need to specify the following parameters: initial condition (packing is fully saturated with the W phase); pores, connected with reservoirs of W and NW phases; and wettability (defined by the value of contact angle θ of W-NW-solid interface). In this work we assume uniform wettability (θ is constant everywhere).

We assume that during the displacement process, interfaces between phases exist in two configurations: *pendular rings* at grain contacts and *menisci* at pore throats (Fig 1).

The geometrical features of these shapes are defined by the curvature of the interface, which relates to the global applied capillary pressure by the Young-Laplace equation [1]:

$$P_C = \gamma J \,, \tag{1}$$

where $P_c = P_{nw} - P_w$ is the pressure difference between NW and W phases; γ is the interfacial tension between them and J is the sum of the two principal curvatures, or twice the mean curvature of the interface. In spite of the fact that equation (1) describes a static configuration, it is commonly applied to the displacement of one immiscible phase by another, when that displacement occurs sufficiently slowly.

The detailed description of computing geometry of the interfaces and their movement as the curvature changes can be found in [11].

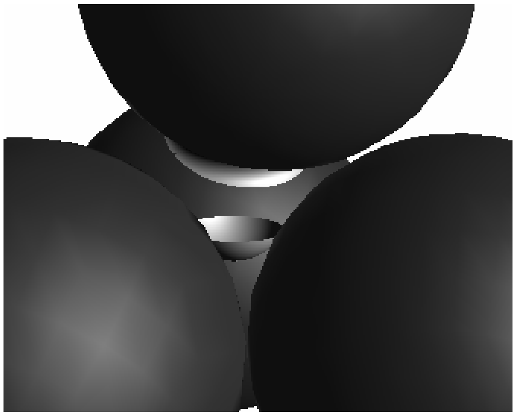

Fig. 1 Four grains and tetrahedral pore, which is formed by them. The light grey shape between the top and rear grains is a pendular ring of W phase, which fills the gap between the grains. The spherical cap in the center of the pore is the interface of the meniscus, which is assumed to have locally spherical shape. Fluid below this cap is W phase, above – NW phase.

MODEL OF DRAINAGE

Drainage is modeled in the network extracted from the model porous medium as a quasi-static bond invasion percolation process [16, 22]. Each pore throat is assigned a critical curvature for drainage, and the pore is allowed to drain only if 1) its immediate neighbor is already drained and 2) the current curvature is larger than the critical value for the pore throat which connects the pore to this neighbor. Critical curvatures of pore throats were computed with the simplest Haines insphere approximation [12]:

$$J_H = \frac{2\cos\theta}{r_t}, \tag{2}$$

where θ - contact angle and r_t – radius of sphere that just passes through the pore throat. This algorithm for drainage was described by Bryant and Blunt [3] and by Mason and Mellor [16] and also applied by Bryant and Johnson [8] with the accurate computation of fluid configurations (pendular rings of W phase at grain contacts, menisci between phases, lenses of W phase at pore throats). In this work we use an approach similar to that described in [8].

MODEL OF IMBIBITION

Imbibition is simulated in the network as a quasi-static site invasion percolation process [22]. As the criterion of imbibition of a single pore we use the physically consistent Melrose criterion [18], which suggests that the given pore is imbibed when one of the menisci within it comes into contact with one of the pendular rings. This criterion is dynamic – we cannot prescribe critical curvatures for imbibition in advance because we cannot know in advance which throats will contain menisci for any given pore. The influence of wettability on imbibition follows naturally from the application of the Melrose criterion, since we compute fluid interfaces explicitly from geometry [11]. In contrast to drainage, imbibition capillary pressure curves depend nonlinearly upon $\cos\theta$. The Melrose criterion quantitatively accounts for this remarkable effect [11].

MODEL OF ELECTRIC CURRENT FLOW

To model DC current flow in the model rock, we follow the approach proposed by Bryant and Pallatt [7], who have shown good quantitative agreement between *a priori* predictions of formation factor and resistivity index during drainage with experimental data. The goal of this work is to investigate the behavior of electrical properties (resistivity index and electrical efficiency) for both drainage and imbibition and the influence of reservoir wettability (specified by the value of contact angle) on these properties.

The algorithm is applied as follows. For each value of dimensionless curvature (or, interchangeably, capillary pressure, Eq. (1)) during either drainage or imbibition, when static equilibrium configuration of the liquid phases is achieved and the geometry and distribution of phases within the packing is known, we simulate electric current flow in the natural network extracted from the packing by Delaunay tessellation [9, 15, 17]. It is necessary to define whether W or NW phase is conductive (or, in other words, to specify whether the rock is water- or oil-wet, since we consider water (brine) to be conductive and oil, gas and solid grains as insulators). Each site of the network (pore body), occupied by the conductive phase is specified by the value of the *voltage*. The voltage drop within sites (pore bodies) is neglected.

For each bond (pore throat) of the network the value of *bond electrical resistivity* is readily computed since the cross-sectional area of the pore throat is approximately constant along the flow path [7]. Pendular rings (Fig 1), which exist at grain contacts, also contribute to the electrical conductivity of the packing. If the conductive phase is

NW (oil-wet rock) then pendular rings simply decrease the cross-sectional area of the pore throat available for the flow of electric current. If the conductive phase is W, then pendular rings provide connections between pores filled with the W phase, even if these pores are not immediate neighbors and are not connected directly by the pore throats.

The problem of computing the overall conductivity of the network is solved as follows. Because the Finney pack is a spherical conglomerate, it is convenient to impose a spherically symmetric field on the network. To do this, pores in a small spherical region at the center of the pack are assigned a fixed voltage (V = 1, say), and pores at the external surface of the packing are assigned a different voltage (V = 0). Then the total steady electric current flow I through the network is computed by solving the system of linear equations of the mass balance at each site using the method of conjugate gradients. The conductivity of the packing is given by Ohm's law in spherical coordinates:

$$C = \frac{4\pi I}{dV \Big/ d\left(\frac{1}{r}\right)}. \tag{3}$$

The detailed description of the technique can be found in [7], and also in [3 – 6], where similar methodology was applied to compute fluid flow in the Finney pack.

ELECTRICAL EFFICIENCY

To quantify the influence of pore geometry on electrical properties of porous media, Herrick and Kennedy [13] suggested the concept of electrical efficiency instead of the frequently used correlation of resistivity index with water content as used in the purely empirical Archie's equation [20]. The latter correlation does not possess any underlying physical basis and lacks the connection between pore-level geometry and rock properties.

The electrical efficiency E_0 of a brine-saturated rock sample is defined by

$$C_0 = \phi \, E_0 \, C_w , \tag{4}$$

where porosity ϕ and electrical efficiency are coefficients correcting the brine conductivity C_w for brine volume and brine geometry, respectively, to give the rock conductivity C_0.

Thus defined, electrical efficiency of the sample (E_0) depends only on pore space geometry and is equal to 1 for the most efficient geometry, i.e. that of a cylindrical tube.

When hydrocarbons are present, (4) should be modified as [13]

$$C_t = S_w \, \phi \, E_t \, C_w, \tag{5}$$

where the product $S_w\phi$ gives the water content of a partially saturated rock and E_t accounts for the conducting phase geometry.

RESULTS: COMPARISON WITH EXPERIMENTAL DATA

We present results of the simulation of electric current flow during both drainage and imbibition as both resistivity index and electrical efficiency.

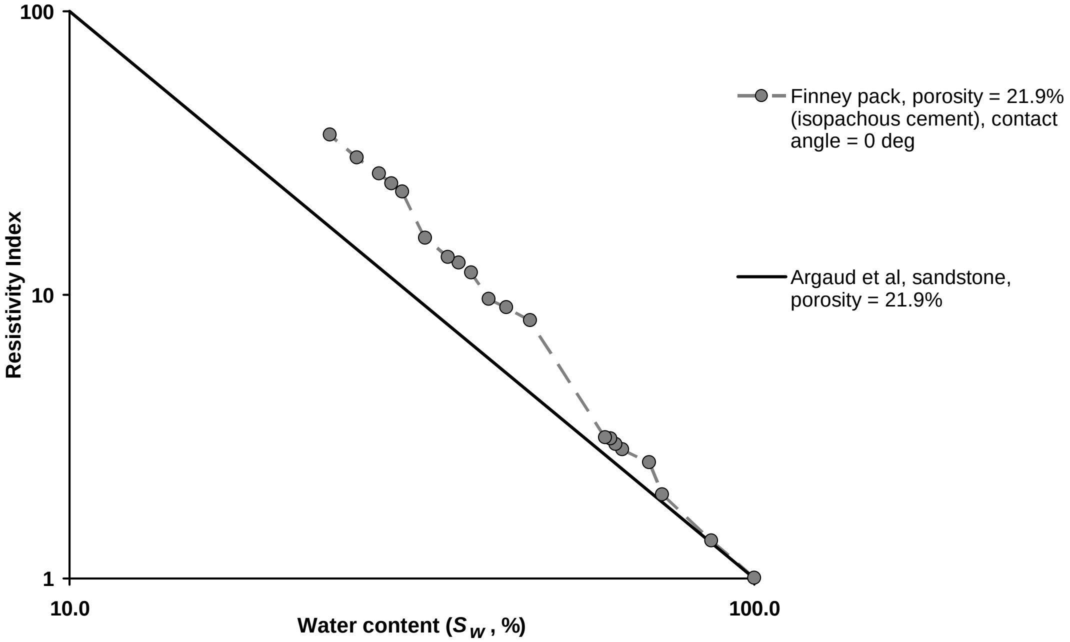

Fig. 2 Comparison between predictions of resistivity index during drainage in the cemented Finney packing (isopachous cement, porosity = 21.9%, contact angle = 0 degrees, 9 entrance pores) and the experimental trend for clean Cretaceous sandstone, with porosity of 21.9%, Argaud *et al* [2].

Fig 2 shows a comparison between simulated resistivity index during drainage and experimental data for the drainage in clean Cretaceous sandstone by Argaud *et al* [2]. Simulation of electric current flow was computed in the Finney pack with isopachous cementation, so that its porosity reached the same value as that of the experimental sample (21.9%). The value of contact angle is 0 degrees. The number of pores, connected with the NW phase reservoir (entrances) is chosen to be 9 pores in order to achieve strong percolation threshold behavior in the packing [16]. The smaller experimental values of the resistivity index of the Cretaceous sandstone may be attributed to the presence of conductive thin films of W phase on grain surfaces, the contribution of which was neglected in our model.

Fig 3 presents a comparison between two predicted electrical efficiency trends during drainage in the unconsolidated and cemented (isopachous cement, porosity = 21.9%)

Finney pack (value of contact angle is 0 degrees, number of entrances is 9 pores) and experimental data [13]. Fig 3 shows that predicted trends for the model rocks lie in the same range of efficiencies and are similar to the experimental trends. This allows concluding that the simulations adequately capture the influence of one type of diagenetic alteration (isopachous cement) on electrical efficiency.

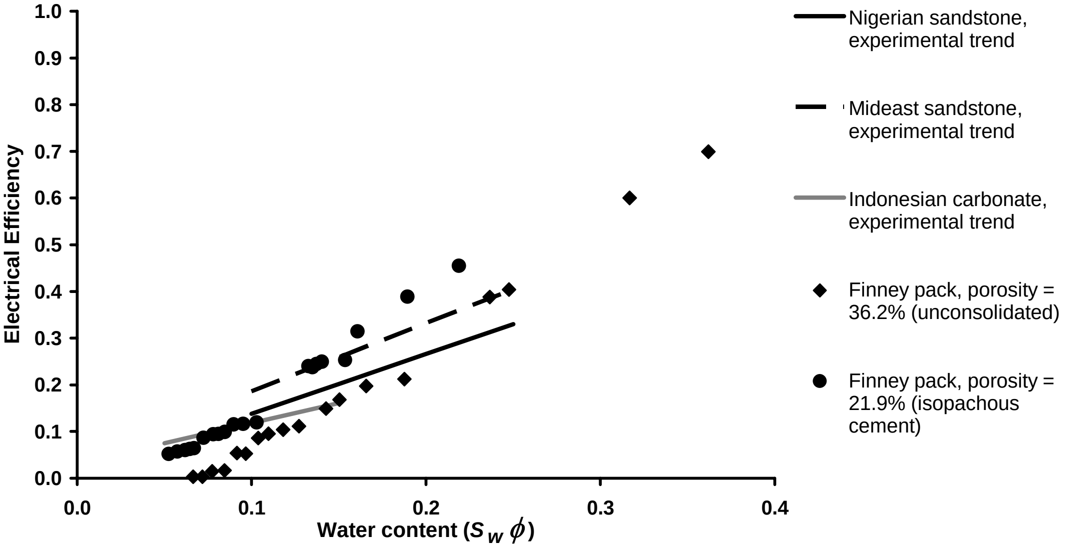

Fig. 3 Comparison between predictions of electrical efficiency during drainage (water-wet system) in the Finney packing and experimental trends (Herrick and Kennedy, [13]).

RESULTS: INFLUENCE OF WETTABILITY

Figs 4 – 7 present the predicted hysteresis in resistivity index (Figs 4 and 5) and electrical efficiency (Figs 6 and 7) in the Finney pack for different values of contact angle (0 and 30 degrees). It is important to distinguish between two cases: water (brine)-wet conditions and oil-wet conditions. Since we consider brine to be the conductive phase and oil along with solid grains to be insulators, these two cases are qualitatively different. In the water-wet sample the W phase is conductive (brine), in the oil-wet sample NW phase is conductive. Therefore, when plotting the electrical data against *water* (brine) saturation, we must be aware that this saturation corresponds to the W phase saturation in the water-wet sample and the NW phase saturation in the oil-wet sample. Arrows in Figs. 4 – 7 indicate the direction (increase or decrease of water content) of the corresponding process (i.e. drainage or imbibition).

It should be noted also that in the simulations, shown in Figs 4 – 7, the number of entrance pores was chosen to be 200 (which is about 10% of the number of actual surface pores of the packing). In this case the percolation threshold is not as sharp as it is for real samples and for the simulations in Figs 2 – 3 (only 9 entrances), but such a choice allows computing more points at intermediate saturations for large values of contact angle (30 degrees in Figs 4 – 7), when the invasion is very rapid. One undesirable consequence of this is the presence of edge effects – the part of the drainage efficiency curve in Fig 6 at high S_w which shows an increase in electrical efficiency as saturation decreases. This part should be absent for the measurements of sufficiently large real samples and simulations that give strong percolation threshold behavior (cf. Fig 3).

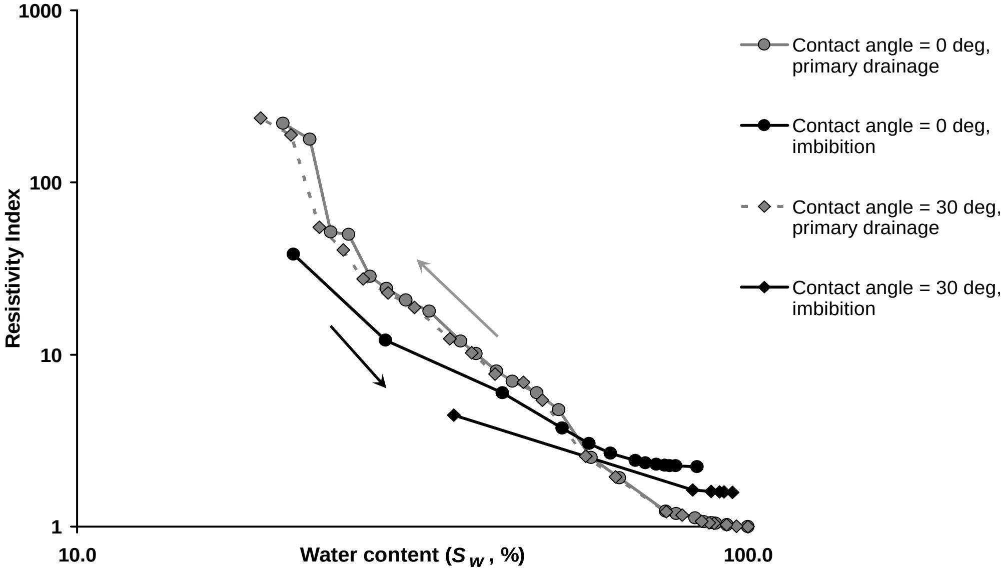

Fig. 4 Hysteresis in resistivity index in the unconsolidated Finney pack. Water-wet conditions.

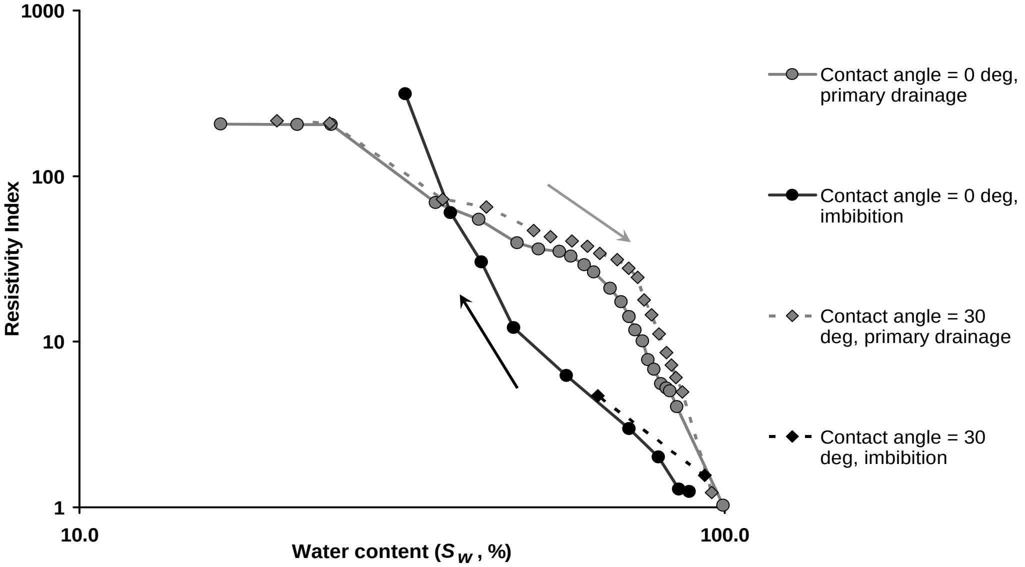

Fig. 5 Hysteresis in resistivity index in the unconsolidated Finney pack. Oil-wet conditions.

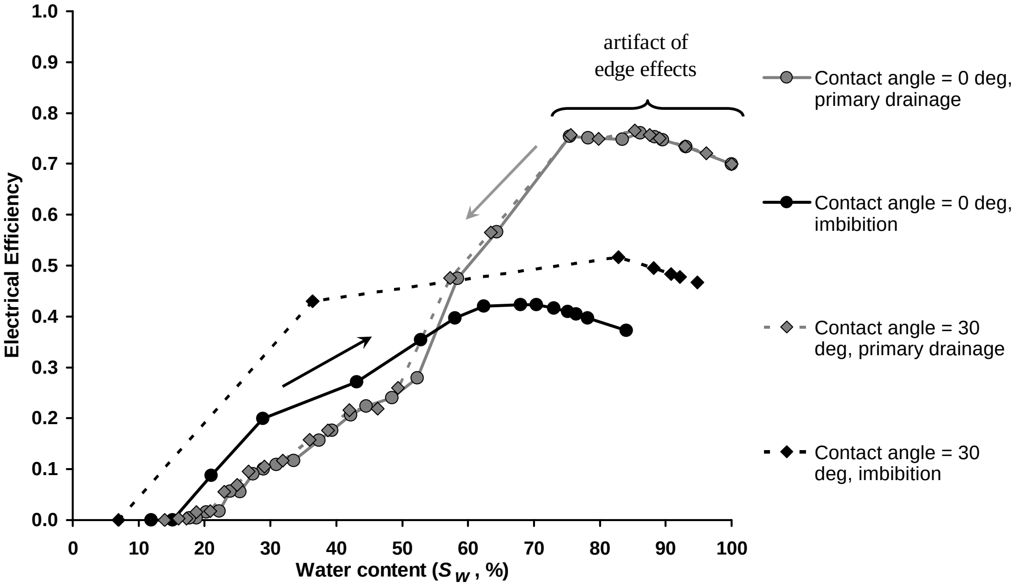

Fig. 6 Hysteresis in electrical efficiency in the unconsolidated Finney pack. Water-wet conditions.

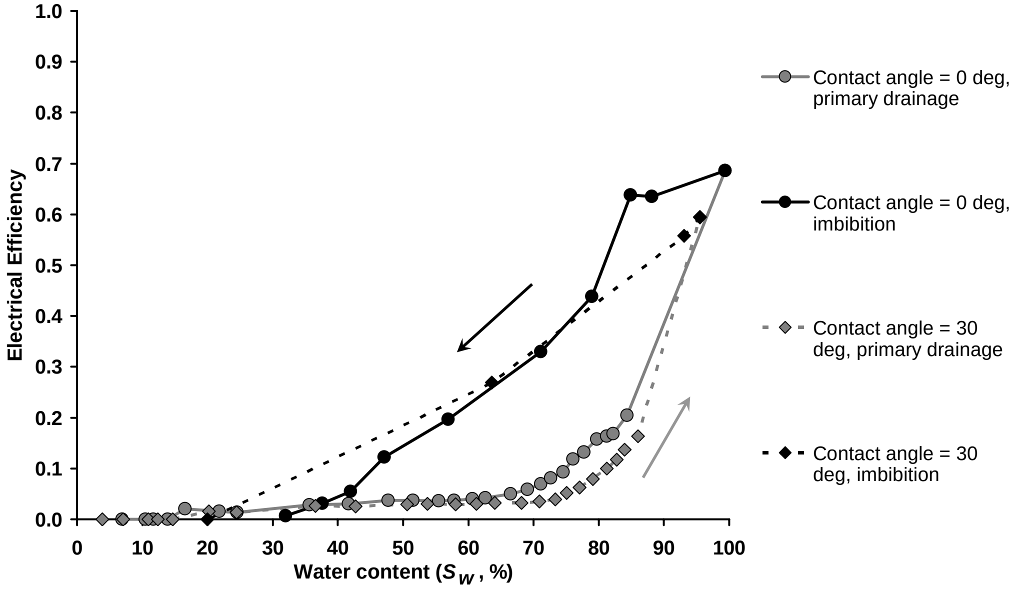

Fig. 7 Hysteresis in electrical efficiency in the unconsolidated Finney pack. Oil-wet conditions.

We can notice two important results: 1) imbibition is more electrically efficient than drainage for any water content; 2) the influence of contact angle on electrical properties in water-wet system during drainage is small, but has a great effect during imbibition. The latter result is due to the fact that for the modeling of drainage we use Haines' face insphere criterion, which is linear with cosine of contact angle (Eq. (2)). Thus the sequence of pore-level events computed with this criterion is independent of contact angle. The topology of the W phase during drainage is therefore exactly the same for any contact angle and the difference between two curves is due to the change in the shapes of pendular rings. To model imbibition, though, we use the Melrose criterion, which is inseparable from the pore space geometry and spatial correlations within it [5]. A change from strongly to weakly wetting conditions leads to the change in the behavior of W phase invasion during imbibition. This effect is caused by the different *topology* of the W phase for different contact angles. When the value of contact angle increases, W phase tends to invade the packing as a *compact body* [11]. In contrast, at zero contact angle the W phase configuration exhibits many more *dendritic branches* with many dead ends.

The existence of hysteresis in electrical properties of water-wet samples is qualitatively supported by the measurements of Knight [14]. Knight measured the resistivity of different sandstones during both drainage and imbibition and observed hysteresis in the electrical resistivity of the samples. On the other hand, several other authors [10, 19, 20] did not observe any hysteresis in resistivity index during displacement cycle for glass beads [20] as well as for different sandstones. This contradictory behavior may be attributed to the measurement technique [10, 21] or to the presence of the conductive films of the W phase on grain surfaces [20]. We speculate that the absence of hysteresis in electrical properties during these measurements is due to the presence of thin films of the W phase. The thickness of these films can be estimated as 10^{-4} of grain radius (about 100 Å for the beads of 0.1 mm radius [20]). The conductive thin films cover grain surfaces continuously during earlier stages of drainage but break up at high pressure at drainage end-point and do not contribute to electrical conductivity during subsequent imbibition. Such behavior would possibly eliminate the predicted hysteresis in electrical properties of water-wet rocks (Figs 4 and 6) if the conductivity of such films is large enough. Overall, this question is subject to further investigation.

For oil-wet conditions the effect of contact angle is qualitatively different. The hysteresis in electrical properties of oil-wet rocks is attributed to the fact that during imbibition the NW phase is trapped within porous media and the bulk connectivity of the conductive phase (brine, which is the NW phase in the oil-wet case) is very low. Therefore, the resistivity can be very high for some finite value of brine saturation. This effect leads to the observed hysteresis in electrical properties of oil-wet rocks for small saturations [20, 21, 23]. The predictions shown in Figs 5 and 7 are qualitatively consistent with these experimental observations.

CONCLUSIONS

In this work we present a methodology for *a priori* prediction of electrical properties of model sedimentary rocks for different wettability conditions and for both drainage and imbibition. The approach is based on the mechanistic modeling of capillarity-controlled displacement and DC current flow at the grain scale in a simple but physically representative model rocks. Meniscus motion at the grain scale is entirely mechanistic, so the method accounts for hysteresis automatically. Hysteresis during the fluid displacement cycle (drainage then imbibition of the W phase) has a significant effect on electrical properties for both water-wet and oil-wet conditions. Simulations also show that contact angle strongly affects electrical properties during imbibition. The predictions made in this paper are compared with existing experimental data and found consistent with most of them.

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NOMENCLATURE

C_0	Electrical conductivity of a rock sample fully saturated with the conductive phase
C_w	Electrical conductivity of water (conductive phase)
C_t	Electrical conductivity of a rock sample partially saturated with water
E_0	Electrical efficiency of a rock sample fully saturated with water
E_t	Electrical efficiency of a rock sample partially saturated with water
e_t	Factor that corrects E_0 for the presence of hydrocarbons
S_w	Water (conductive phase) saturation
J	Curvature of the interface between W and NW phases
P_c	Global capillary pressure
P_w	Pressure of W phase
P_{nw}	Pressure of NW phase
γ	Interfacial tension of W-NW phase interface
J_H	Haines insphere critical curvature of drainage for the pore throat
θ	Contact angle of W-NW-solid interface
ϕ	Porosity
r_t	Radius of circle inscribed into the pore throat
W	Wetting
NW	Non-wetting

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