Geophysical Research Abstracts
Vol. 12, EGU2010-8455, 2010
EGU General Assembly 2010

Streaming Potential during Multiphase Flow: Impact of Fluid and Charge Distribution at the Pore-scale

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A bundle of capillary tubes model has been used to investigate the saturation dependence of the streaming potential coupling coefficient during the flow of water and an immiscible second phase such as air or oil. Models in which the capillaries are water-wet and oil-wet are investigated. Although it is not a good representation of the pore space of most geologic porous media, the advantage of a capillary tubes model is that the distribution of fluid phases and electrical charge at the pore-scale can easily be predicted, allowing petrophysical properties such as relative permeability, electrical conductivity and streaming potential coupling coefficient to be derived in a self-consistent way. Capillary models have been used to provide a simple theoretical basis for the interpretation of single-phase electrokinetic phenomena, and an extension to multi-phase flow in multiple capillaries of different radius is logical.

It is assumed that the charge on the surface of each capillary is constant and that the phase occupancy of capillaries is dictated by capillary equilibrium. The streaming potential coupling coefficient is calculated assuming that the diffuse layer containing the mobile counter-charge is (i) much less than the capillary radius ('thin') and (ii) comparable to the capillary radius ('thick'). The relative streaming potential coupling coefficient generally decreases with decreasing water saturation, falling to zero at the irreducible water saturation. In the limit of a thin double layer, the relative streaming potential coupling coefficient at partial saturation is independent of capillary-size distribution, and depends upon the wettability of the capillaries only if surface electrical conductivity is significant and the irreducible water saturation is small. In the limit of a thick double layer, the relative streaming potential coupling coefficient depends upon the capillary size distribution, wettability and the irreducible water saturation.

If water is the only phase that contains an excess of charge, the multiphase electrokinetic coupling can be described in terms of the water relative permeability, the relative electrical conductivity (the inverse of the resistivity index), and the relative excess counter-charge transported by the flow of water. This latter quantity generally increases with decreasing water saturation in water-wet models, and decreases with decreasing water saturation in oil-wet models. The relationship between the excess counter-charge transported by the flow and water saturation depends upon the pore-scale distribution of fluid and charge. It does not scale inversely with water saturation, as has been assumed previously. At best, this assumption is a first-order approximation for water-wet porous media, and is inappropriate in oil-wet porous media. These results suggest that fine grained rocks such as mudstones, which are saturated with brine of relatively low salinity (so the 'thick double layer' assumption is valid) are likely to exhibit different multiphase coupling behaviour to medium-coarse grained rocks such as sandstones, saturated with brine of moderate to high salinity (so the 'thin double layer' assumption is valid).