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More general relationship between capillary pressure and resistivity data in gas-water system

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ABSTRACT

Capillary pressure data, with fundamental significance in reservoir engineering, can be determined in laboratory through different methods. However, these methods are expensive, complex and time consuming. Scarce literature has been published to describe the relationship between capillary pressure and resistivity data. In this study, a more general model inferring dimensionless capillary pressure directly from resistivity index data was derived from correlating the modified Kr-RI (relative permeability and resistivity index) model with the widely-used Kr-Pc (relative permeability and capillary pressure) model based on the same function of Kr. This model demonstrated a linear relationship between capillary pressure and $(I{\cdot}S_w)^{1/2}/S_w^*$ (I is the resistivity index, S_w is wetting phase saturation, and S_w^* is the normalized wetting phase saturation). The feasibility of this model was verified by experimental data from different literatures and ours. The results demonstrated that the model works satisfactorily in most cases except for cores with extra-low permeability (generally, permeability less than 10 mD). In addition, this proposed model could also match the experimental data both at ambient and reservoir conditions, indicating that it reveals a more general relationship applicable for determining capillary pressure from resistivity data both in laboratories and reservoirs.

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1. Introduction

Capillary pressure is one of the most fundamental properties of multiphase flow transporting in porous media. It is widely used in pore size distribution analysis, irreducible water/residual oil saturation determination, numerical reservoir simulation, and many other aspects of petroleum engineering. Capillary pressure curve is usually determined in the laboratory by mercury injection, porous plate, or centrifuge techniques. However, those methods have many limitations. For example, too much time would be taken and the capillary pressure is limited below 200 psi when porous plate method is applied. For mercury intrusion method, the core can no longer be reused and the mercury has environmental risks. Data analysis in centrifuge method is complicated and even likely to result in errors. It would be useful if the desired capillary pressure data could be obtained through some other methods.

It is known that resistivity measurement is relatively easier than capillary pressure measurement in the laboratory. Besides, large volumes of resistivity data are available from well-logging. Therefore, a new model inferring capillary pressure from resistivity data could be significant in many ways.

According to experimental results, Szabo found a linear relationship between capillary pressure and resistivity index (Szabo, 1974). However, the proposed model has not been widely accepted because single straight lines could not be obtained from the relationship between capillary pressure and resistivity index in many cases. The model is expressed as:

$$\frac{R_t}{R_o} = a + bP_c \tag{1}$$

where R_0 is the resistivity of rock at a water saturation of 100%, R_t is the resistivity at a specific water saturation of S_w, P_c is the capillary pressure, a and b are two constants.

Li formulated a new theoretical model to correlate capillary pressure and resistivity index based on the fractal scaling theory (Li and Williams, 2007). The proposed model indicates a power law relationship between the two parameters and fits well with the experimental results of fourteen core samples from two formations located in one oil reservoir. The model proposed by Li is

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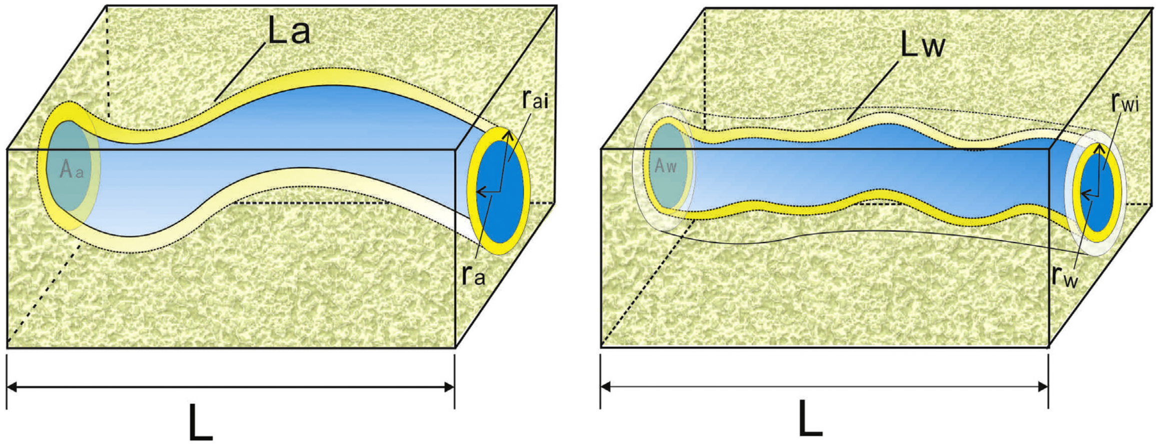
Nomenclature

A	Apparent across area of rock
A_a	Across area of tortuous capillary tube
A_w	Across area of wetting phase effective flow path
I	Resistivity index
K_a	Permeability at a water saturation of 100%
K_w	Permeability at a specific water saturation of S_w
k_{rnw}	Relative permeability of non-wetting phase
k_{rw}	Relative permeability of wetting phase
L	Apparent length of rock
L_a	Length of tortuous capillary tube
L_w	Length of wetting phase effective flow path
n	Saturation exponent
P_c	Capillary pressure
P_{cD}	Dimensionless capillary pressure
P_e	Entry capillary pressure
ΔP	Pressure gradient
Q	Volumetric rate of flow
r_a	Movable water radius of tortuous capillary tube at a water saturation of 100%
r_w	Movable water radius of tortuous capillary tube at specific saturation of S_w
r_{ai}	Radius containing irreducible water at a water saturation of 100%
r_{wi}	Radius containing irreducible water at specific saturation of S_w
R_o	Resistivity of rock at a water saturation of 100%
R_w	Resistivity of rock at a specific water saturation of S_w
S_w	Wetting phase saturation
$S_w{}^*$	Normalized wetting phase saturation
S_{wi}	Irreducible water saturation
μ	Viscosity of water
λ	Pore size distribution index
λ_{rw}	Tortuosity ratio (τ_a/τ_w)
ϕ	Porosity of the rock.
τ_a	Tortuosity at a water saturation of 100%
τ_w	Tortuosity at a specific water saturation of S_w
β	Exponent in the Li model



(a)Water saturation of 100% (b)Specific water saturation of Sw

Fig. 1. Fluid flow path at different water saturation in tortuous capillary tube.

Table 1
Properties of core samples.

Core number	ϕ (%)	k (md)	S_{wi} (%)
1	25	280	0.37
2	26	250	0.39
3	19	70	0.35
4	20	15	0.48
5	21	10	0.46
6	27	100	0.5
7	17	40	0.28
8	26	75	0.4

written as follows:

$$P_{cD} = (I)^{\beta} \tag{2}$$

where P_{cD} is the dimensionless capillary pressure (P_c/P_e); I is the resistivity index. β is the exponent.

According to Li's research, the value of parameter β, not a constant, varies with core permeability. The value of parameter β could be obtained from Li's model. In addition, based on Toledo et al.'s (1994) conclusion, Li model works better in a specific range of low water saturations than in high water saturations. According to Li, the power law relationship between capillary pressure and resistivity index does not exist at high wetting phase saturations (Li and Williams, 2007).

Literature on the relationship between capillary and resistivity index has been scarce. In this study, a more general model was derived theoretically to infer dimensionless capillary pressure from resistivity index data. Compared with previous researches, the dimensionless capillary pressure from our model is the function of irreducible water saturation (S_{wi}) and resistivity index (I) without any indeterminate coefficients. In order to verify the proposed model, capillary pressure data calculated from this new approach are compared with the experiment data of 24 core samples from different literatures and our experiments.

2. Mathematics

After modification of the Kr-RI (relative permeability and resistivity index) model proposed by Ma et al. (2015), a more general relationship between capillary pressure and resistivity index data

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