Study on the rock-electric and the relative permeability characteristics in porous rocks based on the curved cylinder-sphere model

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ABSTRACT

Usually, in conventional reservoirs, the rock-electric properties can be explained by Archie's law, and the relative permeability is only considered as a function of fluid saturation. However, as for the complex reservoirs, Archie's law fails to accurately describe the rock-electric properties and the relative permeability is not only affected by saturation, the reason is that both rock-electric and relative permeability characteristics are influenced by multi-factors, including the complex pore structure, fluid distribution, and wettability. Currently, there lacks the theoretical method to comprehensively study the multi-factors effect on rock-electric and relative permeability characteristics. In this paper, the curved cylinder-sphere model is developed to illustrate the complex pore-throat structure, fluid distribution, and wettability in real rocks, which can be characterized by two important parameters: the ratio C_d of the curved cylinder radius to the sphere radius and the tortuosity τ. Based on the curved cylinder-sphere model, and by using Ohm's law, one can carry out the research on the effect of pore geometry, fluid distribution, and wettability on rock-electric characteristics. Moreover, by combining the curved cylinder-sphere model with Li's model, the effect of pore structure, fluid distribution, and wettability can be incorporated into the relative permeability calculation model. By means of the numerical simulation and analysis, it comes to conclusions that pore structure, fluid distribution, and wettability are the principal factors affecting both rock-electric and relative permeability characteristics, which may cause different formation factor, resistivity index, and relative permeability even in those reservoirs with the same porosity and fluid saturation. Besides, the study demonstrates that the complex pore structure, fluid distribution, and wettability may cause the non-Archie phenomenon of rock-electric characteristics, in addition, the complex pore structure can lead to the decrease of water relative permeability and the increase of oil relative permeability, and when the rock wettability changes from water-wet to oil-wet, water relative permeability increases and oil relative permeability decreases. Furthermore, by the comparison of the simulation results and Lab data, the important effect of complex pore structure and fluid saturation is confirmed.

1. Introduction

In terms of the conductive model in two-phase flow medium, the classic Archie equation can give a good description of rock-electric characteristics in pure sandstone reservoirs with simple pore structure. However, the study shows that there always exists non-Archie phenomenon and low-resistivity oil layers in complex reservoirs caused by some factors, such as the complex pore structure, fluid distribution, and wettability, which cannot be well explained by Archie law. As the water saturation decreases and the pore structure becomes complex, the non-Archie phenomenon becomes more evident, and non-Archie behaviors of porous rocks (i.e., $F - \phi$ and $I - S_w$ relationships are not linear on a log-log scale) have been increasingly observed in electrical logging interpretation. Diederix (1982), Li (1989), Worthington and Pallatt (1992), Jing et al. (1993), Montaron (2009), and Padhy et al. (2006,

2007) have extensively studied the non-Archie phenomenon in porous rocks.

Besides, some studies indicate that the relative permeability can intuitively reflect oil-water seepage characteristics, which is related to rock-electric characteristics, and the study of oil-water seepage characteristics is the key to water flooding development of low permeability reservoir. Generally, the relative permeability can be measured in laboratory by using the steady state and unsteady state methods. However, as for those rocks with the low permeability and complex pore structure, it is not only time-consuming and expensive but also hard to obtain directly by the lab measurement. Later, some studies published have focused on the estimation of the relative permeability from capillary pressure data. Purcell (1949) established the relationship between the relative permeability and pore size, capillary pressure. According to Gates and Leitz (1950) report, this relationship has been

applied to multiphase flow in porous media. Burdine (1953) then took the tortuosity factor into consideration in the model, which is a function of fluid saturation. By summarizing the previous work, Corey (1954) and Brooks and Corey (1966) modified the capillary pressure as a power function of wetting-phase saturation, and proposed a new model to determine the relative permeability, which has been widely used in the field. However, capillary pressure is not only hard to measure but also not practical for field data processing. Li (2005, 2008, 2011) found a relationship between relative permeability and resistivity index from the analogy between fluid flow and electric flow properties. Pairoys et al. (2013) improved Li's model by considering residual non-wetting phase saturation. Ma et al. (2015) derived two-phase relative permeability from resistivity by combining Poiseuille's law with Darcy's law and introducing tortuosity ratio into the model. Ge (2015) predicted the relative permeability based on theory of coupled electricity-seepage and capillary bundle model. However, few work is conducted to study and model the important effect of pore structure, fluid distribution, and wettability on the relative permeability.

In this work, the objective of the study is to study the effect of pore structure, fluid distribution, and wettability on the rock-electric and relative permeability characteristics in two-phase flow medium (water is wetting phase, and oil is non-wetting phase). A curved cylinder-sphere model is proposed to describe the complex pore-throat structure, fluid distribution, and wettability properties, which is described by two parameters: the tortuosity and the ratio of curved cylinder radius to sphere radius. By the comparison of the simulation results and the experimental data, it shows that the formation factor and the resistivity index are greatly affected by pore structure, fluid distribution, and wettability, and the theoretical results are in good agreement with experimental data, besides, by considering the complex pore structure, fluid distribution, and wettability, the non-Archie phenomenon can be interpreted. Furthermore, by combining the curved cylinder-sphere model with Li's model, the pore structure parameters can be introduced into the relative permeability model, and the modified model can be used to model and explain the effect of the complex pore-throat structure, fluid distribution, and wettability on the relative permeability.

2. Resistivity index and relative permeability in rocks with simple pore structure

In real reservoirs, pore structure is very complex. However, for the sake of simplicity, pore model should be simplified to illustrate the pore structure.

Usually, reservoir rock is simplified into a unit volume cylinder, and pore structure is simplified as a curved cylindrical pore containing oil-water two-phase flow, as shown in Fig. 1, A is the apparent cross-section area of rock, and is equal to 1.0, L is the length of rock, and equals 1.0; Aw is the apparent cross-section area of effective water flow pathway, l' is the length of the tortuous water flow pathway and L' is the length of the tortuous cylindrical pore. Based on Archie's law (Archie, 1942; Cai et al., 2017), the resistance of rock at a 100% water

Fig. 1. The oil-bearing curved cylinder model.

saturation and at a specific water saturation of S_w can be derived:

$$R_o = \frac{\tau_o^2}{\phi}R_w \tag{1}$$

$$R_t = \frac{\tau_t^2}{\phi S_w}R_w \tag{2}$$

where τ_o is the tortuosity at a 100% water saturation, $\tau_o = L'/L$, a dimensionless quantity whose value is always ≥ 1; τ_t is the tortuosity at a specific water saturation of S_w, $\tau_t = l'/L$, a dimensionless quantity whose value is always ≥ 1; R_o and R_t are the resistance of rocks at a saturation of 100% and a specific saturation S_w, respectively; R_w is the resistance of brine; ϕ is rock porosity.

According to Archie's law, the resistivity index can be written as:

$$I = \frac{\tau_t^2}{\tau_o^2}\frac{1}{S_w} \tag{3}$$

For rocks with simple pore structure, both τ_o and τ_t take the value of 1, then the resistivity index becomes:

$$I = \frac{1}{S_w} \tag{4}$$

Eq. (4) is considered as the simplest form of Archie's law, which can be used to describe the resistivity index property of the simple capillary model, while it can't illustrate the complex pore structure.

Li (2008) found a relationship between relative permeability and resistivity index from the analogy between fluid flow and electric flow properties. Li's model is expressed as:

$$K_{rw} = S_w^* \frac{1}{I} \tag{5}$$

$$S_w^* = \frac{S_w - S_{wi}}{1 - S_{wi}} \tag{6}$$

where S_w^* is normalized saturation, dimensionless unit, S_w is the wetting phase saturation, dimensionless unit, and S_{wi} is the irreducible saturation of the wetting phase, dimensionless unit.

Substituting Eq. (3) into Eq. (5), the relative permeability is expressed as:

$$K_{rw} = \frac{\tau_o^2}{\tau_t^2}S_w^*S_w \tag{7}$$

Burdine (1953) gave an empirical expression of tortuosity ratio, which is a function of wetting phase saturation:

$$\frac{\tau_o}{\tau_t} = \frac{S_w - S_{wi}}{1 - S_{wi}} = S_w^* \tag{8}$$

Substituting Eq. (8) into Eq. (7) yields the relative permeability:

$$K_{rw} = S_w^{*3}S_w \tag{9}$$

Note that the derived Eq. (9) is similar to the semi-empirical relative permeability model proposed by Corey (1954), and the relative permeability can be easily inferred from water saturation, but it only contains the effect of fluid saturation, which is not suitable for complex reservoir rocks.

3. Study on rock-electric characteristics of complex rocks based on the curved cylinder-sphere model

3.1. Rock-electric characteristics in single-phase flow medium

Here a real reservoir rock is still simplified into a unit volume cylinder with a cross-section area of 1.0 and a length of 1.0, however, the complex pore structure is considered as a curved cylinder-sphere model, which is composed of sphere pore and curved cylinder pore, and the pore space is fully saturated wit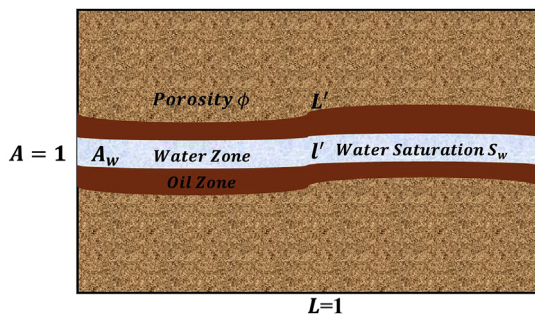h water, as shown in Fig. 2. The pore