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Electrical conductivity models in saturated porous media: A review

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ABSTRACT

Electrical transport properties of saturated porous media, such as soils, rocks and fractured networks, typically composed of a non-conductive solid matrix and a conductive brine in the pore space, have numerous applications in reservoir engineering and petrophysics. One of the widely used electrical conductivity models is the empirical Archie's law that has a practical application in well-log interpretation of reservoir rocks. The Archie equation does not take into account the contributions of clay minerals, isolated porosity, heterogeneity in grains and pores and their distributions, as well as anisotropy. In the literature, either some modifications were presented to apply Archie's law to tight and clay-rich reservoirs or more modern models were developed to describe electrical conductivity in such reservoirs. In the former, a number of empirically derived parameters were proposed, which typically vary from one reservoir to another. In the latter, theoretical improvements by including detailed characteristics of pore space morphology led to developing more complex electrical conductivity models. Such models enabled us to address the electrical properties in a wider range of potential reservoir rocks through theoretical parameters related to key reservoir-defining petrophysical properties. This paper presents a review of the electrical conductivity models developed using fractal, percolation and effective medium theories. Key results obtained by comparing experiential and theoretical models with experiments/simulations, as well as advantages and drawbacks of each model are analyzed. Approaches to obtaining more reasonable electrical conductivity models are discussed. Experiments suggest more complex relationships between electrical conductivity and porosity than experiential models, particularly in low-porosity formations. However, the available theoretical models combined with simulations do provide insight to how microscale physics affects macroscale electrical conductivity in porous media.

1. Introduction

Electrical conductivity of saturated porous media has numerous applications in reservoir engineering and petrophysics. In recent years, the number of theoretical methods to model electrical conductivity of complex porous media has dramatically increased as new theories were developed and modern technologies became available (Thompson et al. 1987; Sahimi 1993; Hunt 2004). Nevertheless, the process of modeling the spatial conductivity distributed function continues to present challenges when these models used in reservoirs, particularly in porous media with strongly heterogeneous pore-space distributions. Multiple interactions (Revil and Glover 1997, 1998), including chemical process (such as grain surface coordination reaction and redox of metal ion) and physical process (such as electrical double layer and stern layer), occur between solid grains and interconnected pores at various spatial scales. To date, no universal methodology exists that can accurately and effectively model the electrical conductivity systems.

This paper reviews the state of the art of scientific knowledge and practice for modeling porous structural systems, with the purpose of identifying current limitations and defining a blueprint for future modeling advances. We compare conceptual descriptions of electrical current flow processes in pore space considering several distinct modeling approaches. The complexity of the electrical conductivity at the micro-scale results in a high degree of uncertainty and an incomplete understanding of the interactions between physical processes (Sahimi 2011) and chemical processes (Telford et al. 1990; Revil and Glover 1997). Since the process of electrical current flow needs to take into account the effect of pore structure at multiple scales, availability of data is still a strong limitation to the accuracy and validity of models. Gaps between theory and practice exist in which electrical conductivity processes take place and the pore structure characterized by theoretical models. Therefore, electrical conductivity models are often simplified as a function of pore size distribution. Many approaches devoted to specific objectives are case-dependent and therefore may not applicable

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to all types of porous media.

Here we review advances in our understanding of electrical conductivity models in porous media, and analyze the applicability of several well-known methods/theories to electrical characteristics of porous rocks as a function of pore volume, tortuosity and interconnection, to estimate electrical conductivity based on the microgeometrical properties of rocks. With these objectives, Section 2 focuses on experiential or theoretical model findings, including conductivity measurements and their features, and details of theoretical models recently developed to estimate electrical conductivity of porous media. A discussion of future development and directions for electrical conductivity is presented in Section 3, with concluding remarks provided in Section 4.

2. Electrical conductivity models

Since the electrical conductivity property depends on rock type, electrical conductivity measurements have been widely used in the analysis and interpretation of the electrical resistivity logging of wellbores (Porter and Carothers 1971; Rivero 1977; Salem 1993; Bourlange et al. 2003) and electrical-resistivity-image data (Singha and Gorelick 2006a, 2006b; Swanson et al. 2012; Ye et al. 2015), which could provide reliable information of reservoirs and resource characteristics in the sedimentary areas. Knowledge of porosity and electrical conductivity of a rock and its structural characteristics should be further investigated. Furthermore, electrical conductivity values can also be obtained through additional parameters derived by simple reconstruction of a rock's component parts (Lemaitre et al. 1988; Mualem and Friedman 1991; Bernabé and Revil 1995; Friedman and Seaton 1998), which results in a “structure factor” (Glover 2009, 2016) representing an approximate representation of the true geometrical configuration of the porous rock (Ghanbarian et al. 2014).

To obtain the “structure factor” (or geometrical factor), the values of electrical conductivity must be related to the geometrical structure of the porous media by using experiential or theoretical routines. One of the earliest known and most applied methods to obtain the formation factor is Archie equation (Archie 1942; Winsauer 1952; Katz and Thompson 1985; Moshier 1989; Singha and Gorelick 2006a) based on physical properties of a reservoir rock which can be derived by analyzing data in the laboratory. To evaluate the validity of the linear form of the formation factor derived by log-log crossplotting, the data distribution needs to be carefully considered. The scatteredness of the distribution defines the error, in terms of the percentage difference, between the measured and calculated values. In general, the more closely the data follow a linear distribution on a log-log crossplot, the fewer the number of feasible fits that can be applied to the data (Kennedy and Herrick 2012). However, Ghanbarian et al. (2014) found that the nonlinear distribution of formation factor could occur in many situations. They identify a particular porosity value to describe the change from a linear distribution to nonlinear distribution. Therefore, the character of the data distribution is important in determining the choice of theoretical model to apply. Although the Archie equation is the most-widely-applied method, many other theoretical models are currently proposed and applied to represent the electrical conductivity model in saturated porous media with no clay mineral effects (see Table 4 and Section 2.3).

Due to the absence of other critical variables describing the geometrical factors (such as tortuosity, pore size distribution, interconnectivity) of porous media in practice, experimentally measured porosity (used to roughly characterize porous structures, actually, description of pore structure need the J function, distribution of pore radius and formation factor in rock physics) is widely applied in experiential models. The electrical conductivity of the solid matrix is considered as the insulator component, which is usually ignored in practical applications to reduce model complexity. Also, the possibility or necessity to address the electrical conductivity of fluid and solid separately, makes effective medium theory or other approaches more suitable for the analysis of interconnected pores (or tortuosity, pore network) than models applying a single experiential fit.

Theoretical improvements have achieved much progress in electrical conductivity modeling of porous media. These have provided more effective and accurate methods and more representative frameworks. They have also facilitated the development of improved measurement technologies (Arns et al. 2001; Ju et al. 2014; Shabro et al. 2014; Zhang et al. 2016) for recording geometrical structures, and creating reconstructions of their pore space distribution. Over the past 60 years, the number of systems and models applied to electrical conductivity research has grown remarkably.

Several inherent properties of porous media influence current flow, such as pore-throat, interconnection and tortuosity. The shape of the component-mineral grains and pores are more important to current flow than its dependence on the degree of cementation in compacted-porous reservoirs (Babadagli 1999; Per Atle 2011; Pan and Connell 2012; Li et al., 2015b; Kadkhodaie and Rezaee 2016). In particular, various pore-scale image analysis methods (Tsakiroglou and Ioannidis 2008; Wang et al. 2012) were used to explore the factors controlling the accurate estimation of the formation factor. These methods have made it easier to analyze the effects of current flow in porous rock, particularly where the pore conditions are advantageous (i.e., better connected pores with surface conductivity is usually caused by the irreducible water and clay minerals (Revil and Glover 1997, 1998)).

The development of theoretical models for the electrical conductivity made it easier to analyze the experimental data and generate structural factors to use for the characterization of the natural media being investigated, i.e., to provide information concerning the geometrical configuration of sedimentary rocks (i.e. pore size, interconnection). The process of extracting structural factors is an inverse procedure (Tarantola 1987) (such as the least squares method) by means the experimental data. This is extremely important as it allows electrical conductivity models not only to define the geometrical characteristics of rock core, but also to relate those findings as basic trends within a larger-scale rock formation. The literature reports some examples of electrical conductivity models in porous media with their main aim being to investigate the effects of rock fabrics, geometries and configuration (Bussian 1983; Dalla et al. 2004; Brovelli et al. 2005; Bernard et al. 2007; Hunt et al. 2014). Although some reconstruction of rock geometries and numerical simulations of field data acquired have already been carried out, more work of this nature is required; especially, to quantify the relationships between the variation of the electrical conductivity and changes in various rock parameters.

2.1. Empirical models based on experimental measurement

Archie's first equation $F = \phi^{-m}$ (in which F is the formation factor or formation resistivity factor defined as the electrical conductivity of internal fluid divided by the electrical conductivity of rock, ϕ and m are respectively porosity and cementation exponent) was originally proposed to capture the trend of electrical resistivity with various brine volumes in the Nacatoch sandstone. Sedimentary rocks with similar trends are called “Archie rocks” in the literature. Winsauer (1952) extended Archie's first equation to apply more type of rocks:

$$F = a\phi^{-m} \tag{1}$$

where a is empirical constant based on experimental data. It is worth noting that $a = 1$ in $\phi = 1$ as a result of $F = 1$. Nevertheless, Winsauer (1952) found $a = 0.62$ based on 29 sandstone experiments for better fitting error. More values of a are given in Table 1. Ghanbarian et al. (2014) argued that values $a < 1$ are less common than $a > 1$. It does not take much of a change in the contact angle to produce $a < 1$. Therefore, any type of diagenesis that preferentially affects pore throats over pore volume can also result in $a < 1$.

However, not all rocks follow the same porosity-resistivity trends