



Numerical calculation of the rock permittivity using micro computerized tomography image



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ABSTRACT

A numerical evaluation of the permittivity of sandstones through the micro computerized tomography (micro CT) images at 1.1 GHz is conducted by using an image porosity extracting algorithm and an improved Finite Difference Method (FDM). Within the acquired physical properties by 3D micro CT scanning, numerical method is used to compute the permittivity of the rock samples. A resonant cavity is used for experimental measurement. The simulated results of 2 clastic sandstone samples with dry state and saturated state are compared with experimental data for validating the accuracy of the proposed numerical method. The results show great agreement and the error of permittivity evaluation is less than 3%.

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1. Introduction

Deterministic models and empirical formulas are methods used in predicting conductivity, permittivity, porosity, permeability and other petro-physical properties that define a reservoir (Abou El-Anwar and Gomaa, 2013; Greeney and Scales, 2012; Hu and Liu, 2000; Knight and Nur, 1987; Rogers et al., 2011; Shen et al., 1985; Todd and Shi, 2005; Zeng et al., 2006). However, these methods are created to honor data measured in specific environments, thus they fail when applied to a wider range of rocks under different conditions. Especially according to some researching cases in gas and oil reservoirs recently, it was seen that the dielectric dispersion can result in huge dielectric constant enhancement at low frequencies (Asami, 2006; Felix, 2011; Sengwa and Soni, 2006), which can hardly be measured by any experimental devices. Based on the effective medium theory, numerous analytic formulas were developed to compute the effective dielectric constant of the composite materials that consist of spherical inclusions (Hanai, 1968). However, all these analytic methods could only compute the composite media with very simple structures (e.g., the inclusion is spherical or ellipsoidal). For the mixtures which contain cubic or cylindrical inclusions, there is no analytic formula to compute its effective dielectric constant so far.

Therefore a new approach is needed to provide an accurate way of unraveling the physics behind the observed phenomenon which could be applied to different scenarios. Nowadays, high resolution 3D rock

morphology can be acquired by using micro computerized tomography (micro CT). This 3D image can be used to numerically calculate desired physical parameters of the material usually conducted experimentally over a sample core, such as horizontal and vertical permeability, porosity, etc. (Golab Alexandra and Knackstedt, 2010; Wang et al., 2010). In this paper, micro CT is used in scanning the rock to determine its physical properties in 3D. Within the acquired geometry restrictions, numerical methods are used to compute the electric properties of the rock at 1.1 GHz to minimize the dielectric dispersion effect. For accurately calculating the electrical properties of composite media with very fine structures, an improved 3D Finite Difference Method (FDM) with special gridding principles is needed to handle the membrane structures. The numerical data is compared and evaluated by measurements done using a resonant cavity. Numerical method confirmation conducted on homogeneous sandstones will give space for further research to be conducted on modeling and numerical evaluation of properties of more complex structures. Moreover, this process will give us greater degrees of freedom in accessing the different morphological rock components that are taking part in the physics of the studied phenomenon without core destruction.

2. Numerical method

In this paper, numerical calculation using Finite Difference Method (FDM) (Kärkkäinen et al., 2001; Luo, 2009; Luo and Liu, 2010) is coded for calculating the dielectric constant at 1.1 GHz of micro CT images of 5 mm diameter rocks. According to Anderson's research (Anderson et al., 2007), surface redox reactions in the presence of an external electric field will generate a polarization layer which is

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presented as a membrane structure between grain and pore space of rock. This phenomenon is thought to exist due to two main mechanisms: polarization of the double layer at the metallic grains and polarization of the double layer at insulating grains. The proposed 3D-FDM method is based on a cubic capacitor model under quasielectrostatic assumptions and periodic boundary conditions, which can be used to simulate general mixtures and mixtures with membrane structure. A special FDM grid is introduced to handle the membrane that coats the inclusions of the composite medium. For the structure with membranes, it is impractical to discretize the membrane by general FDM grids, because the thickness of the membrane may be 0.1% or less of the inclusion size. Fig. 1 shows the special FDM grids used to handle the membrane. The membrane is placed on the interface of the involved grids. So the membrane area doesn't need discretization when the FDM meshes are generated. The thickness and electrical parameters of the membrane are considered when we calculate the admittance between the grid points where the membrane presents (Fig. 1(d)).

The cubic subset of the original micro CT image is $n \times m \times k$ elements. Each element is a cube with side lengths equal to $3.2 \mu\text{m}$, which is the resolution of the micro CT scanner. The distribution of the nodes with respect to the cubic elements was done by considering the center of every element as a node as shown in Fig. 2(a) and (b). The theory is based on quasi-electrostatic approximation of Laplace's equation.

$$\nabla \cdot \vec{J} = \nabla \cdot (j\omega\epsilon \vec{E}) = 0. \quad (1)$$

with

$$\vec{E} = -\nabla\Phi \quad (2)$$

where Φ is the electric potential, ϵ is permittivity, ω is the angular frequency, $\vec{E}$ is the electric field intensity and $\vec{J}$ is the current

density. Each node has 6 connections with the surrounding 6 nodes in the neighboring elements. As a result, the total electric current flowing into a given element from its neighboring nodes is zero. Finally by applying the finite differences approximation on Eq. (1) would result in Eq. (3), (15) respectively with boundary conditions seen in Eq. (17), (20).

$$I_1 + I_2 + I_3 + I_4 + I_5 + I_6 = 0 \quad (3)$$

$$I_1 = (\Phi_{i,j+1,k} - \Phi_{i,j,k}) \cdot Y_1 \quad (4)$$

$$I_2 = (\Phi_{i,j-1,k} - \Phi_{i,j,k}) \cdot Y_2 \quad (5)$$

$$I_3 = (\Phi_{i-1,j,k} - \Phi_{i,j,k}) \cdot Y_3 \quad (6)$$

$$I_4 = (\Phi_{i+1,j,k} - \Phi_{i,j,k}) \cdot Y_4 \quad (7)$$

$$I_5 = (\Phi_{i,j,k-1} - \Phi_{i,j,k}) \cdot Y_5 \quad (8)$$

$$I_6 = (\Phi_{i,j,k+1} - \Phi_{i,j,k}) \cdot Y_6 \quad (9)$$

$$Y_1 = d \frac{2\sigma_{i,j+1,k}^* \sigma_{i,j,k}^*}{\sigma_{i,j+1,k}^* + \sigma_{i,j,k}^*} \quad (10)$$

$$Y_2 = d \frac{2\sigma_{i,j-1,k}^* \sigma_{i,j,k}^*}{\sigma_{i,j-1,k}^* + \sigma_{i,j,k}^*} \quad (11)$$

$$Y_3 = d \frac{2\sigma_{i-1,j,k}^* \sigma_{i,j,k}^*}{\sigma_{i-1,j,k}^* + \sigma_{i,j,k}^*} \quad (12)$$

$$Y_4 = d \frac{2\sigma_{i+1,j,k}^* \sigma_{i,j,k}^*}{\sigma_{i+1,j,k}^* + \sigma_{i,j,k}^*} \quad (13)$$

$$Y_5 = d \frac{2\sigma_{i,j,k-1}^* \sigma_{i,j,k}^*}{\sigma_{i,j,k-1}^* + \sigma_{i,j,k}^*} \quad (14)$$

$$Y_6 = d \frac{2\sigma_{i,j,k+1}^* \sigma_{i,j,k}^*}{\sigma_{i,j,k+1}^* + \sigma_{i,j,k}^*} \quad (15)$$

Where I and Y are the current and admittance of each path respectively, Φ is the electric potential of each node, d is the distance between each 2 nodes, and σ^* is the complex conductivity.

Substituting Eqs. (4) and (15) in Eq. (3) this will result in the following Finite difference equation:

$$\Phi_{i,j,k} = \frac{\Phi_{i,j+1,k} \cdot Y_1 + \Phi_{i,j-1,k} \cdot Y_2 + \Phi_{i-1,j,k} \cdot Y_3 + \Phi_{i+1,j,k} \cdot Y_4 + \Phi_{i,j,k-1} \cdot Y_5 + \Phi_{i,j,k+1} \cdot Y_6}{Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6} \quad (16)$$

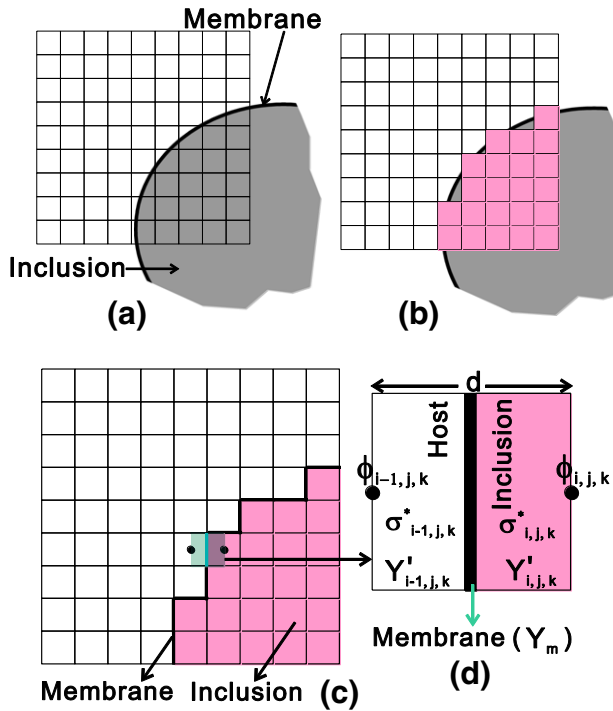


Fig. 1. Mesh generation of the inclusion coated by a membrane. (a) The original state of the boundary; (b) grid the inclusion; (c) place the membrane on the interface of the grids; (d) the interface with a membrane between node $(i-1, j, k)$ and (i, j, k) .

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