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Predicting gas–water relative permeability using Nuclear Magnetic Resonance and Mercury Injection Capillary Pressure measurements

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A B S T R A C T

Relative permeability functions are useful in understanding gas–water two–phase flow in rocks and reservoirs. When direct laboratory data of relative permeability are not available for evaluating gas-water two-phase flow in rocks and reservoirs, indirect prediction models using gas-water relative permeability functions are widely used.

In this research, four typical existing predicting models of relative permeability based on capillary pressure are investigated (the Purcell, Burdine, Brooks–Corey and Li models). These models notably simplify the gas–water spatial distribution in rocks: the Purcell, Burdine and Brooks–Corey models all assume that gas flows in large tubes, while water flows in small tubes, and irreducible water adsorbed on tube surfaces is not considered. Alternatively, the Li model considers irreducible water adsorbed on tube surface; however, the proportion of irreducible water, mobile water and gas are assumed to be constant in tubes with different radii, as this model was derived from a single tube flow structure.

This research proposes a new relative permeability model in which the pore–size distribution, the tortuosity and the gas–water spatial distribution are all considered. A bundle of capillary tubes model and modified single-tube flow model are applied in the proposed model. Capillary tubes in the rock are divided into large tubes and small tubes. In large tubes, the water phase contacts the tube surface and is partially adsorbed onto the surface and partially mobile, while gas phase flows in the center of tubes and is surrounded by water. In small tubes, only irreducible water exists. Variables in the proposed model such as the thickness of irreducible water, mobile water and gas are usually unknown. Combined with a capillary pressure curve, the shift of the transversal time (T2) distribution of Nuclear Magnetic Resonance is used to determine these variables.

The proposed model is validated by experimental data from six rock samples that have different lithology, diagenesis characteristics, pore structure characteristics, irreducible water saturation and different grades of T2 distribution shifts. The model results are compared with the calculated values from other four existing models and the experimental data. Our results show that the proposed model matches the experimental data better than other models, and diagenesis and pore structure characteristics are more sensitive to the proposed model than is lithology.

1. Introduction

Understanding two–phase flow in porous rocks is important for recovery enhancement in petroleum industry. Relative permeability functions are useful in understanding gas–water two–phase flow in rocks and reservoirs. The commonly used methods for acquiring relative permeability information can be classified as direct laboratory methods and indirect predictive methods. Direct laboratory data from steady–state or unsteady–state techniques (Krevor et al., 2012; Alizadeh and Piri, 2014, Chen et al., 2014; Kianinejad et al., 2014, 2015a, 2015b) are not always available (Honarpour et al., 1986), so some indirect predictive models are used widely. Purcell (1949) proposed a permeability model based on the capillary pressure curve. Supposing that water flows in small

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capillary tubes and gas flows in large capillary tubes, a simple relative permeability model may be derived. Following Purcell's research, relative permeability models based on capillary pressure were proposed by Burdine (1953), Corey (1954), Brooks and Corey (1966). The advantage of these models is that pore size distribution and tortuosity are considered, though irreducible water film is not considered. Since Helba et al. (1992) first introduced percolation theory into relative permeability calculations, this method has been used or improved by many researchers, including Salomao (1997), Dixit et al. (1998), Phirani et al. (2009), Kadet and Galechyan (2014). However, coordination numbers and fractions of pores in the network used in these models are hard to determine precisely.

With the development of industrial measurement technology, more and more powerful experimental methods have been used to describe the microscopic characteristics of the rock. Schembre and Kovscek (2003) measured the relative permeability in spontaneous imbibition experiments, where the saturation profiles were acquired via an X-ray CT scanner. Turner et al. (2004) directly imaged the distribution of the fluid phases of water-wet Berea sandstone via micro-CT, and determined the relative permeability of non-wetting phase at water saturation of 60%. Based on Turner's work, Hussain et al. (2014) computed the relative permeability directly from micro-CT images of actual fluid distributions of a strongly water-wet Bentheimer sandstone; however this image-based relative permeability model is limited by the finite resolution of CT equipment and small volume of rock sample.

As a practical and powerful alternative to X-ray CT, Nuclear Magnetic Resonance (NMR) is widely used in the study of porous media (Gallegos et al., 1988; Arns, 2004; Mohnke, 2014). Romanenko and Balcom (2013) designed a new core holder to perform the drainage process (dodecane displacing D_2O). With the help of NMR methods, the end effect was quantified and exploited for the assessment of non-wetting phase relative permeability. Xu and Torres-Verdín (2013) proposed a computer algorithm to construct 3D cubic pore networks by using NMR and Mercury Injection Capillary Pressure (MICP) measurements, and then predicted the gas-water relative permeability by two different methods which were based on fluid distribution and fluid phase connectivity. However, mobile water and irreducible water in large pores are completely ignored in the 3D cubic pore networks.

The novelty of this research is using the NMR and MICP to predict gas-water spatial distribution and relative permeability. In this research, four typical existing relative permeability predictive models based on capillary pressure curve are investigated and compared with the proposed model.

2. Mathematical background

2.1. Purcell model

Purcell (1949) proposed a permeability model based on the capillary pressure curve. This model supposes that water flows in small capillary tubes and gas flows in large capillary tubes. Relative permeability can be calculated by the following equations:

$$K_{rw} = \frac{\int_0^{S_w} dS_w \Big/ p_c^2}{\int_0^1 dS_w \Big/ p_c^2} \tag{1}$$

$$K_{rg} = \frac{\int_{S_w}^1 dS_w \Big/ p_c^2}{\int_0^1 dS_w \Big/ p_c^2} \tag{2}$$

where K_{rw} is relative permeability of water, K_{rg} is relative permeability of gas, p_c is capillary pressure, and S_w is water saturation.

2.2. Burdine model

Following Purcell's research and considering tortuosity, Burdine (1953) proposed a similar relative permeability model:

$$K_{rw} = \frac{(S_w - S_{wc})^2}{(1 - S_{wc})^2} \frac{\int_0^{S_w} dS_w \Big/ p_c^2}{\int_0^1 dS_w \Big/ p_c^2} \tag{3}$$

$$K_{rg} = \frac{(1 - S_w - S_{gc})^2}{(1 - S_{wc} - S_{gc})^2} \frac{\int_{S_w}^1 dS_w \Big/ p_c^2}{\int_0^1 dS_w \Big/ p_c^2} \tag{4}$$

where S_{wc} is irreducible water saturation, and S_{gc} is residual gas saturation.

2.3. Brooks–Corey model

Based on Purcell and Burdine's work, Corey (1954) proposed another relative permeability model. This model is more convenient to use, but square of capillary pressure and normalized water saturation should have a linear relationship. Realizing the restriction to the capillary pressure curve, Brooks and Corey (1966) modified the capillary pressure and normalized water saturation to a power law relationship. Using the pore–size distribution index, the Brooks-Corey model is expressed as

$$K_{rw} = \left(\frac{S_w - S_{wc}}{1 - S_{wc} - S_{gc}}\right)^{(2+3\lambda)/\lambda} \tag{5}$$

$$K_{rg} = \left[1 - \left(\frac{S_w - S_{wc}}{1 - S_{wc} - S_{gc}}\right)\right]^2 \left[1 - \left(\frac{S_w - S_{wc}}{1 - S_{wc} - S_{gc}}\right)^{(2+\lambda)/\lambda}\right] \tag{6}$$

where λ is the pore–size distribution index, which is measured directly from a best-fit regression line drawn through capillary pressure data points.

2.4. Li model

Using the concept of momentum balance, Poiseuille's law and Newton's law of viscosity, and considering the influence of irreducible water and tortuosity, Li et al. (2014) derived a gas–water relative permeability model with the assumption of gas–water flow in a single tube. The Li relative permeability equations are given as follows:

$$K_{rw} = \tau_{rw} \frac{(S_w - S_{wc})^2}{(1 - S_{wc})^2} \tag{7}$$