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Influence of pore structure parameters on flow characteristics based on a digital rock and the pore network model

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ABSTRACT

Many approaches have been developed to study the role that pore structure parameters play in flow characteristics. In this paper, regular network models are used to study the influence of the porosity, particle size, pore throat ratio, coordination number, shape factor and pore throat orientation on the absolute permeability. Among them, every parameter has obvious effect except shape factor when single-phase fluid flows in the models. Then the random pore network model is developed to analyze the relative permeability curve with a changing pore throat ratio, coordination number and shape factor. When the water saturation is constant, the oil relative permeability is higher for models that have a higher coordination number or have a lower pore throat ratio, and the wet phase has low permeability because of the corners. In order to study the dominant factor of the pore structure for two-phase flow further, a digital core, based on CT scanning, is constructed to firstly research the capillary influence of internal structure that determines whether the fluid can flow at a certain pressure difference.

1. Introduction

The structure parameters of a porous medium define its absolute permeability, relative permeability and whether flow occurs at a certain pressure difference. For a tight reservoir, in particular, the structures are various and the flow limit is of particular concern (Yao et al., 2013). To clarify the flow mechanism with different transmission parameters, as early as 1856, French engineer Darcy did massive experiments, and obtained relations between the pressure gradient and the seepage velocity, namely for Darcy Law(Bell, 1983), where the permeability k contains the effect of pore structures for flow. With the deepening of the study and the level of research to improve, some scholars have begun to consider the internal structure of porous media. Firstly, the single pipe model was used to study this phenomenon at the pore scale (Carman, 1937; Kozeny, 1927). Next, the classical capillary bundle model was used to accurately represent the porous media more (Purcell, 1949); the model can be used to explain wetting hysteresis. Other researchers improved this model further by defining the concept of the pseudo mean radius and tortuosity. In 1952, famous Ergun equation was proposed by Ergun (1952) and this equation have considered the relations between permeability and porous medium porosity and equivalent mean sphere diameter. Subsequently, statistical models and simple regular pore networks were gradually proposed (Childs and Collis-George, 1950; Dullien, 1975). The relations between permeability and pore structures have been proposed quantitatively.

Currently, there are two main approaches for modeling pore-scale transport: one method is a direct method that is usually solved by N–S equation or Boltzmann equation based on scanning images or reconstructed images; the other method is the pore network model method, which is an approximate way for real structure. In direct modeling, CT is a higher accuracy approach, that was first applied to describe reservoir characteristics by Dunsmuir et al. (1991), compared with the numerical reconstruction method and the 2D scanning electron microscope method. The pore network model is similar to the single pipe and capillary bundle model in principle (Fatt, 1956). The network of pores and throats with simple geometric shapes can be extracted from the 3D image of a core (Blunt et al., 2013); methods that accomplish this extraction include the grain-based method (Bakke and Øren, 1997), the medial-axis based method (Sheppard et al, 2005) and the maximal-ball based method (Dong and Blunt, 2009). In addition, a random algorithm can be used to simulate flow by changing the structure parameters. In direct modeling, the modeled structure is very close to the real core, but most of the direct methods are very

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computationally demanding when addressing multi-phase fluid flow in porous media (Meakin and Tartakovsky, 2009; Raeini et al, 2012), such as the finite element method (FEM) and the Lattice-Boltzmann method (LBM) (Gunstensen et al., 1991). The pore network model is a better approach in computational cost for multi-phase flow, so pore network model is usually constructed based on real pore structure to analyze relative permeability. Arns et al. (2004) introduced the importance of incorporating realistic 3D topologies in network models for predicting multiphase flow properties. The parameters of pore network model obtained by this approach cannot be adjusted. Thus, random three-dimensional pore network model is used in this paper to research the influence of pore structure parameters.

After modeling, a suitable equation should be chosen to control the fluid flow, which is usually based on Knudsen number (Kn) for gas reservoir and is defined as the ratio of the molecular mean free path to the characteristic length. The Knudsen number is useful for determining whether statistical mechanics or the continuum mechanics formulation of fluid dynamics should be used: If the Knudsen number is near or greater than one, the mean free path of a molecule is comparable to a length scale of the problem, and the continuum assumption of fluid mechanics is no longer a good approximation. In this case statistical methods must be used(Colin, 2005). For conventional oil reservoir, the size of the pores is much greater than the size of fluid particle or element, which is far more than fluid molecules (Adler, 1992), so the fluid in a porous media can be regarded as a continuous medium and the N–S equation is valid.

Due to the limitation of the number of computer calculations, many researchers simplify the N–S equation into the Poiseuille formula in the simulation. In this paper, we directly study the influence of structure parameters on the flow characteristics of a transmission based on the N–S equation for simple pore network models and real digital model. In addition, three methods with different strengths are used to study the absolute permeability, the relative permeability and the flow limit. The simple regular network models are designed to research absolute permeability based on N–S equation and random pore network is developed to analyze relative permeability. Besides, the real digital core model is firstly used to study the capillary influence of internal pore structure.

2. Mathematical model and validation

2.1. Flow equation

The fluid flowing in a porous media can be regarded as a continuous fluid. Considering the real condition, the liquid can be idealized as an uncompressed fluid.

When the gravity is neglected, N–S equation can be deduced as follows:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)+\nabla p-\nabla\cdot\left[\mu\left(\nabla\mathbf{u}+\nabla\mathbf{u}^{T}\right)\right]=0 \tag{1}$$

$$\nabla\cdot\mathbf{u}=0 \tag{2}$$

where $\mathbf{u}$ is the flow velocity for one point and ρ is the corresponding density.

This equation with highly nonlinear variables is typically a second-order non-self-adjoint equation (Yuan and Lin, 2007; Jian and Chao, 2010). It is difficult to find the appropriate variational principles for this equation, so the Galerkin finite element method is used to solve this function (Ye and Liu, 2008).

The interpolatory basic function of pressure p and velocity u_i are chose to be weight function of continuity equation and momentum equation respectively. Galerkin weaker form of N–S equation is derived firstly based on Green equation. And then, total finite element equation is deduced as following:

$$A_{nr}^{(e)}\,\overline{u}_{\alpha r}+B_{n\beta rs}^{(e)}u_{\alpha r}u_{\beta s}+C_{\alpha nt}^{(e)}P_t+D_{\alpha n\beta s}^{(e)}u_{\beta s}=E_{\alpha n} \tag{3}$$

$$F_{m\beta r}^{(e)}u_{\beta r}=G_m^{(e)} \tag{4}$$

where, $\alpha=1,2$; $n=1,2\cdots\cdots N_u$; $m=1,2\cdots\cdots N_p$; β is 1, 2and take the sum; r,s is $1,2\cdots\cdots N_u$ and take the sum; t is $1,2\cdots\cdots N_p$ and take the sum. N_u and N_p are total number of velocity nodes and pressure nodes respectively. The symbols in above equation are listed as following:

$$A_{nr}^{(e)}=\int_{\Omega^{(e)}}\rho\Phi_n\Phi_r\cdot d\Omega$$

$$B_{n\beta rs}^{(e)}=\int_{\Omega^{(e)}}\rho\Phi_n\frac{\partial\Psi_r}{\partial x_\beta}\Phi_s\cdot d\Omega$$

$$C_{\alpha nt}^{(e)}=\int_{\Omega^{(e)}}\delta_{\alpha\beta}\frac{\partial\Phi_n}{\partial x_\beta}\Psi_t\cdot d\Omega$$

$$D_{\alpha n\beta s}^{(e)}=\int_{\Omega^{(e)}}\mu\frac{\partial\Phi_n}{\partial x_r}\left(\delta_{\alpha\beta}\frac{\partial\Phi_s}{\partial x_r}+\delta_{r\beta}\frac{\partial\Phi_s}{\partial x_\alpha}\right)\cdot d\Omega$$

$$E_{\alpha n}^{(e)}=\int_{\Omega^{(e)}}\rho f_\alpha\Phi_n\cdot d\Omega+\int_{\Gamma_2^{(e)}}\overline{p}_{\alpha m}\Psi_m\Phi_n\cdot d\Gamma$$

$$F_{m\beta r}^{(e)}=\int_{\Omega^{(e)}}\frac{\partial\Psi_m}{\partial x_\beta}\Phi_r\cdot d\Omega$$

$$G_k^{(e)}=\int_{\Gamma_1^{(e)}}\overline{u}_{nr}\Phi_r\Psi_k\cdot d\Gamma$$

where, Φ_j is unit interpolatory basic function of velocity; Ψ_k is unit interpolatory basic function of pressure; Φ_j is one order higher than Ψ_k; δ represents weight function; Γ is natural boundary.

When the flow is steady flow, finite element equation can be expressed as following. This equation is solved by linearized iterative method.

$$\begin{bmatrix} B_{n1rs}u_{1r}+D_{1n1s} & B_{n1rs}u_{1r}+D_{1n1s} & C_{1nt} \\ B_{n1rs}u_{2r}+D_{2n1s} & B_{n2rs}u_{2r}+D_{2n2s} & C_{2nt} \\ F_{m1} & F_{m2} & 0 \end{bmatrix}\begin{bmatrix} u_{1s} \\ u_{2s} \\ p_t \end{bmatrix}=\begin{bmatrix} E_{1n} \\ E_{2n} \\ G_m \end{bmatrix} \tag{5}$$

2.2. Model validation

To validate the accuracy of the above-described numerical model that describes the control of the fluid through porous media, the physical model is designed as shown in Fig. 1. The parallel circles of infinite extent represent solid cylinders, with fluid flowing in the gray area from the left boundary to the right boundary. Constant pressures are assigned for the inlet and outlet boundaries. The symmetrical boundary condition is used for the top and bottom sides. This two-dimensional model is equivalent to a three-dimensional cylinder structure due to the identical characteristics that are found in every slice.

In adjusting the porosities of models, the radius is set as 5 μm, 10 μm, 15 μm, 20 μm, 25 μm, and 30 μm respectively, and each