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RESEARCH PAPER

A numerical simulation model for multi-scale flow in tight oil reservoirs

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Abstract: A discrete fracture model for multi-scale flow in large-scale fractured tight oil reservoirs is proposed considering the compressibility of reservoir rock and fluid, and the non-linear flow in the tight matrix. Validation of the model is performed, followed by the field application of the model. The two-point flux-approximation scheme is adopted in the model to calculate conductivity, and small grids at the fracture intersections are eliminated by the "star-delta" transformation method to improve the computational stability. The fully implicit discretization scheme is performed on the temporal domain. Automatic differentiation technique which can improve model establishment efficiency and computational accuracy is applied in the model to solve the numerical model. The model is validated with the simulation results of Eclipse and the historical production data of a long fractured horizontal well in a tight oil reservoir in Xinjiang oilfield. Simulation results of a field-scale reservoir show that the model proposed can simulate reservoirs with large-scale complex fracture systems; well productivity is positively correlated with the scale of the stimulated reservoir volume, and the difference in planar fracture density and fracture connectivity are proved to be the key factors that lead to the heterogeneous distribution of remaining oil in tight oil reservoirs.

Key words: tight oil reservoir; discrete fracture model; multi-scale coupling; fracture network; volume fracturing

Introduction

The dual-continuum model and local refine PEBI grid model in Eclipse are two main models used for simulating fractured reservoirs in commercial numerical simulators at present. The double media model is applied in Logarithmically Spaced, Locally Refined, and Dual Permeability model (LS-LR-DK)[1–2] of CMG-GEM and the whole grid logarithm refine model[3] of Nexus. The dual media models in CMG-GEM and Nexus, both taking continuous and large-scale orthogonal simplification method to describe fractures, can't characterize the discrete features of fractures in the reservoir. The PEBI grid model in Eclipse, although capable of describing discrete fractures, is less adaptable to small-scale fractures and large-area fracture network systems[4]. In addition, the dual (and multiple) media model has some inherent disadvantages[5–7]. For these reasons, numerical simulation methods for discrete fractures have been a study focus of researchers. There are some preliminary methods proposed by foreign researchers, but all based on the assumption that rock and fluid in reservoir are incompressible, only capable of handling small scale fracture system and a small number of fractures, and adopting Darcy law for conventional reservoir to simulate flow law of fluid in matrix, these methods are not suitable for simulation of large-scale complex fracture systems in tight oil reservoirs[8–10]. Meanwhile, research in this area is still relatively inadequate in China.

In this study, a discrete fracture numerical simulation model for multi-scale flow in tight oil reservoirs considering the compressibility of reservoir rock and fluid, and non-linear flow in matrix is proposed. "Star-delta" transformation method is introduced into this model to calculate transmissibility, and automatic differential (*AD*) method is used in the solution module. The model has been validated by the simulation results of Eclipse and a fractured horizontal well located in a tight oil reservoir in Xinjiang oilfield. Finally, the model was used to simulate a tight reservoir with large-scale complex fracture network in the "factory well pad" operation mode of Xinjiang oilfield.

1. Multi-scale flow theory

Composed of tight matrix and fracture, the tight reservoir

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shows multi-scale characteristic, including differences in size and spatial distribution of the two media[11], differences of mass flow rate in time scale[12]; and differences in mechanism of mass transfer in different media. Therefore, special characterization method for multi-scale flow is needed for simulation of this kind of complex multi-scale reservoir.

The fractures in reservoir should be characterized by unstructured grids since the existence of fractures makes the spatial distribution of media highly discontinuous, and regular structured grids can't meet the requirements. Moreover, the huge difference in size between the matrix and the fracture is bound to bring great challenge to the calculation stability, so in this study, special methods of gridding such as reduced dimension of fractures was adopted to avoid forming small grids when gridding in tiny fractured space.

The different velocities of fluid flow in the matrix and fracture, and the randomness of the unstructured grid connectivity make it impossible to calculate the system transmissibility with one uniform method. Therefore, the half transmissibility correction method for a single grid was used to calculate the transmissibility of different porous media, and then the control volume two-point flow approximation (TPFA) method and "star-delta" transformation method were adopted to calculate the total transmissibility of different types of connections (matrix-matrix, matrix-fracture, fracture-fracture), to reflect the coupling of all different flows in the multi-scale porous media.

Different from Darcy flow in fracture, fluid flow in tight matrix shows obvious non-linear feature. To characterize the different flow mechanisms in different media, taking advantage of half transmissibility calculation method in different media, the non-linear flow in the matrix was characterized by modifying the half transmissibility of the matrix grid in this study, while the fluid flow in the fracture grid was simulated by Darcy flow, forming the calculation flow of total transmissibility considering differences and coupling of matrix-matrix, matrix-fracture and fracture-fracture transmissibilities.

2. Mathematical model

At present, the popular development mode of tight oil reservoir is depletion development relying on the elasticity of rock and fluid. Therefore, rock and fluid compressibility are considered in this mathematical model. The continuity equation is written as:

$$\frac{\partial(\rho\phi)}{\partial t}+\mathrm{div}(\rho\boldsymbol{v})=q_{\mathrm{v}} \tag{1}$$

Mathematical models of compressible rock and fluid are expressed as:

$$\phi(p)=\phi_0\mathrm{e}^{C_{\mathrm{r}}(p-p_0)} \tag{2}$$

$$\rho(p)=\rho_0\mathrm{e}^{C_{\mathrm{o}}(p-p_0)} \tag{3}$$

The matrix in tight oil reservoir, containing micro-nano-pores, has apparent micro-scale effect[13–14]. Considering the fluid boundary layer and the yield stress, the non-linear flow in the matrix is described by the following equation[15]:

$$\boldsymbol{v}_{\mathrm{m}}=-\frac{K}{\mu}\ \mathbf{grad}\ p\left(\frac{m}{m+|\mathbf{grad}\ p|}-1\right) \tag{4}$$

The fluid flow in the fracture still followed the classical Darcy law.

Peaceman's model used universally in the current commercial numerical simulator was adopted as well model[16].

3. Gridding method

The target area is divided into unstructured grids using the constrained Delaunay triangulation[17–18] (Fig. 1). The flexibility of the triangular grid shape allows the subdivision module to handle various complex distributed fractured networks.

The fractures in the grid domain of Fig. 1 are treated as one-dimensional line grids. Dimension reduction of fracture is a key approach to improve the efficiency and stability of multi-scale simulation. If the fractures are considered as two-dimensional in the grid system, they will be triangulated in the fracture space with very small width, generating many small grids, making the subsequent solving process very difficult. Juanes et al.[19] found through study that the simulation had much higher computational convergence in which the fractures were taken as one-dimensional than that in which the fractures were taken as two-dimensional.

4. Numerical solving method

4.1. Calculation method of multi-scale transmissibility

The main purpose of discrete space in mathematical model is to calculate spatial transmissibility. For any grid shape, the spatial mass transfer between adjacent grids can be described as follows:

$$q_{ij}=T_{ij}\frac{\rho}{\mu}\left(p_j-p_i\right) \tag{5}$$

Using the TPFA method, the expression for T_{ij} can be deduced[20]:

$$T_{ij}=\frac{T_iT_j}{T_i+T_j} \tag{6}$$

T_{ij} is essentially the total transmissibility of adjacent grids, and its calculation adopted the concept of half transmissibility, that is, the transmissibility between single grid and grid inter-

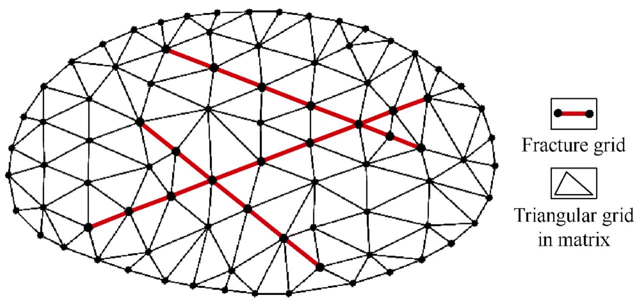

Fig. 1. Schematic diagram of constrained Delaunay triangulation.