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Investigation of flow model and flow behavior in typical fractured-vuggy structure of carbonate reservoirs

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Investigation of flow model and flow behavior in typical fractured-vuggy structure of carbonate reservoirs

Li Xiaobo¹, Yang Min¹, Li Qing¹, Liu Yuewu^{2,3,*}

¹Sinopec Petroleum Exploration and Production Research Institute

²Institute of Mechanics, Chinese Academy of Sciences

³University of Chinese Academy of Sciences

Corresponding author's e-mail address: gaodapeng2009@163.com

Abstract. The storage space and pore structure of fractured-vuggy carbonate reservoirs are complicated. This paper analyzed the flow model for different storage spaces in such reservoir, and proposed the model of free and porous media coupled flow, which is a transition flow pattern between free flow and Darcy flow. The applied flow model for simulation study was the corrected Brinkman equation. Based on the CT scanning images of cores obtained from Tahe Oilfield, we constructed the 3-D digital core and then extracted the distinct fractured-vuggy structures. The COMSOL Multiphysics software was employed to simulate pressure field, velocity field, and streamline of single-phase flow in fracture-vuggy area under different differential pressures. Applying three different flow models, we investigated the fluid flow behaviors of free flow, Darcy flow, and free and porous media coupled flow, respectively.

1. Introduction

With the increasing global demand for energy, the development of unconventional resources has developed rapidly. Carbonate fracture-cavity reservoirs are rich in reserves and high in production, and their related research has attracted widespread interest [1]. Many large oilfields at home and abroad are carbonate reservoirs, with reserves accounting for more than half of global oil reserves. Generally speaking, fracture-cavity reservoirs are very different from conventional homogeneous reservoirs. The distinguishing feature of porous media is strong heterogeneity, which is mainly composed of rock matrix, natural fractures and pore structures of different sizes [2]. The rock matrix can provide some storage space, but the flow capacity is limited. Natural fractures have strong conductivity but low porosity, which can be used as the main way of fluid flow. The cave structure existing in the rock matrix has good fluid storage capacity and is usually connected with natural fractures [3]. Therefore, the flow of fluid in the fractured cavity structure is very complicated. According to the filling situation of the seam structure. Many literatures describe this flow as a mixed flow of free flow (unfilled slit-cavity structure), transition flow (not completely filled slit-cavity structure), and highly permeable porous media flow (completely filled slit-cavity structure) [4-5]. These three different flow models have important effects on well production. However, before studying the coupled flow, the description of fracture-cavity structure is more complicated. The related research methods in recent years are mainly macroscopic and core scales.

The exploration and development of carbonate fracture-cavity reservoirs are relatively difficult. Therefore, during the exploration and development process, the research on the test and evaluation of oil-water flow patterns in this type of reservoir has the following features: Important theoretical and practical significance. In this study, we constructed digital cores based on CT images of these types of



reservoir rock samples, thereby extracting the fracture-cavity space within the sample as the research object. The flow of fluid in a multi-hole connected structure is mainly analyzed. With the help of COMSOL multi-physics model software, we have simulated the flow of fluids under three flow models, namely laminar flow, Darcy flow, and free and porous medium flow. For each fracture-cavity structure, we set the inlet and outlet of the fluid, set the inlet boundary constant pressure, change the outlet boundary pressure, and obtain the pressure field and velocity field of the flow space by solving the governing equations corresponding to different models.

2. Elaboration of fracture-cavity reservoir flow model

Mediums with smaller characteristic scales (including dissolved voids, cracks, and filled caves) belong to porous media, and their flow rules belong to percolation. For mediums with larger scales (large cracks, incompletely filled caves), the fluid is in the porous medium. The medium flow state is laminar, so the Brinkman equation is used for simulation; for large unfilled caves, there is no porous medium inside, so it does not belong to percolation, and the flow rule belongs to free flow, which conforms to the Navier-Stokes equation. Theoretically, the N-S model can also be used for the flow in porous media, but the boundary of porous media is complicated and it is difficult to establish the flow boundary. Therefore, reservoirs with small interstitial scales still need to be simulated with seepage models. Tarim fracture-cavity reservoirs have a variety of reservoir spaces, ranging from small-scale porous media to free-flowing open caves. Different flow regions correspond to their respective flow patterns. The flow model should use the coupled model of percolation and free flow, namely the Darcy-Brinkman-Stokes model.

Table 1 Flow model for fractured-vuggy reservoirs

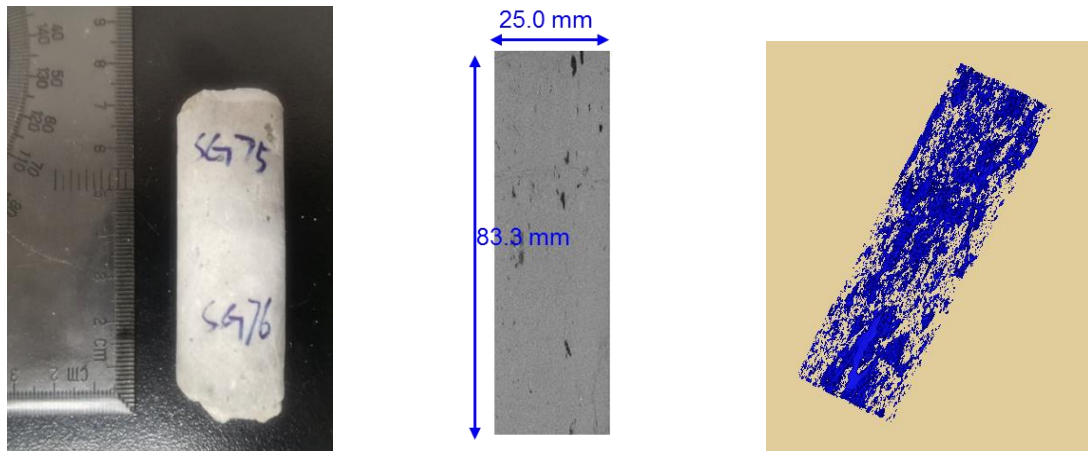
Flow state	Flow model	Application range
Free flow	Laminar flow	Characterize the laminar flow of free space fluid, suitable for Reynolds number less than 2000, unfilled area. Governing equation: Navier-Stokes formula
Free and porous media coupling flow	Modified Brinkman equation	Characterize the high-speed flow of fluids in a porous medium with large porosity. Suitable for semi-filled caves or cracks Governing equation: modified Brinkman equation
Seepage	Darcy's Law	Simulates the relatively low velocity of fluids flowing through the matrix or fully filled cave Governing equation: Darcy's formula

3. Research method

Core samples were taken from the outcrops in the Songmen section of Longmen Mountain, Sichuan. The core is first scanned with a micron CT scanner to obtain a high-resolution image; then the image is imported into the MIMICS software, where different grayscale seams and holes in the image are identified and identified, and individual measurements are made. The diameter of the hole and the average diameter of all holes; in the MIMICS software, the three-dimensional structure of the target slit is obtained by selecting a threshold range. The typical cave group and fracture-hole connected structure were extracted as our research object.

The 3D structure is imported into 3-MATIC software for meshing, and the obtained surface mesh is converted into a volume mesh before it can be exported to a mesh format recognized by COMSOL. The COMSOL import mesh model will automatically recognize the 3D structural domains, boundary surfaces, and nodes for the setting of boundary conditions in later simulations. So far, a 3D digital mesh structure model can be used for COMSOL simulation.

The COMSOL software module was used to perform secondary programming to numerically solve the single-phase flow model, and the pressure field, velocity field and streamline field were obtained.



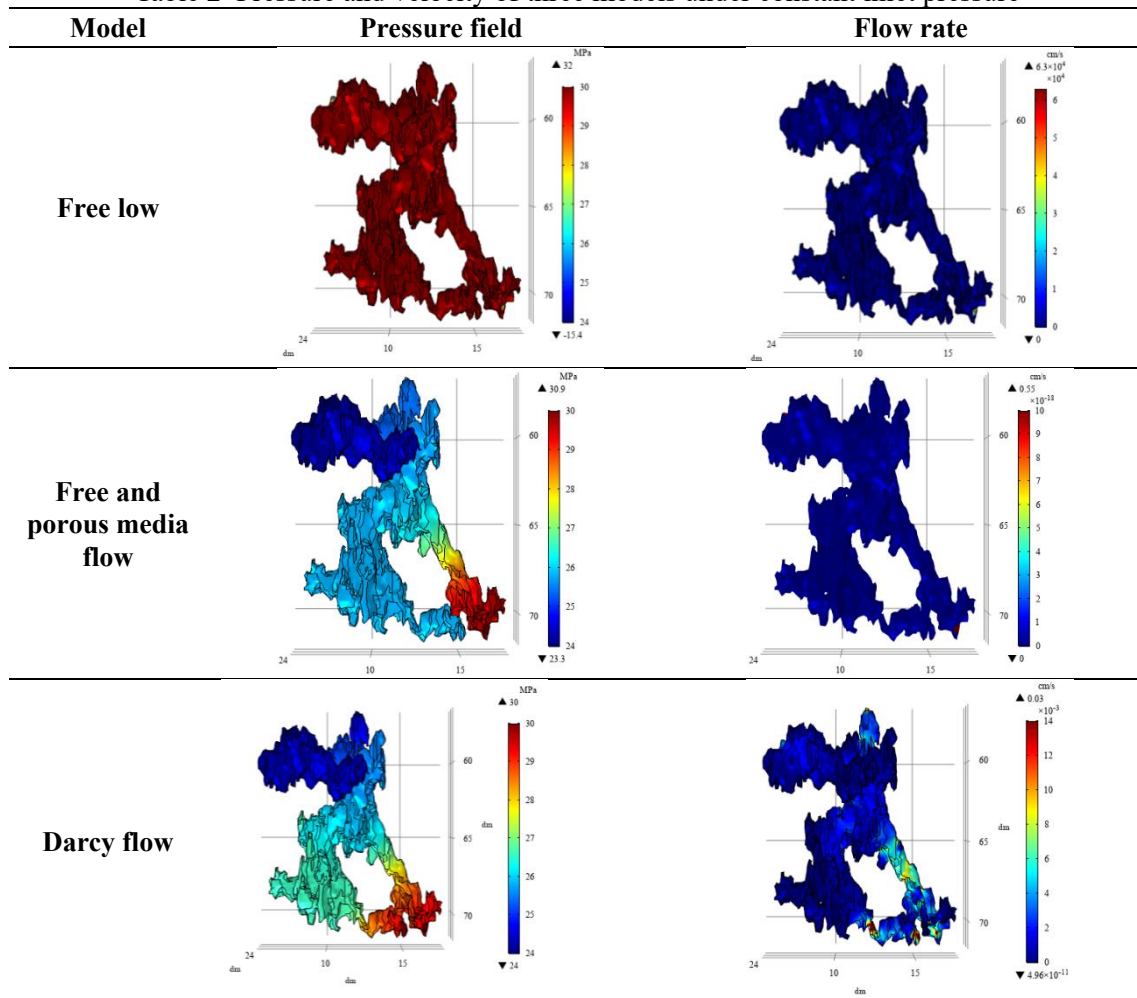
a. SG76 core b. core CT scan longitudinal section core c. core cavity structure extraction

Figure 1 Core sample photo and fracture-vuggy structure extracted from CT scanning image

4. Simulation results and analysis

Table 2 shows the pressure field and flow field characteristics of the three models under constant pressure at the inlet and outlet ($P_{in} = 30\text{MPa}$, $P_{out} = 24\text{MPa}$). Free-flow (laminar flow) model: The pressure field is controlled by the injection pressure at the inlet, and there is no significant pressure drop in the system, which is equivalent to the injection pressure; the flow velocity at the inlet is extremely large. Free-porous media coupled flow (modified Brinkman) model: The pressure drop characteristics of the system are obvious, and the flow velocity at the inlet end is much smaller than that of the free flow model. Darcy flow model: Due to the low permeability of the porous medium in this model, the pressure drop characteristics are obvious, and the flow velocity is 1/20 of the free and porous medium flow.

Table 2 Pressure and velocity of three models under constant inlet pressure



5. Conclusions and discussions

By constructing digital core, this study extracted typical seam hole structure, the flow of the fluid is studied under different flow model, especially in not completely fill the reservoir space of the flow of the coupled flow and free flow of porous media model, the modified Brinkman equations of better simulated the fluid flow in the structure of this kind of stitch holes.

The flow pattern is mainly influenced by the slot structure, filling degree, boundary conditions of inflow and outflow, and fluid viscosity. The characteristics of slot structure and cavity filling play a decisive role in the pressure field, velocity field and streamline field, so they are the main controlling factors of the flow pattern. There are many types of inflow boundary as supply sources, including complete encapsulation of the cave body, single boundary surface as supply, constant pressure supply, constant flow supply and depletion supply. The outflow boundary is mainly a single point outflow, a single boundary surface outflow and the outflow of the connection crack contact surface. Fluid viscosity has a significant effect on velocity and pressure loss. Generally, the fracture structure, filling degree and fluid viscosity are the fixed parameters of the reservoir, and the boundary conditions of inflow and outflow will change under the influence of well production system and the intrusion of bottom and edge water.

The flow in the slot structure is mainly affected by three forces: displacement pressure, gravity and inertial force. The displacement pressure has a direct influence on the distribution characteristics of velocity and pressure field in the structure. Gravity has little effect on the pressure and velocity in the slotted structure under the condition that the elevation difference between inflow and outflow boundary

is small, but the effect of gravity is more obvious under the condition that the elevation difference is large. The influence of inertial forces is relatively weak and can be ignored in the Darcy flow with lower velocity, but it needs to be considered in the free flow with faster velocity and the coupling flow with free porous media.

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