Petroleum Research 5 (2020) 164–169

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/

Full Length Article

A novel pore-fracture dual network modeling method considering dynamic cracking and its applications

Yukun Chen [a], Kai Yan [b], Jigang Zhang [a], Runxi Leng [a], Hongjie Cheng [a], Xuhui Zhang [c], Hongxian Liu [d], Weifeng Lyu [e,*]

[a] PetroChina Xinjiang Oilfield, Research Institute of Exploration and Development, Karamay, Xinjiang, 843000, China
[b] College of Mechanical and Transportation Engineering, China University of Petroleum (Beijing), Beijing, 102249, China
[c] Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China
[d] Department of Petroleum Engineering, China University of Petroleum-Beijing at Karamay, Karamay, Xinjiang, 834000, China
[e] State Key Laboratory of Enhance Oil Recovery, Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, 100083, China

ARTICLE INFO

Article history:
Received 10 October 2019
Received in revised form
6 December 2019
Accepted 9 December 2019
Available online 17 December 2019

Keywords:
Pore-fracture dual network model
Micro-fracture
Dynamic cracking
Digital core
Dimensionless parameters
Seepage characteristics

ABSTRACT

Unconventional reservoirs are normally characterized by dual porous media, which has both multi-scale pore and fracture structures, such as low permeability or tight oil reservoirs. The seepage characteristics of such reservoirs is mainly determined by micro-fractures, but conventional laboratory experimental methods are difficult to measure it, which is attribute to the dynamic cracking of these micro-fractures. The emerging digital core technology in recent years can solve this problem by developing an accurate pore network model and a rational simulation approach. In this study, a novel pore-fracture dual network model was established based on percolation theory. Fluid flow in the pore of two scales, micro-fracture and matrix pore, were considered, also with the impact of micro-fracture opening and closing during flow. Some seepage characteristic parameters, such as fluid saturations, capillary pressure, relative permeabilities, displacement efficiency in different flow stage, can be predicted by proposed calculating method. Through these work, seepage characteristics of dual porous media can be achieved.

1. Introduction

The development of unconventional oil and gas reservoir reservoirs is a challenge work for petroleum industry. Most of unconventional reservoirs are characterized by dual porous media, studying the effect of micro-fractures distribution and dynamic characteristics on seepage is a promising issue. (Deng, 1995; Li et al., 2009; Xie and Zhou, 2008; Zhang and Zheng, 2009). For the complex pore structure in such reservoirs, it is difficult to study them by macroscopic seepage theory (Hao, 2006; Hao et al., 2007a, 2007b; Huang, 1999; Lin, 2009; Liu et al., 2006; Xu et al., 2007; Zhang et al., 2007). Therefore, conducting microstructural features and microscopic seepage mechanism research could be an ice break approach.

At present, the methods of modeling and simulation of pore network mainly include equivalent continuum model, discrete network model, hybrid model, and percolation model. The pore network model based on percolation theory had shown certain advantages in understanding the development mechanism of conventional oil and gas reservoirs (Grimmett, 1999; Hammersley and Handscomb, 1957; Simon and Kelsey, 1971; Torelli and Scheidegger, 1971; Xue and Chen, 2007; Zheng et al., 2011; Wang et al., 2001). Traditionally, the method do not consider the dynamic cracking process of micro-fractures, including opening and closing of them during flow, resulting in a certain error comparing with a real displacement process.

In this study, a novel pore-fracture dual network model was established based on percolation theory. Fluid flow in the pore of two scales, micro-fracture and matrix pore, were considered, also with the impact of micro-fracture opening and closing during flow. Some seepage characteristic parameters can also be predicted by proposed calculating method.

* Corresponding author.
E-mail address: lweifeng@petrochina.com.cn (W. Lyu).

https://doi.org/10.1016/j.ptlrs.2019.12.001

2. Analysis of pore-fracture dual network

2.1. Determination of dimensionless parameters

Pore-fracture dual network model considering dynamic cracking, whose porous medium is mainly characterized by weak closed micro-fractures, pores and micro-throat. Fluid flow in the pore network model is similar to the displacement process which hydraulic cracking and displacement carried out simultaneously. The opening of micro-fractures is attribute to the pore fluid pressure. Therefore, the impact factors controlling fluid flow are mainly related to reservoir pore structure characteristics, fracture parameters, rock mechanics characteristics, connate water saturation, fluid property parameters, displacement pressure difference, permeability, etc.

The fluid flow in the pore network model is mainly impacted by the pore structure and fractures in the formation rock. Define the physical quantity that impacts the fluid flow as a geometric quantity, such as pore radius r_b, number of pores N_p; pore throat radius r_{th}, throat length l_{th}, number of throats N_{th}; closed fracture length τ_f, number of closed fractures N_f.

The parameters of fluid properties, rock mechanics and formation characteristics mainly include water density ρ_w, water viscosity μ_w, oil density ρ_o, oil viscosity μ_w, elastic modulus of rock solid structure E, closed fracture opening tension τ_f, rock porosity Φ_0, absolute permeability K_0.

The main condition parameters include differential pressure between inlet and outlet $\triangle P$ and surface tension coefficient σ_c. The dependent variables include connate water saturation S_{rw}, opening number of closed fracture N_{df}, cracking width r_{df}/r_{th}, effective permeability K_e/K_o.

Dimensional analysis was carried out by selecting the length of the throat, the closed fracture opening tension, and the fluid density as the basic units. Seven important dimensionless parameters were obtained as follow:

Pore structure and volume fraction: $\dfrac{N_p r_p^3}{N_{th} r_{th}^2 l_{th}}$

Closed fracture size and proportion: $\dfrac{l_f}{r_{th}}$ *and* N_f

Ratio of effective stress to fracture strength: $\dfrac{\sigma_c - \Delta p}{\tau_f}$

Ratio of deformation modulus to fracture strength: $\dfrac{E}{\tau_f}$

Ratio of displacement differential pressure to flow viscous force: $\dfrac{\rho_w \cdot \Delta p \cdot r_{th}^2}{\mu_w^2}$

Initial porosity: φ_0

For some fluid flow parameters in the pore-fracture dual network considering dynamic cracking, such as water saturation, number of closed fractures, fracture width, effective permeability. These seven dimensionless parameters could be the key factors for the calculation.

2.2. Modeling process

The proposed pore network model is a two-dimensional quasi-static network model. Assuming that the pore structure, fracture and pressure distribution are equivalent in the Z direction of the rock interior space, thus flow in Z direction can be ignored. The quasi-static network model is between the static network model and the dynamic network model. Invasion percolation theory and capillary channel single-phase flow and two-phase flow motion law were combined to investigated the seepage in pore-throat unit. Fracture unit in the network were simplified to plate flow and the cubic law was used to simulate the seepage in the pore-fracture dual porous media.

There are three steps to establish this pore-fracture dual network model.

Firstly, the statistical properties and topological parameters of the pore structure are obtained through experiments (such as pore and throat distribution, coordination number and spatial correlation). The distribution of the pore, throat, fracture and closed fracture could be expressed by a certain statistical distribution function. Through this process, the actual pore-fracture porous media can be transformed into a pore-fracture network which can be simulated by computer.

Secondly, simulating the law of fluid motion in a pore network by a specific algorithm determined by the microscopic seepage mechanism of pores and fractures. Whether the fractures are open or closed in this process could be judged by the fracture opening mechanism. The pore network was continuously updated, which shows the microscopic mechanism of the displacement process.

Finally, the macroscopic parameters of fracture and pore network at different stages could be obtained by the simulation of microscopic flow, including pore-throat-fracture invasion state, capillary pressure curve, relative permeability curve, fluid saturation, fluid velocity and so on.

3. Establishment of pore-structure dual network model considering dynamic cracking

3.1. Model introduction

According to the first step of the modeling, the range and frequency of the pore size distribution of the real core could be obtained through nuclear magnetic resonance (NMR) data. After fitted with Matlab, the fitted data was assigned as statistical data to the throat and pore in this model. The results of the pore throat radius distribution and Matlab fitting data measured by NMR are shown in Fig. 1 and Fig. 2, wherein the porosity component is defined as the product of the pore throat radius distribution frequency and the

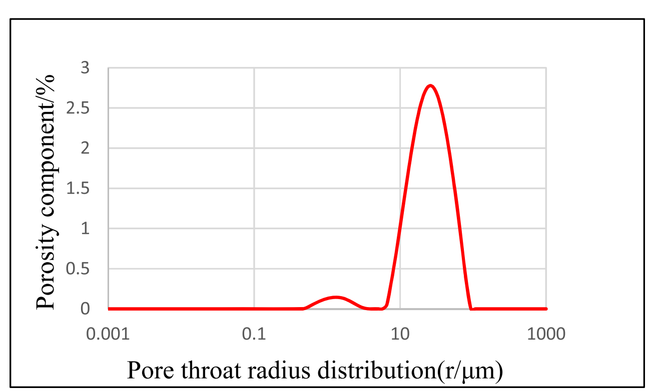

Fig. 1. Pore throat radius distribution obtained by NMR.

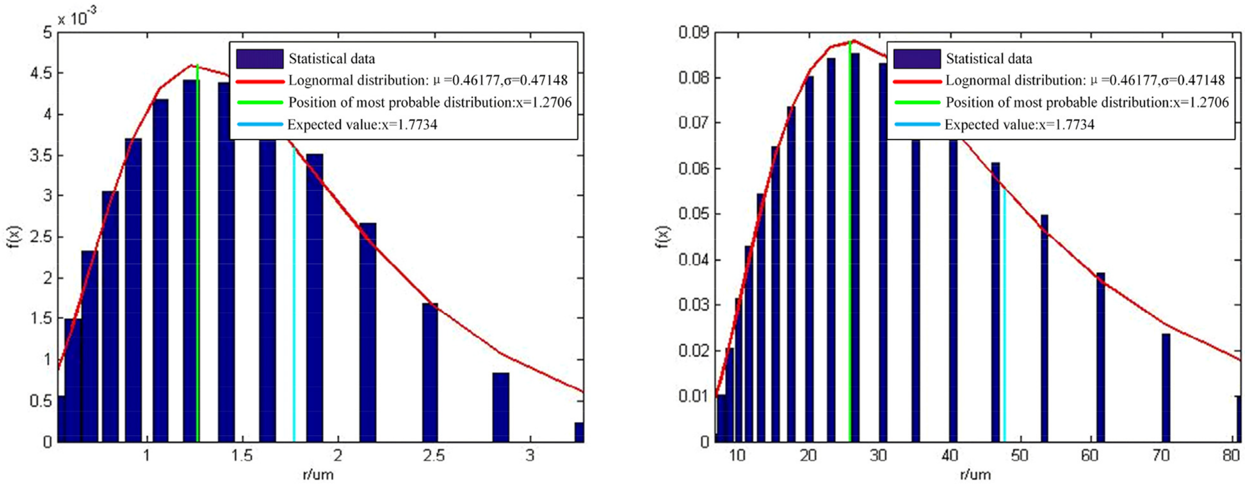

Fig. 2. Matlab fitted data.

porosity.

The distribution of pore, throat, fracture and closed fracture is represented by a statistical distribution function. The pore units are spherical cavity ones, and the radius distribution of the units is evenly distributed. The density function can be expressed as:

$$p(x) = \begin{cases} \frac{1}{R_{\max} - R_{\min}} & R_{\min} \le R \le R_{\max} \\ 0 & otherwise \end{cases} \tag{1}$$

The section of the throat unit is considered to be a channel cross section with a fixed length, and the distribution of the radius conforms to a lognormal distribution, a bimodal or multimodal logarithmic normal distribution. The density function truncated normal distribution can be expressed as:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}, r_{\min} \le r \le r_{\max} \tag{2}$$

3.2. Displacement rule

The flow in the pore-fracture dual network model considering dynamic cracking can be divided into two parts: flow in single channel and the flow in fractures. Following assumptions can be made for the flow rules in single channel in the network: two-phase fluid is incompressible and immiscible, small Reynolds number for fluid flow, ignore inertial effects, part of the dynamic effect of surface tension is not considered when interfacial flow; the flow rate is zero if the number of single channel interfaces exceeds two.

Based on the above assumptions, the Poiseuille flow of the cylindrical channel can be established by the Stokes equation.

Single-phase fluid flow formula:

$$q_{ij} = -\frac{r_{ij}^2}{8\overline{\mu}L_{ij}}\left(p_j - p_i\right) \tag{3}$$

Two-phase single interface flow formula:

$$q_{ij} = -\frac{r_{ij}^2}{8\overline{\mu}L_{ij}}\left(p_j - p_i - p_c\right) \tag{4}$$

Two-phase multi-interface flow formula:

$$q_{ij} = -\frac{r_{ij}^2}{8\overline{\mu}L_{ij}}\left(p_j - p_i - p_c\right) \times 10^5 \tag{5}$$

The purpose of introducing the multi-interface formula is to eliminate the singularity when establishing the flow matrix and the pressure matrix operation, that is, to avoid the matrix not being decomposed and ensuring accuracy.

The P_c be expressed as:

$$p_c = \pm\frac{2\cos\theta\sigma^{wn}}{r} \tag{6}$$

Take a positive sign when the wetting phase displaces the non-wetting phase; take a negative sign when the non-wetting phase displaces the wetting phase. q_{ij} represents the flux of fluid through the unit area of the section, μ_{ij} represents the coefficient of dynamic viscosity of the fluid, a represents the density of the fluid, a represents the interface between different fluids in the single channel.

Make the following assumptions for the fracture flow rule in the network: the flow law satisfies the cubic law.

$$q = -\frac{e^3}{12\mu}\frac{\Delta P}{L}, \Delta P = p_j - p_i - p_c \tag{7a}$$

Take a positive sign when the wetting phase displaces the non-wetting phase; take a negative sign when the non-wetting phase displaces the wetting phase. The initial fracture radius is set at 0, and the fracture opens when the apex pressure reaches the critical pressure value. The critical pressure value can be set randomly or according to the experimental measurements. The fracture is instantaneously filled after the fracture is opened.

The schematic diagram of displacement is shown in Fig. 3.

3.3. Fracture searching and judging

Firstly, the state of the channel is divided into six types, the state of the node is divided into two types, and the state of the fracture is divided into two types.

The status setting rules are as follows:

Element status = 0 indicate that the channel is filled with wetting phase;

Element status = 1 indicate that the channel is filled with non-wetting phase;

Element status = 2 indicates that the channel is in the border

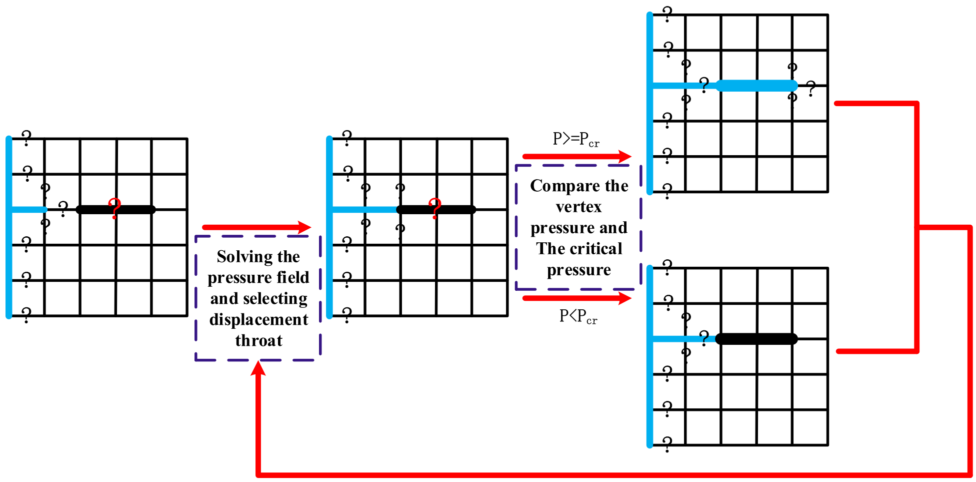

Fig. 3. Schematic of displacement.

state;

Element status = 3 indicates that the channel is filled when it is updated;

Node status = 0 indicates that the node is full of wetting phase;

Node status = 1 indicates that the node is full of non-wetting phase;

Fracture status = 0 indicates that the node is full of wetting phase;

Fracture status = 1 indicates that the node is full of non-wetting phase.

Secondly, the wetting phase is assumed to be water and the non-wetting phase is oil in the oil flooding water process. The boundary conditions are set as following: set all the pores, throats and fractures at the state of 0, which indicates the network is filled with water at the beginning; set pores and throats at the inlet boundary at the state of 1, which indicates the oil phase invades from the inlet. The state connected to the pore of state 1 is the initial state of displacement after being stabilized.

The process of fracture searching and judging is as follows:

Step1: Change the throat status to 2 when the search status of 0 throat is 1. Search fractures on the boundary until the network is stable. Search for the network state pore to connect to the fracture with the status still ’0’, if not, exit the program.

Step2: If the network pores are connected to the 0-state fracture, the cracking condition needs to be judged. If the apex pressure a>b, the fracture is opened and filled, than its state changes from 0 to 1. The state of the pore connected to these new full fractures also becomes 1, If the apex pressure $P > P_{cr}$, the fracture is opened and filled, and the state of the pores connected to these new full fractures becomes 1, than the state of the throat around the newly filled pore becomes an impending state. If the apex pressure $P < P_{cr}$, the fracture is still closed and its state remains unchanged at 0.

Step3: Continue to search whether the pore of state 1 is connected with a fracture whose state is still ’0’ until the search process is exited. When the fracture is not found, the network is at stable state.

3.4. Modeling process

Following processes are simulated in the model:

First, oil flooding water to make connate water, which can be seen as a process of simulating reservoir formation.

Then the process of water displacing oil, which simulates the process of the oil production. Research on water flooding process is of great importance for oil production.

The program flowchart of this process is shown in Fig. 4.

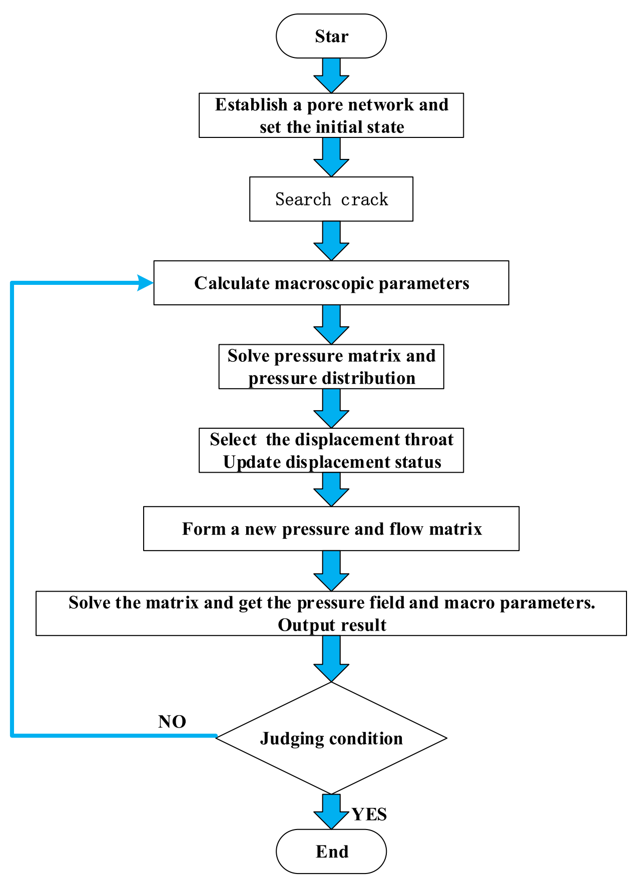

Fig. 4. Program flowchart.

4. Applications

The macroscopic parameters of the pore-fracture dual network model considering dynamic cracking at different stages of displacement can reflect the seepage of the network model. These macro parameters include: saturation, capillary force, relative permeability.

The saturation of the non-wetting phase in the initial state is the sum of the invaded throat and the volume of the pore divided by the total volume of the pore, and the saturation of the wetting phase can be expressed as:

$$S_{wk} = 100\left[1 - \frac{\sum_{i=1}^{mk} \pi r_i^2 l + \sum_{j=1}^{nk} \frac{4}{3}\pi r_i^3}{\sum_{i=1}^{m} \pi r_i^2 l + \sum_{j=1}^{n} \frac{4}{3}\pi r_i^3}\right] \tag{7b}$$

Where m represents the total number of throats and n represents the total number of holes in the network, mk and nk indicate the number of invaded throats and pores, respectively. The capillary force can be calculated by the minimum capillary radius that can be invaded during the displacement process (see Fig. 5)

$$p_c = \frac{2\cos\theta\sigma^{wn}}{r} \tag{8}$$

According to the definition of absolute permeability:

$$K = \frac{Q\mu L}{\Delta P_t \cdot A} \tag{9}$$

Where Q represents the flow through the network, μ represents the viscosity of the liquid, L represents the length of the network, P represents the pressure difference between the two sides of the network, and A represents the cross-sectional area of the network. For relative permeability, different grid cells in the network are occupied by different fluids at different stages of displacement. The distribution of different phase fluids determines the effective permeability of the respective phases. Through the calculation of the above flow pressure matrix, the effective permeability of each phase fluid can be obtained, and the relative permeability of each phase can be calculated finally.

During the dynamic cracking process of fractures, the total pore space within the calculation scale varies with the cracking process.

In the case of dynamic cracking, the numerator and denominator must simultaneously accumulate the volume of the opening fracture. The saturation during dynamic cracking can be calculated as follow:

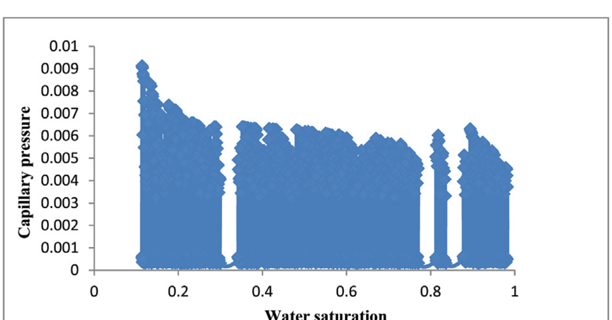

Fig. 5. Capillary pressure curve.

$$S_{wk} = 100\left[1 - \frac{\sum_{i=1}^{mk} \pi r_i^2 l + \sum_{j=1}^{nk} \frac{4}{3}\pi r_i^3 + \sum_{a=1}^{pk} \pi r_i^2 L}{\sum_{i=1}^{m} \pi r_i^2 l + \sum_{j=1}^{n} \frac{4}{3}\pi r_i^3 + \sum_{a=1}^{pk} \pi r_i^2 L}\right] \tag{10}$$

5. Conclusions

(1) In this study, the impact factors of seepage mechanics of porous media considering fracture dynamic cracking are obtained through the dimensional analysis. Seven important dimensionless parameters that determine the percolation parameters are determined, such as residual oil, number of closed fractures, fracture width and effective permeability.

(2) A pore-fracture dual network model considering dynamic cracking with micro fractures was established. The model can analyze the dynamic fracture initiation mechanism, evolution characteristics and displacement mechanism under different pressures, and has important significance for studying the microstructure characteristics and microscopic seepage mechanism.

(3) This model can reflect the macroscopic parameters of seepage state in different displacement stages, such as saturation, capillary force and relative permeability. Changes of reservoirs in different displacement stages can be reflected in the result.

Acknowledgments

The writers greatly appreciate the financial support of the Major Special Project of PetroChina Co Ltd. (2017E-0406), the National Science and Technology Major Project during the 13th Five-year Plan Period (2016ZX05010-00504).

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