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Temperature Distribution of Steam Stimulation in Fractured Heavy Oil Reservoir Using Fractal-like Tree Branching Network

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Abstract: In this study, fractal-like tree branching model is adopted to study the distribution of natural fractures in the reservoir, treating matrix-fracture as the equivalent continuum model to characterize the fracture volume factor and effective permeability of fractured zones. Based on mass and energy balance equations, considering the impact of natural fractures, mathematical models for non-isothermal heating radius of steam stimulation in fractured heavy oil reservoir were established and analytical solutions were obtained to provide temperature distribution. Numerical analysis shows that heating radius of the model derived here is larger than that of conventional model without considering fractures. Besides, the increase of fractal dimension of fracture and tortuosity lead to heating radius increasing, due to fracture volume fraction and equivalent permeability increasing

Key words: Fractured network, fractal method, Steam stimulation, heavy oil, temperature distribution

INTRODUCTION

Proven reserves of heavy oil resources in the world is over 3,000 tons(Mohebati *et al*., 2012) while the fractured heavy oil reservoir has accounted for about 30% (Castle *et al*., 2002). Thus deepening the study of fractured heavy oil reservoir is very important. Initial mining method of heavy oil is mainly steam stimulation. Determining the scope of steam stimulation is the key for reservoir performance analysis and capacity forecasts. Currently the calculation of heating radius is mainly based on Marx-Langenheim model(Su *et al*., 2005; Mai *et al*., 2009; NRC, 1996). Due to the presence of natural fractures in the reservoir (Dou *et al*., 2007), flow capacity increasing leads to an increase in cyclic steam stimulation.

Because natural fractured media meet three conditions: Self-similarity, scale invariance and fractal dimension (Adler and Thovert, 1999; Sahimi, 1993). In this study, fractal branching tree network of fractal theory is adopted to study the distribution of natural fractures in the reservoir, treating the matrix-the fracture as the equivalent continuum model to characterize the fracture volume factor and effective permeability of fractured zones (Zhu *et al*., 2013;Song *et al*., 2013). Based on mass and energy balance equations, considering the impact of natural fractures, mathematical models for non-isothermal heating radius of steam stimulation in fractured heavy oil reservoir were established and analytical solutions were obtained to provide temperature distribution.

CHARACTERISTICS OF NATURAL FRACTURE

Fracture parameters of fractal-like fractal network: Lorente and Bejan (Golf-Racht, 1982; Fossen and Gabrielsen, 1996) showed that multi-scale heterogeneous anisotropic fracture system in porous media is similar to fractal-like branching network, as shown in Fig. 1.

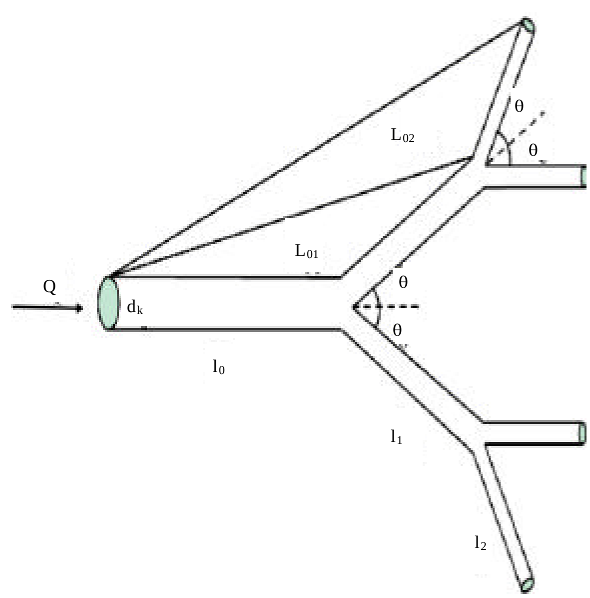

Fig. 1: Schematic of fractal-like branching network (branching No. =2)

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Assuming that each branch is smooth and cylindrical (Mandelbrot, 1982), the total volume of branching network is:

$$V_n = \int_{d_{max}}^{d_{min}} \sum_{k=0}^{m} n^k \frac{\pi}{4} d_k^2 l_k = \frac{\pi D_p l_0^{D_T} d_0^{3-D_T} (1-\bar{d}^{3-D_T-D_p})}{4(3-D_T-D_p)} \frac{1-\xi^{m+1}}{1-\xi} \quad (1)$$

where, D_p is fractal dimension; l_0 is tube length of initial level; D_T is tortuosity; d_0 is tube diameter of initial level, m; ξ is scale factor, defined as $\xi = n\alpha^{\delta}\beta^{3-\delta}$; n is branching number; α is length ratio; l_k is tube length of level k; m is maximum level number; β is diameter ratio, d_{min} is minimum tube diameter of initial level, m; d_{max} maximum tube diameter of initial level, m; $\bar{d}$ is defined as:

$$\bar{d} = \frac{d_{min}}{d_{max}}$$

Volume fraction f_n of fracture system is obtained:

$$f_n = \frac{V_n}{V} = \frac{D_p l_0^{D_T} d_{max}^{3-D_T} (1-\bar{d}^{3-D_T-D_p})}{4h(3-D_T-D_p)(r_m^2 - r_w^2)} \frac{1-\xi^{m+1}}{1-\xi} \quad (2)$$

where, $V = \pi h(r_m^2 - r_w^2)$ is the reservoir volume.

Effective permeability k_n of fracture system is:

$$k_n = \frac{D_p d_{max}^{3+D_T} \ln(r_m/r_w)}{256h(3+D_T-D_p) l_0^{D_T}} \frac{1-(\frac{\alpha^{D_T}}{n\beta^{3+D_T}})}{1-(\frac{\alpha^{D_T}}{n\beta^{3+D_T}})^{m+1}} \quad (3)$$

Volume fraction of matrix is f_m = 1-f_n. Then the equivalent permeability of fracture-matrix systemis:

$$k_e = f_m k_m + f_n k_n \quad (4)$$

Thermal parameters correction: Assuming that reservoir is constituted with matrix and fractures, the total volumetric heat capacity M_{f+m} contains two parts: matrix and fracture system and can be obtained as follows:

$$M_{f+m} = f_n M_f + (1-f_n) M_m \quad (5)$$

M_f denotes volumetric heat capacity in fractures:

$$M_f = C_k \cdot \rho_k \quad (6)$$

where, C_k is specific heat capacity in fractures, kJ/(kg); ρ_k is fluid density in fractures (kg m^{-3}).

Volumetric heat capacity M_m in matrix is:

$$M_m = \phi(\rho_o(1-S_w)C_o + \rho_w S_w C_w) + (1-\phi)\rho_r C_r \quad (7)$$

where, ρ_o, ρ_w, ρ_r denote density of oil, water and rock, respectively, kg^{-3}; C_0 C_w, C_r denote specific heat capacity of oil, water and rock, respectively at constant pressure, kJ/(kg); ϕ is porosity.

Coefficient of thermal conductivity of oil layer K_{f+m} is:

$$K_{f+m} = f_n K_f + f_n K_m \quad (8)$$

where, K_f, K_m denote coefficient of thermal conductivity of fracture and matrix, kJ/(m.d.).
where, K_m is:

$$K_m = \phi(\rho_o(1-S_w)K_o + \rho_w S_w K_w) + (1-\phi)\rho_r K_r \quad (9)$$

CALCULATION OF HEATING RADIUS BY STEAM STIMULATION PROCESS

Conceptual model: According to field experience, temperature distribution in the heating range of steam stimulation is non-isothermal (Nazzal, 2002; Kuhn *et al.*, 2012). Natural fractures are in favor of steam flowing deeply into reservoir. Therefore, thermal convection is of importance for steam stimulation in naturally fractured reservoirs.

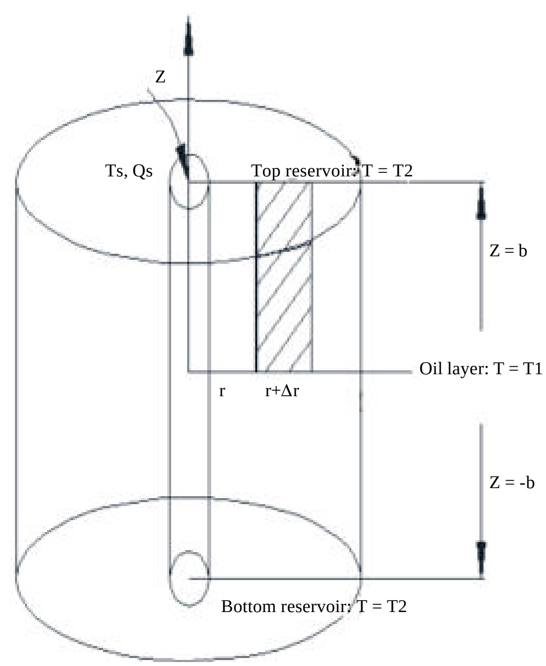

Fig. 2: Schematic of steam injection

The physical model is shown in Fig. 2: Steam with temperature T_S is injected into production well with radius r_w at constant speed Q_S. Steam flows radially into reservoir with initial temperature T_r and thickness h = 2b. Cylindrical coordinate is used, in which z is in the direction along wellbore and r is radial radius. Cap rock and bottom rock are located in z = ±b in which only thermal conduction is considered.

Mathematical model: Considering effect of natural fractures, flow velocity could be obtained according to effective permeability Eq. 4:

$$u_s = \frac{k_e}{\mu(T)}\frac{dp}{dr} \tag{10}$$

Differential equation of energy is as follows considering thermal conduction and convection:

$$bc_k\rho_k\frac{\partial T_1}{\partial t} + bc_s\rho_s u_s\frac{1}{r}\frac{\partial(rT_1)}{\partial r} = K_2\left(\frac{\partial T_2}{\partial z}\right)_{z=b} \tag{11}$$

where, T_1, T_2 are temperature in oil reservoir and cap/bottom rock, respectively, °C; c_s is specific heating capacity at constant pressure of steam, kJ/(kg); ρ_s is density of steam, kg/m^3; K_2 is coefficient of thermal conduction, kJ/(m.d.).

In cap/bottom rock, only thermal conduction is considered and unsteady differential equation of energy is as follows:

$$K_2\left(\frac{\partial^2 T_2}{\partial z^2}\right) = c_2\rho_2\frac{\partial T_2}{\partial t} \tag{12}$$

where, $\mu(T)$ is oil viscosity changing with temperature, mPa.s.

After nondimensionalizion of Eq. 11-12:

$$\frac{\partial T_1}{\partial \alpha} + \frac{1}{\beta}\frac{\partial(\beta T_1)}{\partial \beta} = \frac{K_2}{b}\left(\frac{\partial T_2}{\partial \eta}\right)_{z=b} \tag{13}$$

$$\lambda\frac{\partial^2 T_2}{\partial \eta^2} = \frac{\partial T_2}{\partial \alpha} \tag{14}$$

Where:

$$\alpha = \frac{4K_2 t}{h^2\rho_1 c_1}, \beta = \frac{4K_2 r^2}{h^2\rho_s c_s u_s}, \eta = \frac{z}{b} \tag{15}$$

Initial conditions:

$$\alpha = 0, T_1 = T_2 = \begin{cases} T_s, & \beta < 0 \\ T_r, & \beta > 0 \end{cases}$$

Through Laplace transformation, temperature distribution in cap/ bottom rock is obtained:

$$\beta > 0,\ T_2 = T_r + (T_s - T_r)\text{erfc}\left[\frac{\beta + |\eta| - 1}{2\sqrt{\lambda(\alpha-\beta)}}\right]U(\alpha-\beta) \tag{16}$$

Temperature distribution in oil layer is:

$$T_1 = T_r + (T_s - T_r)\text{erfc}\left[\frac{\beta}{2\sqrt{\lambda(\alpha-\beta)}}\right]U(\alpha-\beta) \tag{17}$$

RESULTS AND DISCUSSION

Numerical analysis is carried out using data of physical properties in Shengli field. Parameters of oil reservoir and fractal-like fracture system are as follows: fractal dimension 1.1, tortuosity 1.1, tube length of initial level 5 m, branching number 2, maximum level number 4, reservoir thickness 10, initial formation pressure 8 MPa, injection pressure 15 MPa, radius of wellbore 0.1 m, porosity 0.25, permeability 300 mD, steam temperature 320°C, steam injection days 10d.

Figure 3 shows the relationship between heating radius and temperature after different days of steam injection. As shown in the figure, under the same rate of steam injection, longer steam injection days lead to heating radius increasing with smaller increment.

Figure 4 shows the relationship between heating radius and temperature under different fractal dimensions. As shown in the figure, the increase of fractal dimensions

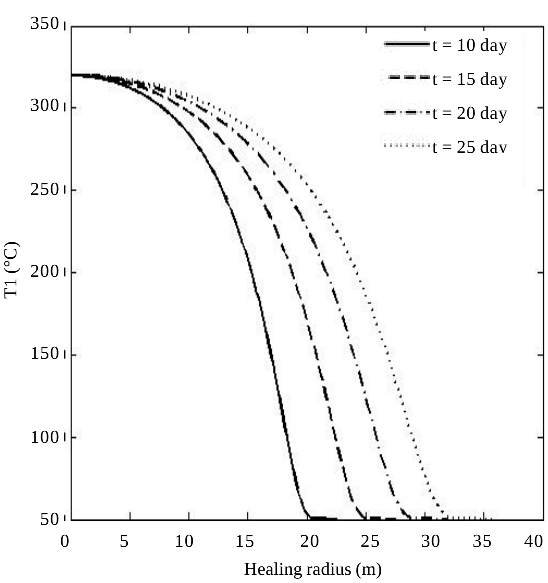

Fig. 3: Relationship between heating radius and temperature after different days of steam injection

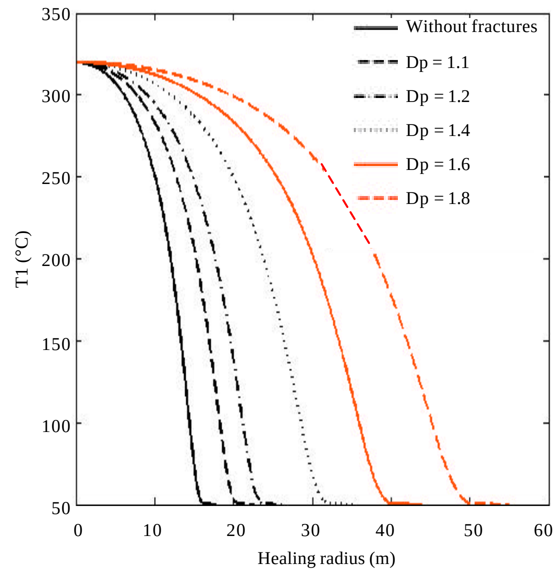

Fig. 4: Relationship between heating radius and temperature under different fractal dimensions

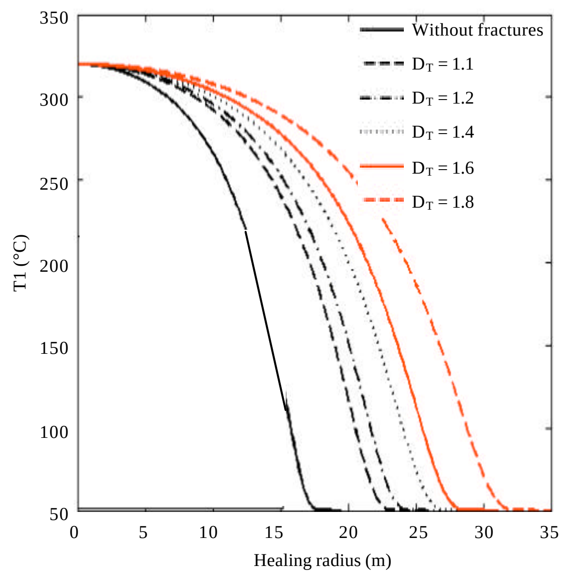

Fig. 5: Relationship between heating radius and temperature under different tortuosity

leads to heating radius increasing with larger increment. The reason is that volume fraction of fractures increases with fractal dimension, resulting in greater conductivity.

Figure 5 shows the relationship between heating radius and temperature under different tortuosity. As shown in the figure, the increase of tortuosity leads to heating radius increasing. The reason is that volume fraction of fractures increase with fractal dimensions of tortuosity, resulting in greater conductivity.

CONCLUSION

- Based on fractal-like branching network model, introducing parameters such as fractal distribution and tortuosity, equivalent permeability and fracture volume fraction in natural fractures are obtained
- Energy conservation equations are established considering fracture system parameters and analytical solutions were derived. Temperature distributions in oil layer and cap/bottom rock were presented
- Numerical analysis shows that heating radius of the model derived here is larger than that of conventional model without considering fractures. Besides, the increase of fractal dimension of fracture and tortuosity lead to heating radius increasing, due to fracture volume fraction and equivalent permeability increasing

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