International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0293

STUDY ON HEAT AND MASS TRANSFER OF SUPERCRITICAL CARBON DIOXIDE IN ENHANCED GEOTHERMAL SYSTEM

Zhang Dongxu[1], Zhang Liehui[1*], Tang Huiying[1], Feng Guoqing[1], Liu Sha[1]

1 State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation,
Southwest Petroleum University, Chengdu, Sichuan 610500, China

ABSTRACT

Geothermal resources for global new energy development because of its wide distribution, huge reserves and environment-friendly. The enhanced geothermal system (EGS) is one of the key technologies for the extraction and utilization of geothermal energy in high-temperature rock masses in deep formations. The use of supercritical carbon dioxide (S-CO2) as a working medium in EGS has many advantages for heat exploitation. But the change of thermal properties of supercritical carbon dioxide is very rapidly during EGS production, which affects the transport of fluids and rock-fluid heat exchange. To investigate the effect of S-CO2 in EGS, in the present work, we develop the heat and mass transfer models for S-CO2 in EGS based on the Embedded Discrete Fracture Model (EDFM). The simulation results show that the complex fracture network has significant effects on the heat and mass transfer of supercritical carbon dioxide in the reservoir. In addition, S-CO2 not only has higher heating efficiency than water, but also captures and stores carbon dioxide.

Keywords: Enhanced Geothermal System, Supercritical carbon dioxide , Embedded Discrete Fracture Model, Heat and mass transfer.

1. INTRODUCTION

As a kind of clean and renewable energy, hot dry rock geothermal resources have abundant reserves and broad application prospects, and can be used in geothermal power generation, heating and agricultural production [1-2]. However, since the hot dry rock is generally tight granite, the rock matrix has low porosity and poor connectivity of the natural fracture system, resulting in low permeability [3-4]. The enhanced geothermal system is an effective means to develop heat dry rock geothermal resources. It transforms deep underground low-porosity and low-permeability rock mass into high-permeability artificial geothermal reservoir through hydraulic fracturing and other reservoir stimulation methods. With these methods, a considerable amount of thermal energy can be economically extracted and utilized for a long time [5].

The working fluid of an enhanced geothermal system is usually water. In 2000, D.W. Brown[6] first proposed the use of supercritical carbon dioxide instead of water to extract dry hot rock geothermal resources. Compared with water as working medium, supercritical carbon dioxide has the following advantages: (1) supercritical carbon dioxide has higher heat exchange efficiency in the formation and can generate more thermal energy; (2) with supercritical carbon dioxide injection, carbon dioxide can be captured and stored; (3) The chemical properties of supercritical carbon dioxide are stable, and it is not easy to cause problems such as mineral dissolution [7-9].

Based on the research of Jansen G et al. [10], this paper establishes a heat transfer and mass transfer model of supercritical carbon dioxide in an enhanced geothermal system based on the embedded discrete fracture model (EDFM) . The Span-Wagner (SW) model is used to calculate the thermophysical property parameters of carbon dioxide[11]. The embedded discrete fracture model adopts orthogonal structured meshing, which does not require grid refinement, and the simulation operation speed is greatly improved [12].

2. ESTABLISHMENT OF MATHEMATICAL MODEL

Based on the mass balance law, combined with Darcy's law and Fourier's law, the basic seepage and heat transfer differential equations of single-phase fluid flow are derived, which laid the theoretical foundation for the embedded discrete fracture model. The embedded discrete fracture model is a combination of a dual medium model and a discrete fracture model. The embedded discrete fracture model borrows the method of establishing the relationship between the fracture unit and the matrix unit in the dual medium model, and explains the mass and energy exchange between the continuous mediums [13].

2.1 Model *assumptions*

The basic assumptions of the embedded discrete fracture model for enhanced geothermal systems are as follows:

The basic assumptions of models used in this paper are as follows:

(a)The reservoir is homogeneous and isotropic in properties;

(b) The fluid flow is single phase ;

(c) Fluid density, viscosity, compressibility, heat capacity are functions of formation pressure and temperature;

(d)The gravity effects and the stress sensitivity of matrix permeability are not considered;

(e) Fractures are finite conductive.Establishment of the flow model.

2.2 Fluid flow equations

Single-phase continuity equation:

$$\frac{\partial(\rho\phi)}{\partial t}+\mathrm{div}(\rho v)=q\rho \tag{2.1}$$

Flow equation:

$$v=-\frac{\mathrm{k}}{\mu}\nabla p \tag{2.2}$$

State equation:

For elastic porous media:

$$\mathrm{C_r}=\frac{\partial\phi}{\phi\partial p} \tag{2.3}$$

For elastic fluids;

$$\mathrm{C_f}=\frac{\partial\rho}{\rho\partial p} \tag{2.4}$$

Solving the left side of the continuity equation:

$$\frac{\partial(\rho\phi)}{\partial t}=\rho\frac{\partial\phi}{\partial t}+\phi\frac{\partial\rho}{\partial t}=\rho\frac{\partial\phi}{\partial p}\frac{\partial p}{\partial t}+\phi\frac{\partial\rho}{\partial p}\frac{\partial p}{\partial t}=\rho\phi(\mathrm{C_r}+\mathrm{C_f})\frac{\partial p}{\partial t} \tag{2.5}$$

Bring the equation of state and the equation of motion into the continuity equation:

$$\phi(\mathrm{C_r}+\mathrm{C_f})\frac{\partial p}{\partial t}=\mathrm{div}(\frac{\mathrm{k}}{\mu}\nabla p)+q \tag{2.6}$$

Therefore, for the matrix system and the fracture system, respectively:

matrix system：

$$\phi_m(\mathrm{C_r}+\mathrm{C_f})\frac{\partial p_m}{\partial t}=\mathrm{div}(\frac{\mathrm{k}_m}{\mu_m}\nabla p_m)+\Gamma_{mf}+q_m \tag{2.7}$$

fracture system：

$$\phi_f(\mathrm{C_r}+\mathrm{C_f})\frac{\partial p_f}{\partial t}=\mathrm{div}(\frac{\mathrm{k}_f}{\mu_f}\nabla p_f)+\Gamma_{fm}+q_f \tag{2.8}$$

Flow transfer between matrix and fracture [10]:

$$\Gamma_{fm}=\mathrm{CI}\cdot\Xi\cdot(p_f-p_m) \tag{2.9}$$

$$\int\Gamma_{mf}dV=-\int\Gamma_{fm}dA \tag{2.10}$$

Where CI : connectivity coefficient between the matrix and fracture; Ξ : the average fluidity of the fluid.

2.3 Heat transfer equations

Energy conservation equation:

$$c_p\rho\frac{\partial T}{\partial t}=\lambda[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}]-c_p\rho v_x\frac{\partial T}{\partial x}+c_p\rho v_y\frac{\partial T}{\partial y}+Q \tag{2.11}$$

Average heat conductivity:

$$\lambda=\phi\lambda_f+(1-\phi)\lambda_r \tag{2.12}$$

Average heat capacity:

$$c_p\rho=\phi(c_{pf}\rho_f)+(1-\phi)(c_{pr}\rho_r) \tag{2.13}$$

Heat source item:

$$Q=\phi Q_f+(1-\phi)Q_r \tag{2.14}$$

Therefore, for the matrix system and the fracture system, respectively:

$$c_p\rho_m\frac{\partial T_m}{\partial t}=\lambda_m[\frac{\partial^2 T_m}{\partial x^2}+\frac{\partial^2 T_m}{\partial y^2}]-(c_p\rho v_x)_m\frac{\partial T_m}{\partial x}+(c_p\rho v_y)_m\frac{\partial T_m}{\partial y}+Q_m+\chi_{mf} \tag{2.15}$$

$$c_p\rho_f\frac{\partial T_f}{\partial t}=\lambda_f[\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}]-(c_p\rho v_x)_f\frac{\partial T_f}{\partial x}+(c_p\rho v_y)_f\frac{\partial T_f}{\partial y}+Q_f+\chi_{fm} \tag{2.16}$$

Heat transfer between matrix and fracture [10]:

$$\chi_{mf}=\chi_{mf}{}^{\nabla}+\chi_{mf}{}^{\nabla^2} \tag{2.17}$$

$$\int \chi_{mf} dV = -\int \chi_{fm} dA \qquad (2.18)$$

Where ρ : fluid density,kg/m^3; ϕ :porosity; t :time,s; q :fluid flow rate,m/s; p :pressure,MPa; k : permeability,m^2; μ : T : temperature,K; $\chi_{mf}{}^{\nabla}$: thermal convection term between fracture and matrix; $\chi_{mf}{}^{\nabla^2}$: heat conduction term between fracture and matrix; viscosity,mPa • s. λ : average heat conductivity , W/(m·K); λ_f : heat transfer coefficient of fluid; W/(m·K); λ_r :heat transfer coefficient of rock; W/(m·K); c_p : average heat capacity, J/(kg℃); c_{pf} : Specific heat capacity of fluid, J/(kg℃); ρ_r : Specific heat capacity of rock, J/(kg℃);

3. PROPERTY CALCAULTION OF CARBON DIOXIDE

In the working process of the enhanced geothermal system, with the injection and production of fluids, the temperature and pressure of the formation are changing, and the supercritical carbon dioxide is used as the working fluid. Because the state equation is very complicated, the calculation can be time consuming. The calculation of the physical parameters of supercritical carbon dioxide is essential for studying the heat transfer and mass transfer process. In this paper, the carbon dioxide physical parameters are calculated using the Span-Wagner (SW) model, and the thermophysical property equation is based on Helmholtz free energy [14]. The S-W model uses the deviation function calculation method, taking the ideal gas as a reference, and calculating the actual fluid thermal property parameters by means of the Helm hertz function. The Helmholtz free energy consists of two parts (formula (3.2)), one part is the ideal part ϕ^0, and the other part is the residual part ϕ^r.

$$\delta = \frac{\rho}{\rho_c}, \tau = \frac{T_c}{T} \qquad (3.1)$$

dimensionless Helm Hertz free energy:

$$\phi(\delta,\tau) = \phi^o(\delta,\tau) + \phi^r(\delta,\tau) \qquad (3.2)$$

Ideal gas term:

$$\phi^o(\delta,\tau) = \ln(\delta) + a_1^o + a_2^0\tau + a_3^o \ln(\delta) + \sum_{i=4}^{8} a_i^0 \ln[1-\exp(-\tau\theta_i^o)] \qquad (3.3)$$

Residual part:

$$\phi^r(\delta,\tau) = \sum_{i=1}^{7} n_i \delta^{d_i} \tau^{t_i} + \sum_{i=8}^{34} n_i \delta^{d_i} \tau^{t_i} e^{-\delta^{c_i}} + \sum_{i=35}^{39} n_i \delta^{d_i} \tau^{t_i} e^{-\alpha_i(\delta-\varepsilon_i)^2 - \beta_i(\tau-\gamma_i)^2} + \sum_{i=40}^{42} n_i \Delta^{b_i} \delta e^{-C_i(\delta-1)^2 - D_i(\tau-1)^2} \qquad (3.4)$$

Intermediate function:

$$\Delta = \{(1-\tau) + A_i[(\delta-1)^2]^{1/(2\beta_i)}\}^2 + B_i[(\delta-1)^2]^{a_i} \qquad (3.5)$$

Where δ: dimensionless contrast density; τ: dimensionless inverse contrast temperature; ρ is fluid density, kg / m^3; T is fluid temperature, K; ρc is critical density, kg/m^3; Tc is critical temperature; R_c is the universal gas constant; the superscript "o" indicates the ideal gas term, and the superscript "r" indicates the residual portion. The rest are fitting coefficients, as described in the literature [14].

$$\mu(\rho,T) = \mu_0(\rho,T) + \Delta\mu(\rho,T)$$

$$\mu_0(\rho,T) = \frac{\alpha T^{0.5}}{\eta_0(T)}$$

$$\eta_0(T) = \exp[\sum_{i=0}^{4} b_i (\ln(\frac{T}{c}))^i]$$

$$\Delta\mu(\rho,T) = d_1\rho + d_2\rho^{-4} + d_3\frac{\rho^6 c}{T^3} + d_4\rho^8 + d_5\frac{\rho^8 c}{T} \qquad (3.6)$$

For viscosity, it is often impossible to solve with Helmholtz free energy. The basic formula for solving the viscosity is as follows [15]:

Tc=30.957°C is the critical temperature, the corresponding critical density is ρ_c=467.69 kg/m^3, and the critical pressure is Pc=7.3721MPa; the rest are fitting coefficients, see the literature [15].

If the temperature and pressure values are known and the basic equations formed by the above formula are used, the expression of the thermophysical property parameters of carbon dioxide can be derived:

Density:

$$\rho(\delta,\tau) = \frac{p}{R_c T(1+\delta\phi_\delta^r)} \qquad (3.7)$$

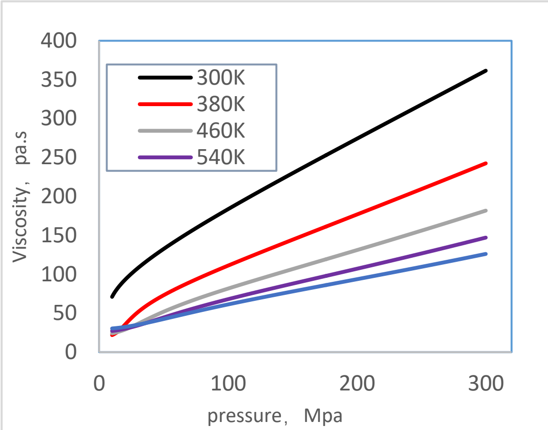

Figure 1 Comparison of viscosity changes with different temperature

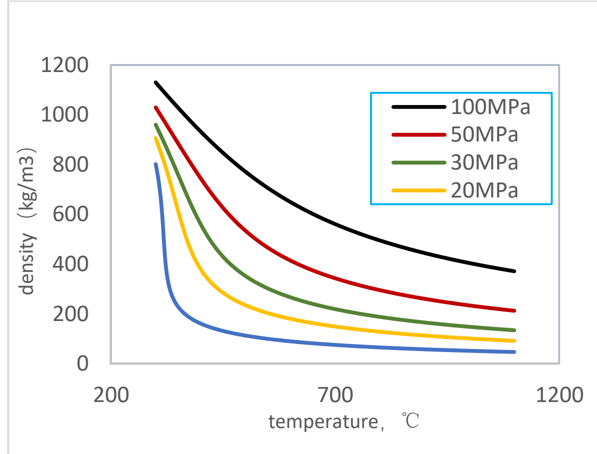

Figure 2 Comparison of density changes with different pressure

Constant pressure heat capacity:

$$c_p(\delta,\tau)=R_c[-\tau^2(\phi^o{}_{\tau\tau}+\phi^r{}_{\tau\tau})+\frac{(1-\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau})^2}{1+2\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta}}] \tag{3.8}$$

Enthalpy:

$$h(\delta,\tau)=R_cT[1+\tau(\phi^o{}_\tau+\phi^r{}_\tau)+\delta\phi^r{}_\delta] \tag{3.9}$$

Compression factor:

$$C_{co_2}=\frac{1}{\rho}\frac{\partial\rho}{\partial p} \tag{3.10}$$

4. NUMERICAL STUDIES

In this paper, the finite volume method (FVM) is used to discretize the mass and energy conservation equations, and the continuous implicit method is used to solve the equations by decoupling fractures and matrix equations [10][16].

4.1 Model Validation

Table 1 Parameters for calculation

Parameter	Value	Unit
Densit of rock matrix y ρ_r	2500	kg/m^3
Specific heat capacity of rock	1000	J/(kg℃)
Heat transfer coefficient of rock	2	W/(m·K)
Density of fluid ρ_w	1000	kg/m^3
Specific heat capacity of fluid c_w	1600	J/(kg℃)
Opening of fractures b	0.003	m
Length of fractures	60	m
Temperature of initial formation T_0	180	K
Temperature of injection fluid T	20	K

In 1975, Gringarten gave an analytical solution for seepage-heat transfer in single fractured rock [17]. The stemperature distribution can be written as:'

（4.1）：

$$T_D(x,y,t)=erfc\left[\frac{\lambda_r+bu_w\rho_wc_w|y|}{2bu_w\rho_wc_w}\sqrt{\frac{u_w\rho_rc_r}{\lambda_r(u_wt-x)}}\right] \tag{4.1}$$

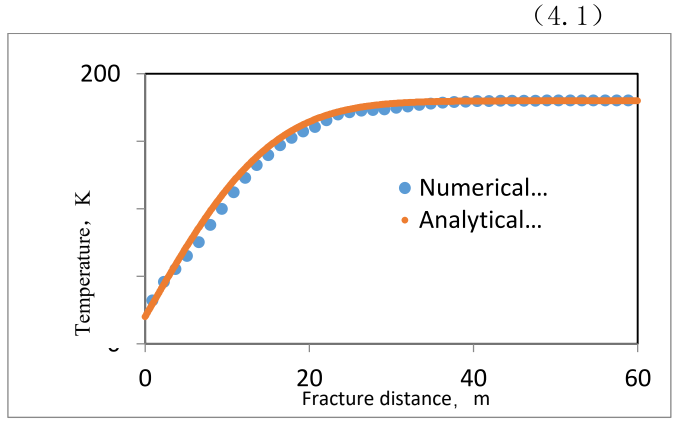

Figure 3 The distribution of temperature of fluid in fracture

The simulation results show that the numerical solution agrees with the analytical solution and proves the accuracy of the model.

4.2 Comparison of injected water and injected supercritical carbon dioxide

Case design: 49m × 49m Reservoir, there is a fracture in the center, the formation temperature is 180 ° C, the fluid is injected at a constant flow rate and temperature, the injection fluid is water and supercritical carbon dioxide, respectively, the injection

Calculation results:

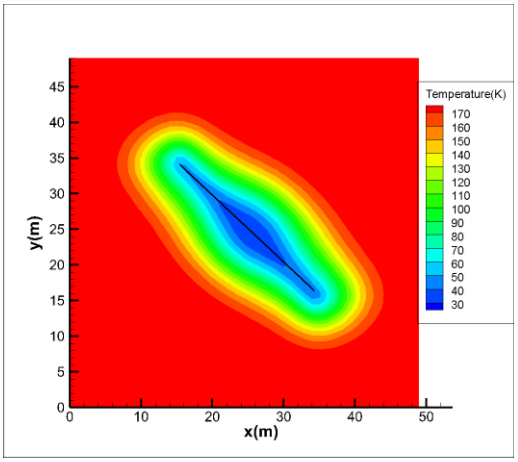

Figure 4 Temperature distribution of injected water(1 fracture)

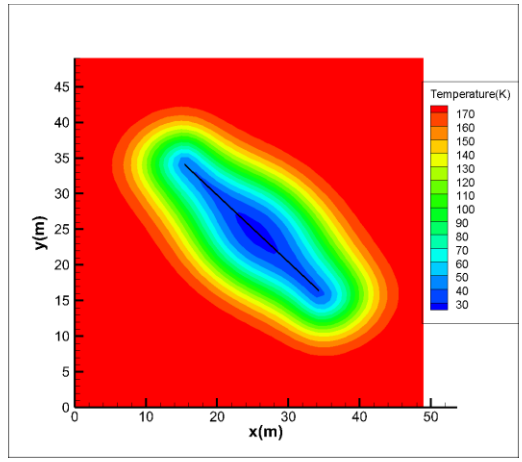

Figure 5 Temperature distribution of supercritical carbon dioxide injection(1 fracture)

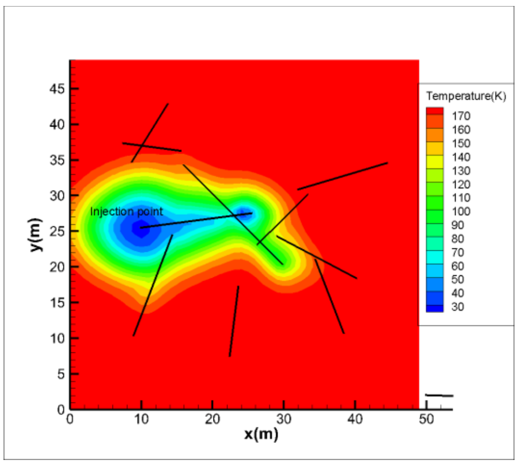

Figure 6 Temperature distribution of injected water(10 fractures)

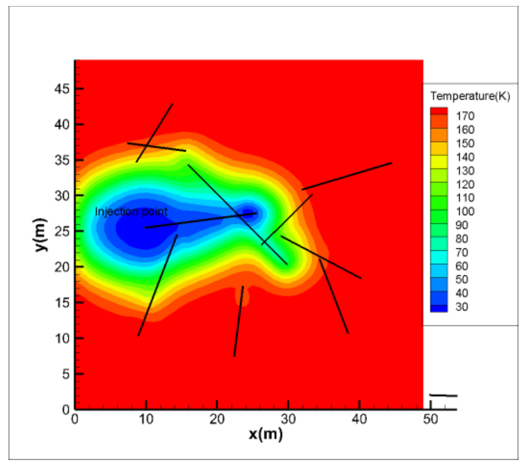

Figure 7 Temperature distribution of supercritical carbon dioxide injection(10 fractures)

time is 70d, Table 2 is selected Specific calculation parameters.

Table 2 Numerical simulation parameters

Parameter	Value	Unit
Rock matrix Density ρ_r	2450	kg/m^3
Rock Specific heat capacity c_r	1600	J/(kg°C)
Rock Heat transfer coefficient λ_r	2	MPa
Temperature of initial formation T_0	180	K
Temperature of injection fluid T	20	K
Porosity of fracture φ_f	0.003	m
Porosity of matrix φ_o	0.2	m
Permeability of fracture k_f	5×10^{-12}	m^2
Permeabilityof matrix k_f	1×10^{-15}	m^2
Injection rate v_l	0.001	m^3
Density of injected water ρ_w	1000	kg/m^3

The numerical simulation results show that supercritical carbon dioxide has faster temperature propagation and higher heat exchange efficiency in the enhanced geothermal system. It can be used as a working fluid for extracting geothermal resources. At the same time, complex fracture networks facilitate the full contact heat transfer between the fluid and the high temperature formation.

5. CONCLUSIONS

Based on the embedded discrete fracture model, the research on heat transfer and mass transfer of supercritical carbon dioxide in enhanced geothermal system is carried out. The numerical simulation results show that the use of supercritical carbon dioxide to extract geothermal resources has higher heat transfer efficiency. Also the complex fracture network can greatly benefit the exploitation of geothermal energy.

REFERENCE

[1] Barbier E. Geothermal energy technology and current status: an overview[J]. Renewable and sustainable energy reviews, 2002, 6(1-2): 3-65.

[2] Lu S M. A global review of enhanced geothermal system (EGS)[J]. Renewable and Sustainable Energy Reviews, 2018, 81: 2902-2921.

[3] Gallup D L. Production engineering in geothermal technology: a review[J]. Geothermics, 2009, 38(3): 326-334.

[4] Xie L, Min K B. Initiation and propagation of fracture shearing during hydraulic stimulation in enhanced geothermal system[J]. Geothermics, 2016, 59: 107-120.

[5] Olasolo P, Juárez M C, Morales M P, et al. Enhanced geothermal systems (EGS): A review[J]. Renewable and Sustainable Energy Reviews, 2016, 56: 133-144.

[6]Brown D W. A hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water[C].Proceedings of the twenty-fifth workshop on geothermal reservoir engineering, Stanford University. 2000: 233-238.

[7] Pan C, Romero C E, Levy E K, et al. Fully coupled wellbore-reservoir simulation of supercritical CO2 injection from fossil fuel power plant for heat mining from geothermal reservoirs[J]. Journal of CO2 Utilization, 2018, 27: 480-492.

[8] Fritz B, Jacquot E, Jacquemont B, et al. Geochemical modelling of fluid–rock interactions in the context of the Soultz-sous-Forêts geothermal system[J]. Comptes Rendus Geoscience, 2010, 342(7-8): 653-667.

[9]Shi Y, Song X, Wang G, et al. Study on wellbore fluid flow and heat transfer of a multilateral-well CO2 enhanced geothermal system[J]. Applied Energy, 2019, 249: 14-27.

[10] Jansen G, Valley B, Miller S A. THERMAID-A matlab package for thermo-hydraulic modeling and fracture stability analysis in fractured reservoirs[J]. arXiv preprint arXiv:1806.10942, 2018.

[11] Span R, Wagner W. A new equation of state for carbon dioxide covering the fluid region from the triple - point temperature to 1100 K at pressures up to 800 MPa[J]. Journal of physical and chemical reference data, 1996, 25(6): 1509-1596.

[12] Lee S H, Jensen C L, Lough M F. An efficient finite difference model for flow in a reservoir with multiple length-scale fractures[C]. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1999.

[13] Moinfar A.. Development of an efficient embedded discrete fracture model for 3D compositional reservoir simulation in fractured reservoirs[D]. Texas:the University of Texas at Austin,2013.

[14] Span R, Wagner W. A new equation of state for carbon dioxide covering the fluid region from the triple - point temperature to 1100 K at pressures up to 800 MPa[J]. Journal of physical and chemical reference data, 1996, 25(6): 1509-1596.

[15]Fenghour A, Wakeham W A, Vesovic V. The viscosity of carbon dioxide[J]. Journal of Physical and Chemical Reference Data, 1998, 27(1): 31-44.。

[16] Hajibeygi H, Karvounis D, Jenny P. A hierarchical fracture model for the iterative multiscale finite volume method[J]. Journal of Computational Physics, 2011, 230(24): 8729-8743.

[17] Gringarten A C, Witherspoon P A, Ohnishi Y. Theory of heat extraction from fractured hot dry rock[J]. Journal of Geophysical Research, 1975, 80(8): 1120-1124.