Application of 3D embedded discrete fracture model for simulating CO₂-EOR and geological storage in fractured reservoirs

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Abstract. For the purpose of greenhouse gas control and environment protection, CO₂ emission reduction has become a hot spot in global research. CO₂-EOR and geological storage are widely regarded as one of the most economical and promising emission reduction measures. In this paper, the 3D embedded discrete fracture model (EDFM) is built to simulate the inter-fracture CO₂ flooding and geological storage process in fractured reservoirs. This model can deal with the complex geological conditions of three-dimensional arbitrary inclined fracture networks, significantly improve the calculation efficiency, and accurately evaluate the CO₂-EOR process of real reservoirs. The obtained CO₂ reserves and saturation distribution can provide key technical parameters for field operations.

1. Introduction
For more than 20 years, issues such as “global climate change” and “global warming” have entered the agenda of national summits from the theme of academic papers and become a hot topic in the media such as newspapers, magazines, radio, television and internet. It is now widely accepted that CO₂ is one of the major greenhouse gases that cause global warming, and global climate change is related to CO₂ emissions [1]. According to the current state of the technology, the direct injection of CO₂ into the formation is a technically feasible and environmentally safe solution [2]. Technologies that indirectly use CO₂ and store it permanently in the formation include: injecting it in oil & gas reservoirs to enhance oil & gas recovery (CO₂-EOR), injecting it in coal seams to increase methane recovery and directly injecting CO₂ into the groundwater layer for permanent geological storage [3-4]. Owing to its economy and effectiveness, injecting CO₂ into oil & gas reservoirs becomes one of the ideal storage technologies currently. It not only has a large demand for CO₂ and meets the requirement of permanent CO₂ isolation, but also can increase oil and gas production. It has certain economic returns and can compensate for the cost of CO₂ separation, transportation and injection.

The proportion of low and ultra-low permeability fractured reservoirs in Ordos Basin is increasing year by year. How to develop such reserves economically and effectively has become a hot spot in the research of major oil fields in China [5]. Although CO₂ injection into high-permeability fractured reservoirs to enhance oil recovery has been used for many years, the study of combining CO₂-EOR with geological storage has just begun. Now the focus of CO₂-EOR and geological storage is to
maximize the CO₂ storage potential while ensuring oil recovery enhancement, and to ensure the safety and reliability of the storage [6]. More importantly, the precondition of above work is making a detailed description and characterization of complex hydraulic fracture networks. Preliminary research has found that such reservoirs can be effectively described by embedded discrete fracture model (EDFM), which also meets the calculation needs of high precision and high speed [7-10]. Therefore, the EDFM technology has received more and more attention in fractured reservoirs.

In this paper, the 3D embedded discrete fracture model (EDFM) is built as a framework for the numerical model to deal with complex fracture networks. In 3D EDFM, the non-coordinating grids are used to discretize the base region. By calculating the connection between fracture units and base units, fractures are embedded in the background grids, avoiding difficulties of generating high-quality nonstructural grids to match complex fractures, which can handle more complex three-dimensional reservoir geological conditions, and significantly improve computational efficiency. In this paper, the 3D EDFM is used to simulate the CO₂ injection process of fractured reservoirs, and the obtained CO₂ reserves and saturation distribution can provide key technical parameters for field operations.

2. Methodology

2.1. Basic assumptions and governing equations

Considering the true formation conditions of fractured reservoirs, in order to better establish the three-dimensional embedded discrete fracture model (3D EDFM), the basic assumptions are as follows: 1) Reservoirs are homogeneous, isotropic, and isopachous; 2) The fluid flow in the reservoir is isothermal seepage of oil and gas biphase, and the fluid density and viscosity do not change with pressure; 3) Gravity effects are considered; 4) The boundary of reservoir is closed; 5) Fractures are finite conductivity fractures.

Oil component governing equation:

$$\nabla \cdot \left\{ \frac{kk_{ro}}{B_o \mu_o} \left[ \nabla p_o - \nabla \left( \gamma_o D \right) \right] \right\} + q_o = \frac{\partial}{\partial t} \left( \frac{\phi S_o}{B_o} \right)$$

where $\gamma_o = \rho_{osi} g / B_o$, and $\rho_{osi}$ is oil-phase density under standard surface condition. Therefore, the equation can be rewritten as:

$$\nabla \cdot \left\{ \frac{kk_{ro}}{B_o \mu_o} \left[ \nabla p_o - \rho_{osi} g \left( \frac{D}{B_o} \right) \right] \right\} + q_o = \frac{\partial}{\partial t} \left( \frac{\phi S_o}{B_o} \right)$$

The gas component equation can be written as:

$$\nabla \cdot \left\{ \frac{kk_{rg}}{B_g \mu_g} \left[ \nabla p_g - \rho_{ggi} g \left( \frac{D}{B_g} \right) \right] + \frac{R_k k_{ro}}{B_o \mu_o} \left[ \nabla p_o - \rho_{osi} g \left( \frac{D}{B_o} \right) \right] \right\} + q_g + R_i q_o = \frac{\partial}{\partial t} \left( \frac{\phi S_g}{B_g} + \frac{\phi R_i S_o}{B_o} \right)$$

where $\gamma_g = \rho_{ggi} g / B_g$, and $\rho_{ggi}$ is gas-phase density under standard surface condition.

2.2. Finite volume discretization of the flow equations and discrete schemes from 3D EDFM

Compared to the discrete fracture model (DFM) that uses complex nonstructural grids to match the geometry of the fracture in space, the embedded discrete fracture model (EDFM) only needs to use a fixed set of structured matrix grids, which is the key advantage of EDFM over DFM [9]. For 3D EDFM, rectangular parallelepipeds grids are generally chosen to easily solve the geometrical parameters between the fracture surface and the matrix [10]. In this set of grid systems, the finite volume method that satisfies the local mass balance and has clear physical meaning is the preferred choice. Therefore, in this paper, the finite volume method is used to discretize the flow equation in a cuboid matrix grid. The details are as follows:
This paper takes the oil component equation as an example to illustrate the finite volume discrete scheme of the flow equation. In this paper, the block center finite volume method is adopted. The control volume of a block center is the volume of the gridblock where the block center is located. Integrate the time and control volume on both sides of the oil-phase equation above, and use the divergence theorem to obtain:

\[
\int_{t}^{t+\Delta t} \int \left( k \frac{\partial p_o}{\partial x_o} - \nabla \left( \rho_o D \right) \right) \cdot \mathbf{n} \, ds \, dt + q_o = \int_{V} \left[ \frac{\partial}{\partial t} \left( \frac{\phi S_o}{B_o} \right) \right] \, dV
\]

(4)

The area integral in the left side of equation (4) can be approximated by the sum of the normal flow rates between adjacent gridblocks that conforms to the physical meaning. For the integration of time on the right side of the above equation, it can be solved accurately, which is why the finite volume method has high precision. Equation (4) can be rewritten as:

\[
\sum_{j=1}^{n} \left[ T_{ij} \left( p_{oi,j} - p_{oj} \right) + \left( \gamma_o D_{oi,j} - \gamma_o D_{oj} \right) \right] + q_{gsc}^{n+1} = \frac{\Delta V_i}{\Delta t} \left[ \frac{\phi S_o}{B_o} \right] + \left( \frac{\phi S_o}{B_o} \right)^{n+1}
\]

(5)

where \( n \) is the number of gridblocks adjacent to the gridblock; \( \Delta V_i \) is the volume of the gridblock; \( \Delta t \) is the time interval of the adjacent two time steps; \( T_{ij} \) is the transmissibility of adjacent gridblocks, which is the product of the mobility \( \lambda_{ij} \) and the geometric factor \( G_{ij} \). In the equation, the upstream scheme is used for the value of the physical quantity \( k_{ro} \) subject to saturation. For physical quantities \( \mu_o \) and \( B_o \) subject to pressure, the values are in arithmetic average scheme.

Similar to the oil component equation, the block center finite volume discrete scheme of the gas component flow equation in the matrix grid is:

\[
\sum_{j=1}^{n} \left[ G_{ij} \lambda_{ij} \left( p_{g.i,j} - p_{g.o,j} \right) + R_{s,i,j} G_{ij} \lambda_{ij} \left( p_{g,i,j} - p_{g.o,i,j} \right) + \left( \gamma_o D_{g.i,j} - \gamma_o D_{g.o,i,j} \right) \right] + q_{gsc}^{n+1} = \frac{\Delta V_i}{\Delta t} \left[ \frac{\phi S_g}{B_g} \right] + \left( \frac{\phi S_g}{B_g} \right)^{n+1}
\]

(6)

In this paper, for flow between fracture units, the block center finite volume method is still used to discretize the flow equation. Taking the oil component equation as an example, the discrete scheme can be obtained as follows:

\[
\sum_{j=1}^{n} \left[ T_{ij} \left( p_{o,i,j} - p_{o,j} \right) + \left( \gamma_o D_{o,i,j} - \gamma_o D_{o,j} \right) \right] + q_{conf} = \frac{\Delta V_i}{\Delta t} \left[ \frac{\phi S_o}{B_o} \right] + \left( \frac{\phi S_o}{B_o} \right)^{n+1}
\]

(7)

where \( n \) is the number of fracture units adjacent to the \( i \)th fracture unit; \( T_{ij} \) is the transmissibility of the \( i \)th and \( j \)th fracture units; \( p_{o,i,j}, p_{o,j} \) are the oil-phase pressures at the center of the \( i \)th and \( j \)th fracture units; \( \gamma_o, \gamma_o \) are the oil-phase gravities at the center of the \( i \)th and \( j \)th fracture units; \( D_{o,i,j}, D_{o,j} \) are the depths at which the center of the \( i \)th and \( j \)th fracture units are located (negative number); \( q_{conf} \) is the transfer flux term of the matrix grid to the fracture unit; \( \Delta V_i \) is the volume of the \( i \)th fracture unit; \( \Delta t \) is the time increment; \( \phi, S_{o,j} \) are the porosity and saturation of the \( i \)th fracture unit; \( B_o \) is the oil-phase volume factor corresponding to the \( i \)th fracture unit.

It can be seen from equation (7) that the key to determining the specific discrete scheme of the flow equation of fracture units is to determine the transmissibility \( T_{ij} \) of fracture units, and the calculation of the geometric factor \( G_{ij} \) in the transmissibility is related to the connection mode between fracture units. As shown in Figure 1, after dividing the fracture by matrix grid boundary, four Non-neighboring Connection (NNC) pairs in EDFM are formed, which are the connection between the fracture segment and the matrix grid through which the fracture section passes (NNC Type I), the connection between adjacent fracture segments in a fracture (NNC Type II), the connection between intersecting fracture (different fractures) segments (NNC Type III) and the connections between two adjacent matrix cells.
(NNC Type IV). Introducing NNC pairs to enable flow exchange between grids that are adjacent in the physical model but not adjacent in computational model. The general calculation equation of the transmissibility coefficient of the non-neighboring connection pair is:

$$T_{NNC} = \frac{K_{NNC} A_{NNC}}{d_{NNC}}$$  \hspace{1cm} (8)

where $K_{NNC}$ is the permeability of NNC pair, i.e., the effective permeability, mD; $A_{NNC}$ is the contact area of NNC pair, i.e., the open area, m$^2$; $d_{NNC}$ is the characteristic distance associated with NNC, m.

![Figure 1. The NNCs of embedded discrete fracture model.](image)

### 3. Application cases

In this section, we give two application cases that illustrate the CO$_2$-EOR process of multi-stage fractured horizontal wells in the small-size reservoir to illustrate the practical application of the proposed model. The studied reservoir is located in Ordos Basin of western China and has been considered a potential reservoir for CGS. Table 1 summarizes the used physical parameters of the reservoir and fluid, such as rock, fracture, injection gas (CO$_2$) and oil phase properties. As shown in Figure 2, there is the relative permeability and capillary pressure curves in matrix, which reflects the flowability of oil and gas in reservoir. The producer is at constant bottom hole pressure 10 MPa and 30 MPa when it is producing and injecting respectively.

| Properties                  | Value       | Properties                  | Value       |
|-----------------------------|-------------|-----------------------------|-------------|
| Reservoir volume, m$^3$     | 1000×400×30 | Grid number                | 100×40×3    |
| Depth, m                    | 1500        | Initial reservoir pressure, MPa | 30          |
| Horizontal wellbore length, m | 685        | Constrained pressure, MPa   | 10          |
| Well diameter, m            | 0.178       | Depleted pressure, MPa      | 2           |
| Injection rate, m$^3$/d     | $1\times10^5$ | Skin factor                | 0.1         |
| Matrix density, kg/m$^3$    | 2400        | Fracture aperture, mm      | 10          |
| Matrix compressibility, Mpa$^{-1}$ | $1.07\times10^4$ | Fracture compressibility, Mpa$^{-1}$ | $1\times10^2$ |
| Matrix porosity, fraction   | 0.1         | Fracture porosity, fraction | 0.4         |
| Matrix permeability, mD     | 1           | Fracture permeability, mD   | 20,000      |
| Gas density (SC)            | 1.784       | Oil density (SC)            | 820         |
| Gas viscosity, mPa·s        | 0.01        | Oil viscosity, mPa·s        | 2           |
| Gas Z-factor, fraction      | 0.8         | Oil compressibility         | $3.02\times10^3$ |
3.1. Multi-stages fractured horizontal well with arbitrary inclined fractures in 3D reservoir

In this case, an efficient 3D EDFM for production simulation of a multi-stage fractured horizontal well is developed, and the novelties of proposed 3D EDFM lie on the main differences between the proposed 3D EDFM and the 2D EDFM is that our proposed model can be adaptive to arbitrary inclined fractures with arbitrary shape. Figure 3 shows the front view, overhead view, and 3D view of the reservoir model with a three-stages fractured horizontal well. It can be seen that this simulator can efficiently calibrate the hydraulic fracture networks by microseismic monitoring data and characterize more complex spatial positions and shapes of fractures to figure out connections between fractures cells and matrix gridblocks such that the model can be adaptive to arbitrary inclined fractures in 3D reservoir. The commercial software, such as CMG, which only handles the situation that fractures are aligned with axes. And this is also the obvious advantage of our proposed model in this paper.

This model can be applied to make more accurate appraise of the CO2-EOR and storage process, such as the CO2 huff-n-puff with single well and inter-fracture asynchronous injection and production. Due to the limitation of content length, this case focuses on the advantages of characterizing complex shapes of fractures and arbitrary spatial positions distribution in 3D reservoir and does not discuss the CO2-EOR and storage process in detail here. The next case will elaborate on the inter-fracture CO2 flooding between multi-wells.
3.2. **Inter-fracture CO₂ flooding between multi-wells**

In this case, a hybrid model is developed for simulating the inter-fracture CO₂ flooding process between multi-wells. Figure 4 shows that the sketch of three multi-stages fractured horizontal wells system and the injection gas well is in the middle of two production oil wells. The extra field significance of studying this model is that the asynchronous injection and production process can be stimulated by further controlling the open-shut time of injection gas well. Figure 5 summarizes the plot of the CO₂-EOR and geological storage process of 1 year. The CO₂ injection rate is related to the production pressure difference and the fracture gap spacing, and the oil production drop slows down owing to the effect of gas injection.

**Figure 4.** The sketch of inter-fracture CO₂ flooding between multi-wells.

![Image of inter-fracture CO₂ flooding between multi-wells](image)

(a) CO₂ injection rate under constant pressure  
(b) Oil production rate

**Figure 5.** The plot of the CO₂-EOR and geological storage process of 1 year.

![Image of CO₂ injection rate and oil production rate](image)

The model proposed in this paper can be used to modeling the location of fractures in different layers, which is more consistent with the actual formation background and engineering conditions. In this model, the first fracture of the injection gas well is located in the first and second layers, and the second and third fractures are located in the third and fourth layers. Figure 6 shows that the CO₂ saturation distribution map of four layers of 1 year at different layers in this case.

4. **Conclusions**

This paper presents a CO₂-EOR evaluation model based on 3D EDFM. The model can effectively describe the three-dimensional geological conditions of fractured reservoirs, but previous models cannot effectively deal with this problem. Practical applications of the model in simulating inter-fracture CO₂ flooding between multi-wells are illustrated. In summary, the model can handle the complex shapes of fractures and arbitrary spatial positions distribution in 3D reservoir and can be used to accurately evaluate CO₂-EOR and geological storage in fractured reservoirs.
Figure 6. The CO$_2$ saturation distribution map of 1 year at different layers in this case.

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