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A modified pressure transient analysis model for estimating carbon sequestration capacity of a shale reservoir

Xudong Shen[1,2*], Huiqing Liu [1,2], Mingzhe Guo[1,2], Liangyu Ma[1,2]

1 China University of Petroleum Beijing

2 State Key Laboratory of Petroleum Resources and Prospecting

ABSTRACT

In this work, a modified model considering partial penetration and finite conductivity of hydraulic fractures is introduced to estimate the carbon sequestration capacity of depleted shale reservoir with multiple fractured horizontal well. Firstly, the conservation equations, initial conditions as well as boundary conditions for matrix, natural fractures and hydraulic fractures are deduced with the consideration of partial penetration, finite conductivity, CO_2 diffusion, adsorption and seepage. Then, by means of Laplace transform, Pedrosa transform as well as Fourier transform, the pressure response in real domain is acquired. Finally, based on the pressure response of injection well, the influence of penetration degree combined with hydraulic fracture conductivity and hydraulic fracture half length on carbon storage capacity are analyzed, which were always ignored in the conventional methodologies. The results indicate that the penetration degree has significant impact on the early and mid-stage of carbon storage. With the increase of hydraulic fracture half length and conductivity, the influence of penetration degree decreases gradually. Compared with conventional methodologies, the modified model can provide more precise predictions for carbon storage capacity of shale reservoirs.

Keywords: carbon sequestration capacity, depleted shale reservoir, pressure transient analysis, partial penetration, multiple fractured horizontal well

NONMENCLATURE

P	Real pressure response, MPa
m_D	Dimensionless pseudo-pressure
D_{kD}	Dimensionless Knudsen number
t_D	Dimensionless injection time
V_D	Dimensionless CO_2 concentration
r_D	Dimensionless radial distance in matrix
r_D	Dimensionless radial distance in natural fracture
r_{eD}	Dimensionless boundary radius
z_D	Dimensionless vertical distance
z_{wD}	Dimensionless vertical coordinate of hydraulic fracture midpoint
L_D	Dimensionless performed length
γ_D	Dimensionless permeability modulus
ξ_D	Dimensionless Pedrosa pressure
λ	Dimensionless adsorption index
ω	Storage ratio, dimensionless
q_D	Dimensionless CO_2 injection rate
X_{fD}	Dimensionless hydraulic fracture half length
I_n	First kind of Bessel Function
K_n	Second kind of Bessel Function
s	Laplace transformation variable
P_i	Initial pressure, MPa
P_{fin}	Constrained injection pressure, MPa
Q_{total}	Total volume of CO_2 storage, m^3

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1. INTRODUCTION

At present, with the rapid growth of global population and huge amount of fossil energy consumption, excessive carbon dioxide is being released to the atmosphere causing global warming and more frequently extreme climates. Carbon capture, utilization and storage (CCUS) has great potential as a technology dealing with global warming and climate change. Depleted shale reservoir is a kind of ideal site for CO_2 storage, because its ultra-low permeability which can greatly reduce leakage and environmental risks. In addition, CO_2 molecule could be adsorbed on the surface of shale particles and organic matters, and diffuse inward through Knudsen diffusion which can greatly improve the capacity of carbon storage (Wang[1], Chen[2]). Furthermore, compared with saline aquifers (Zhu[3], Lyu[4]), carbon dioxide storage in depleted reservoirs can make full use of existing wells and greatly reduce costs.

Chen[2] proposed a new methodology to estimate the storage capacity of depleted shale reservoir based on pressure transient analysis. On the basis of this methodology, Kou[5] put forward a new model with consideration of finite conductivity, SRV, and hydraulic fracture half length and got excellent precision. However, the impact of penetration degree and its influence combined with hydraulic fracture conductivity, fracture half length on carbon storage capacity are still not clear. In this study, based on the pressure transient analysis, a modified model is put forward with the consideration of penetration degree, and then sensitivity analysis is performed. This modified model can provide a more precise prediction on carbon storage capacity especially when the injection rate is high and constrained pressure is relatively low.

2. PHYSICAL MODEL AND ASSUMPTIONS

Figure 1. shows the physical model of depleted shale gas reservoir with multiple fractured horizontal well. Depleted shale gas reservoir is a dual-porosity system with cylinder impermeable boundary, which is composed of matrix and nature fractures. Hydraulic fractures are partially penetrated and evenly distributed along the well bore, pressure drop along the well bore is neglected. Other assumptions are as follows:

(1) The flow of CO_2 in the hydraulic fractures and natural fractures follows Darcy's law. The effect of gravity and capillary pressure are neglected.

(2) The adsorption process of CO_2 follows Langmuir isotherm adsorption, and its diffusion process satisfies Knudsen diffusion.

(3) Nature fractures are sensitive to pressure change.

(4) The injection rate of multiple fractured horizontal well is constant.

(5) The reservoir is homogeneous. Permeability, reservoir thickness, porosity, Knudsen diffusion coefficient, adsorption coefficient are constant along the radial and vertical directions.

(6) The initial pressure is evenly distributed equal to p_i.

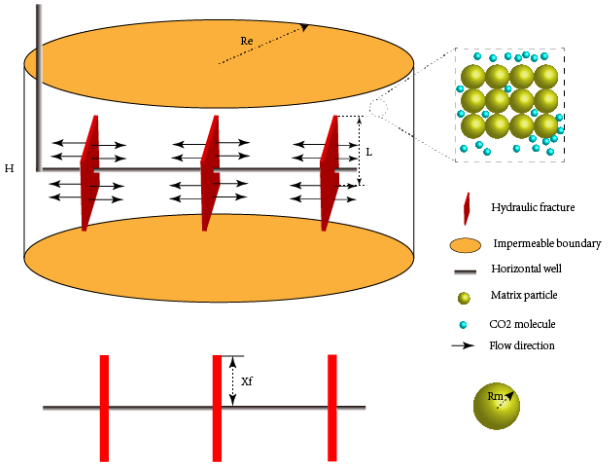

Fig 1. Physical model of partially performed multiple fractured horizontal well in depleted shale reservoir

3. MATHEMATICAL MODEL AND SOLUTIONS

3.1 Matrix system

According to the assumptions in previous chapter, CO_2 flows in the matrix mainly through Knudsen diffusion. Combining with boundary conditions and initial condition, the dimensionless equations describing matrix system are as follows:

$$-\frac{1}{r_{mD}^2}\frac{\partial}{\partial r_{mD}}\left(r_{mD}^2\frac{\partial V_D}{\partial r_{mD}}\right)=\frac{1}{D_{kD}}\frac{\partial V_D}{\partial t_D} \tag{1}$$

$$\frac{\partial V_D}{\partial t_D}=3D_{kD}\frac{\partial V_D}{\partial r_{mD}}\Big|_{r_{mD}=1} \tag{2}$$

$$\frac{\partial V_D}{\partial r_{mD}}\Big|_{r_{mD}=0}=0 \tag{3}$$

$$V_D\big|_{r_{mD}=1}=V_{ED}=\lambda m_{1D} \tag{4}$$

$$V_D\big|_{t_D=0}=0 \tag{5}$$

3.2 Natural fracture system

Natural fractures are the main flow channels for CO_2 in the shale reservoir. Considering stress sensitive effect and partial penetration, the conservation equation, boundary conditions and initial condition can be written as below:

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D e^{-\gamma_D m_D}\frac{\partial m_D}{\partial r_D}\right)+\frac{\partial}{\partial z_D}\left(e^{-\gamma_D m_D}\frac{\partial m_D}{\partial z_D}\right)=\omega\frac{\partial m_D}{\partial t_D}+(1-\omega)\frac{\partial V_D}{\partial t_D} \quad (6)$$

$$r_D e^{-\gamma_D m_D}\frac{\partial m_D}{\partial r_D}\Big|_{r_D=0}=-\frac{q_D}{L_D}, z_{aD}<z_D<z_{bD} \quad (7)$$

$$r_D e^{-\gamma_D m_D}\frac{\partial m_D}{\partial r_D}\Big|_{r_D=0}=0, 0<z_D<z_{aD}, z_{bD}<z_D<H_D \quad (8)$$

$$\frac{\partial m_D}{\partial r_D}\Big|_{r_D=r_{eD}}=0 \quad (9)$$

$$m_D\Big|_{t_{D=0}}=0 \quad (10)$$

Where z_{aD} is the upper boundary of perforation section, dimensionless; z_{bD} is the lower boundary of perforation section, dimensionless.

3.3 Pressure solutions

The stress-sensitive term $e^{-\gamma_D m_D}$ in Eq 6 can be processed by Pedrosa transformation (Pedrosa[6]). After transformation, pseudo pressure m_D in Eq1-Eq10 is transformed into Pedrosa pressure ξ_D. The point source solution in Fourier space can be obtained by Laplace transform and Fourier transform. The Pedrosa transform, Laplace transform, Fourier transform formulas and point source solution in Fourier domain are as follows:

$$m_D=-\frac{1}{\gamma_D}\ln(1-\gamma_D\xi_D) \quad (11)$$

$$F(s)=\int_0^{+\infty}f(t)e^{-st}dt \quad (12)$$

$$F(\eta)=\int_{-\infty}^{+\infty}f(t)e^{-j\eta t}dt \quad (13)$$

$$\hat{\xi}_D=\mathrm{A}K_0(r_D\sqrt{\chi_n})+\mathrm{B}I_0(r_D\sqrt{\chi_n}) \quad (14)$$

Where $\chi_n=s\omega+3\lambda(1-\omega)[\sqrt{s/D_{kD}}\coth(\sqrt{s/D_{kD}})-1]$ (15)

$$\mathrm{A}=\frac{4\bar{q}_D h_D}{L_D n\pi}\cos(n\pi z_{wD})\sin\left(\frac{n\pi}{2}L_D\right) \quad (16)$$

$$\mathrm{B}=\frac{K_1(r_{eD}\sqrt{\chi_n})}{I_1(r_{eD}\sqrt{\chi_n})}\mathrm{A} \quad (17)$$

Through the inverse Fourier transform, the point solution in Laplace domain can be yielded.

$$\bar{\xi}_D=\sum_0^{\infty}\frac{\cos(n\pi z_D)}{N(n)}\hat{\xi}_D \quad (18)$$

$$N(n)=\int_0^{h_D}\cos^2(n\pi z_D)dz_D \quad (19)$$

Where $\hat{\xi}_D$ is the Pedrosa pressure in the Fourier domain, $\bar{\xi}_D$ is the Pedrosa pressure in the Laplace domain.

Each hydraulic fracture of the horizontal well is discretized into multiple segments of equal length (Fig 2.). Based on Eq 18 and the principle of potential superposition, combined with flowrate equations, the relationship between pressure response and flowrate is as follows:

$$\bar{\xi}_{Dji}=\sum_{l=1}^{M}\sum_{k=1}^{N}\bar{q}_{Dkl}\bar{\xi}_{Dji} \quad (20)$$

$$\sum_{j=1}^{M}\int_{-x_{fD}}^{x_{fD}}q_{Dj}dx_D=\frac{1}{s} \quad (21)$$

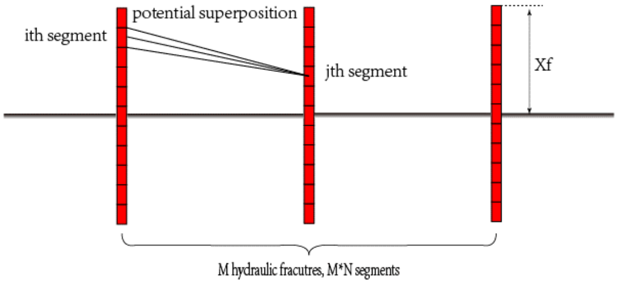

Fig. 2 Hydraulic fracture discretization and potential superposition

According to Duhamel's principle, the bottom hole pressure solution considering wellbore storage and skin effect can be obtained. Where S is skin effect, dimensionless, C_D is wellbore storage coefficient.

$$\bar{\xi}_{Dwcs}=\frac{S+s\bar{\xi}_{Dw}}{s(1+C_D s(S+s\bar{\xi}_{Dw}))} \quad (22)$$

The pressure response in the real domain can be obtained by Stefest inversion (Stefest[7]) and Eq 11.

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4. METHODOLOGY FOR ESTIMATING CARBON STORAGE CAPACITY IN SHALE RESERVOIR

Based on the methodology put forward by Chen and Chu, combined with Eq20-Eq22, the modified methodology for estimating carbon storage capacity is shown in Fig. 3.

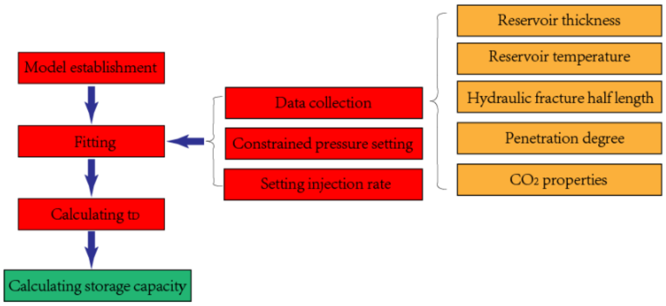

Fig.3 Flow chart of carbon storage capacity evaluation

According to the definition of dimensionless pressure and dimensionless time, the carbon storage capacity can be calculated by Eq23.

$$Q_{total} = q_{in} t_D \frac{\mu \Lambda h^2}{3.6 k_{fi}} \tag{23}$$

5. SENSITIVE ANALYSIS

According to Eq20-Eq22 and the evaluation process of carbon storage capacity, hydraulic fracture conductivity, hydraulic fracture half length and penetration degree are selected for analysis and D_{kD}=0.1152, a=2.4, Re=1500m, ω =0.12, h=30m, fracture spacing=80m, C_D=0.01, S=0.01, z_{wD}=1/2, hydraulic fracture stages=3 are selected as basic parameters for sensitive analysis.

5.1 *Hydraulic fracture conductivity*

Fig. 4 demonstrates the relationship between dimensionless time and hydraulic fracture conductivity when hydraulic fracture half length is set to 60m, the constrained pressure and penetration degree are variable. Total carbon storage volume is shown in Fig. 5.

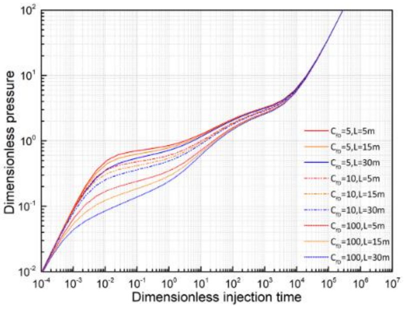

Fig. 4 Dimensionless pressure and dimensionless time curve under different hydraulic fracture conductivity and penetration degree

It indicates that hydraulic fracture conductivity has significant impact on the mid-stage of carbon storage. Besides, with the gradual increase in the conductivity, the influence of the penetration degree gradually decreases.

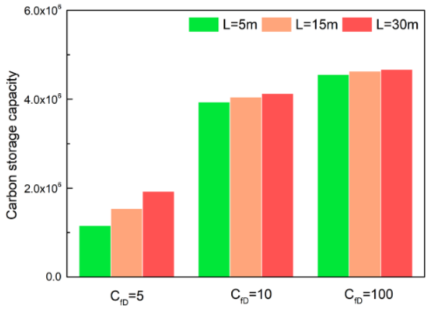

Fig. 5 Carbon storage capacity under different hydraulic fracture conductivity and penetration degree

5.2 *Penetration degree*

Fig. 6 shows the relation between dimensionless injection time and penetration degree when dimensionless hydraulic fracture conductivity is set to 10, the constrained pressure and hydraulic fracture half length are variable. Total carbon storage volume is shown in Fig 7.

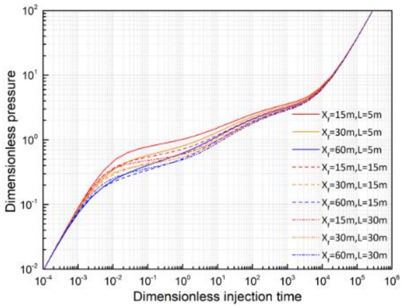

Fig. 6 Dimensionless pressure and dimensionless time curve under different hydraulic fracture half length and penetration degree

It's obvious that penetration degree mainly influences the mid-stage of carbon storage. As the hydraulic fracture half length increases, the impact of penetration degree gradually decreases.

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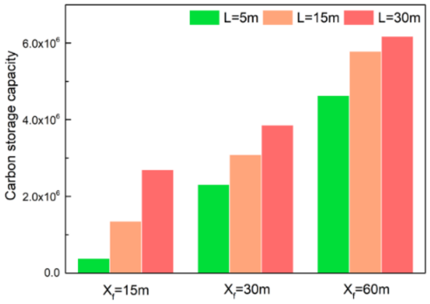

Fig. 7 Carbon storage capacity under different hydraulic fracture half length and penetration degree

CONCLUSIONS

Based on the conventional pressure transient analysis method, a modified model with the consideration of partial penetration is built, and some crucial parameters are well analyzed. Through this study, conclusions are shown below:

1. When the constrained injection pressure is relatively low and the injection rate is high, hydraulic fracture conductivity and penetration degree have significant impact on carbon storage capacity of depleted shale reservoir with multiple fractured horizontal well.

2. Hydraulic fracture conductivity mainly influences the early and mid-stage of carbon storage, the influence of penetration degree on carbon storage capacity gradually decreases when the hydraulic fracture conductivity increases. Similarly, as hydraulic fracture length increases, the impact of penetration degree gradually decreases.

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REFERENCE

[1] Wang, H.-T., Performance of multiple fractured horizontal wells in shale gas reservoirs with consideration of multiple mechanisms. *Journal of Hydrology* **2014,** *510*, 299-312.

[2] Chen, Z.; Liao, X.; Zhao, X., et al., A new analytical method based on pressure transient analysis to estimate carbon storage capacity of depleted shales: A case study. *International Journal of Greenhouse Gas Control* **2015,** *42*, 46-58.

[3] Zhu, L.; Liao, X.; Chen, Z., et al., Analytical model for quick assessment of capillary storage capacity in saline aquifers. *International Journal of Greenhouse Gas Control* **2017,** *65*, 160-169.

[4] Lyu, X.; Voskov, D.; Rossen, W. R., Numerical investigations of foam-assisted CO2 storage in saline aquifers. *International Journal of Greenhouse Gas Control* **2021,** *108*, 103314.

[5] Kou, Z.; Zhang, D.; Chen, Z., et al., Quantitatively determine CO2 geosequestration capacity in depleted shale reservoir: A model considering viscous flow, diffusion, and adsorption. *Fuel* **2022,** *309*, 122191.

[6] Pedrosa, O. A., Jr., Pressure Transient Response in Stress-Sensitive Formations. In *SPE California Regional Meeting*, 1986.

[7] Stehfest; Acm, H. J. C. o. t., Algorithm 368: Numerical inversion of Laplace transforms [D5]. **1970,** *13* (1), 47-49.

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