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Numerical Simulation of Dry Gas Migration in Condensate Gas Reservoir

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Abstract

Dry gas overlies on condensate gases and flows due to the difference in density. This phenomenon affects cyclic injection exploitation and increases production costs. A mathematical model of dry gas migration was developed in this study to investigate the migration characteristics and the overlying law for dry gas in the condensate gas reservoir. On the basis of the theory of convection diffusion, the governing equations were constructed, using dry and condensate gases as two pseudo-components. The distribution and transition belt of dry gas, as well as the effects of condensate oil and the perforation method on overlying of dry gas were discussed based on the dry gas migration model. The results demonstrate that the width of the transition belt of dry and condensate gases increases gradually over time. The mole fraction of gas in the transition belt is dense in the middle, but sparse at the two ends. The overlying of dry gas is easy, taking condensate oil into consideration. The value of F increases by 0.32, but the width of the transition belt becomes narrow. The transition belt under the top perforation of the reservoir is wider than that under symmetric perforation, and the overlying degree of dry gas increases. This study provides a theoretical foundation for in situ adjustment and optimization of cyclic gas injection utilization.

Keywords: Condensate gas reservoir; Gas injection; Condensate oil; Convective diffusion; Dry gas distribution

1. Introduction

The depletion of a condensate gas reservoir results in low recovery efficiency of condensate oil due to retrograde condensation under a pressure lower than dew point pressure. Development based on maintaining pressure production through gas injection can inhibit the precipitation of condensate oil and increase recovery efficiency [1, 2]. At present, gas injection is considered a good method for mining a condensate gas reservoir that is rich of condensate oil. Maintaining pressure production through gas injection is mainly divided into full and partly maintaining pressure production, on the basis of global mining practices concerning condensate gas reservoirs. Appropriate maintenance of pressure production through gas injection is applied in light of the content of condensate oil, the ground-dew point pressure difference and air source condition. Dry gas, nitrogen, air, and CO2 are the main gaseous media of injection [3, 4]. Dry gas is considered an injection medium for condensate gas reservoirs. It is categorized among hydrocarbon gases and can be used to extract heavy components in wet gas effectively after being mixed with wet gas in formation, thereby realizing phase equilibrium. As a result, the gaseous condensate oil content in formation decreases, which results in the reduction of retrograde condensate oil saturation in formation. The recovered wet gas is processed into dry gas and then injected in formation for cyclic use [5, 6]. Therefore, compared to other non-hydrocarbon gases, dry gas can effectively increase the recovery rate of condensate oil.

Although cyclic dry gas injection can increase the recovery efficiency of condensate gas, the dry gas overlying on condensate gas is found to affect recovery efficiency and increase production costs, although the effects of gravity difference and thermodynamics during the migration of reservoir components under high temperature and pressure on the component migration law are unknown. The dry gas overlying on condensate gas is the consequence of their different densities. Decreasing the overlying degree, increasing the conformance factor, and investigating the overlying mechanism and law of dry gas have become problems that must be solved urgently to increase the gas injection recovery efficiency of condensate gas reservoirs [7, 8]. Studies on the mechanism of dry gas migration in condensate gas reservoirs have investigated the dry gas overlying on condensate gas [9, 10, 11, 12]. However, theories on the mathematical model of dry gas migration in condensate gas reservoirs are lacking. At present, a compositional model is the main math-

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ematical model [13, 14, 15]. This model focuses on the natural components of hydrocarbons. Dry and condensate gases contain multiple natural hydrocarbon components, with several components being the same. In addition, the compositional model overlooks the convective diffusion among components, thereby failing to solve the distribution and overlying law of independent dry gas.

In the present work, a mathematical model of dry gas migration during gas injection production of a condensate gas reservoir was constructed on the basis of thermodynamic diffusion theory of components by using dry and condensate gases as two pseudo-components. Moreover, the dry gas distribution and overlying law between its injection and production under different time conditions were discussed. This study provides theoretical references for further optimizing cyclic gas injection production schemes and adjustment measures.

2. State of the art

The maintenance of pressure production on cyclic gas injection is often adopted to condensate a gas reservoir rich in condensate oil; this process can increase the recovery efficiency of condensate gas and oil [16, 17]. During gas injection, dry gas overlying on condensate gas is a newly discovered phenomenon that involves gravitational differentiation theory, non-equilibrium phase state and non-equilibrium diffusion theory [18]. In the cyclic gas injection process involving condensate gas reservoirs, dry gas cannot be mixed with formation fluid in one phase immediately. Instead, a transition belt exists. Dry gas overlies on the condensate gas because of their different densities and the influences of formation anisotropism. This phenomenon reflects that the contents of dry and condensate gases in the upper parts of the formation are different from those in the lower parts. At present, research theories on gravity-induced overlying focus mainly on gas injection production and thermal recovery of thickened oil in oil reservoirs [19, 20, 21]. The overlying law of dry gas on condensate gas in condensate gas reservoirs is rarely investigated.

Existing research on dry gas migration in condensate gas reservoirs focuses mainly on the theory of migration mechanism, instrument test and relevant indoor experiments. Jiao et al. studied the migration mechanism of dry gas and indicated that the flow of dry gas in formations is sensitive to microscopic mixing, viscosity difference, gravity overlying and high-permeability band. A transition belt of dry gas and formation fluid was present in the leading edge of the injected gas [22]. Zhao et al. conducted a scanning test on cyclic gas injection in the Yaha condensate gas field by using the downhole fluid component analyzer, verified the longitudinal distribution characteristics of dry gas-transition belt-condensate gas and formulated the law of dry gas migration [23]. On the basis of an experimental study, Zhang et al. found a stable interface between the injected dry gas and the formation fluid. The gas injection would trigger the condensate gas system to generate dry gas and condensate gas and oil [24]. To date, few studies on the mathematical model of dry gas migration have become available. The full compositional model is a widely used mathematical model [25] based on all the natural components of hydrocarbons and involves a complicated phase equilibrium theory. The results of the full compositional model cannot explain the overlying behavior of dry gas on condensate gas.

A transition belt is found in the leading edge of the injected gas, because dry and condensate gases in the formation are not mixed immediately [26]. Thus, the mathematical model of dry and condensate gas diffusion must be investigated further. The mass transfer process is generally described by Fick's law [27], which implies a linear relationship between diffusion flux and concentration gradient, i.e., the concentration gradient is the impetus of diffusion. However, Fick's law is not true in all situations. Krishna et al. proposed the Maxwell-Stefan model, which considers the non-ideal type of thermodynamics and external force field based on Maxwell and Stefan's theories. This model was used to describe the mass transfer process of a single component or a complicated multi-component system [28, 29]. Ghorayeb et al. created the multi-component diffusion model which involved molecular, temperature, and pressure diffusion according to the non-equilibrium thermodynamics theory and the Maxwell-Stefan model. This model considers diffusion mechanism more comprehensively [30] and is conducive in investigating the mixing problem of dry and condensate gases.

Rsearchers have studied the law of dry and condensate gas migration in condensate gas reservoirs. However, failings are still observed. First, relevant research theories focus mainly on laboratory experiments and instrument testing. Only a few studies have focused on associated mathematical model and overlying law. Second, the compositional model emphasizes inter-phase mass transfer and phase-state changes. It focuses on the natural components of single hydrocarbons. Dry gas is a set of natural components of multiple hydrocarbons. The compositional model overlooks the convective diffusion of components. Thus, it cannot explain the distribution and overlying laws of dry gas.

In this study, the injected dry and condensate gases were divided into two pseudo-components based on the compositional model. A mathematical model of dry gas migration was constructed based on the thermodynamic diffusion model. Using this mathematical model, the distribution of dry gas in the condensate gas resource was analyzed. The difference between the mole fraction of the dry gas at the top and bottom (F) formations could be defined to characterize the overlying capacity of dry gas. Influences of condensate oil and the perforation method on the overlying degree of dry gas were investigated. Some research results can be extended to provide references for the follow-up parameter optimization of gas injection production of condensate gas reservoirs, thereby decreasing the blindness of reservoir production and increasing the recovery efficiency of gas injection.

The remainder of this study is organized as follows. Section 3 describes the mathematical model of dry gas migration

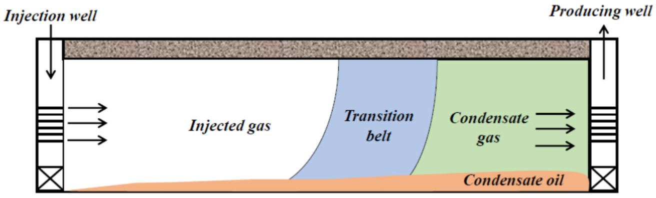

Figure 1: Process of dry and condensate gas migration

in the condensate gas reservoir on the basis of the thermodynamic diffusion model. Section 4 presents the case study and analysis of the influencing factors. Section 5 discusses the conclusions.

3. Methodology

3.1. Fundamental assumption

The densities of dry and condensate gases differ slightly in condensate gas reservoirs with high condensate content. To simplify the model, the gas phase is assumed to contain only two pseudo-components, namely, dry gas (A) and condensate gas (B), and the liquid phase contains only one component of condensate oil in the formation. The formation pressure is assumed to be lower than the dew point pressure. The mixed gas and condensate oil flow in the formation. Influences of gravity are considered in this model. The problems of interphase mass transfer and phase change are ignored. The process of dry condensate gas migration is shown in Fig. 1.

3.2. Establishment of control equations

The mixing diffusion of dry and condensate gases in the formation is based mainly on diffusion and convection. The convection diffusion equation of A is deduced considering the source sink term, as shown below:

$$\frac{\partial\left(C_mX_AS_{gm}\phi\right)}{\partial t}+\nabla\cdot\left(C_mX_A\vec{v}_{gm}\right)+\nabla\cdot\left(\mathrm{J}_AS_{gm}\phi\right)=\delta q_A \quad (1)$$

where C_m is the molarity of the mixed gas (mol/m^3),X_A is the mole fraction of A , J_A is the mole diffusion flux of A (mol/m^2·s^{-1}), S_{gm} is the saturation of the mixed gas, ϕ is the porosity and is a decimal, $\vec{v}_{gm}$ is the velocity of mixed gas (m/s), t is time (s), and q_A is the source sink term of A (mol/m^3·s^{-1}).

To reflect the convective diffusion process of gas, the thermodynamic diffusion model proposed by Ghorayeb and Firoozabadi is applied to calculate the diffusion flux [30]. Therefore, the diffusion flux equation of A can be expressed as:

$$\mathrm{J}_A=-C_m\left(D_{AB}\nabla X_A+D_A^p\nabla p_{gm}+D_A^T\nabla T\right) \quad (2)$$

where D_{AB}^M is the molecular diffusion coefficient of the interaction between A and B (m^2/s), D_A^p is the pressure diffusion coefficient of A (m^2/s·Pa^{-1}), D_A^T is the thermal diffusion coefficient of A (m^2/s·K^{-1}), and T is the formation temperature (K).

The flow behavior of dry and condensate gas mixtures and the condensate oil is considered in the cyclic gas injection production of a condensate gas reservoir. The mass conservation equations of dry and condensate gas mixtures and condensate oil can be written as follows:

$$\frac{\partial}{\partial t}\left(\rho_{gm}\phi S_{gm}\right)+\nabla\cdot\left(\rho_{gm}\vec{v}_{gm}\right)=q_{gm} \quad (3)$$

$$\frac{\partial}{\partial t}\left(\rho_o\phi S_o\right)+\nabla\cdot\left(\rho_o\vec{v}_o\right)=q_o \quad (4)$$

where ρ_{gm} is the density of the mixed gas (kg/m^3), $\vec{v}_o$ is the velocity of the condensate oil (m/s), ρ_o is the density of the condensate oil (kg/m^3), q_{gm} is the source sink term of the mixed gas (kg/m^3·s^{-1}), q_o is the source sink term of the condensate oil (kg/m^3·s^{-1}), and S_o is the saturation of the condensate oil.

Gravity factors can influence the distribution laws of fluid significantly. The bulk velocities of the mixed gas and condensate oil are derived from Darcy's law, as shown below:

$$\vec{v}_{gm}=-\frac{KK_{rgm}}{\mu_{gm}}\left(\nabla p_{gm}-\rho_{gm}g\nabla D\right) \quad (5)$$

$$\vec{v}_o=-\frac{KK_{ro}}{\mu_o}\left(\nabla p_o-\rho_og\nabla D\right) \quad (6)$$

where p_{gm} is the pressure of the mixed gas (Pa), μ_{gm} is the viscosity of the mixed gas ($Pa\cdot s$), μ_o is the viscosity of the condensate oil ($Pa\cdot s$), g is the gravitational acceleration (9.8 m/s^2), D is the vertical height below the seepage reference surface (m), K is the permeability measured with gas in porous media (m^2), K_{rgm} is the relative permeability of the mixed gas, and K_{ro} is the relative permeability of the condensate oil.

3.3. Complementary equation and initial boundary condition

To describe the process of dry gas migration in a condensate gas reservoir, auxiliary equations are required to enhance the mathematical model.

The constraint equation of capillary force is shown in the following equation:

$$p_{cog}=p_{gm}-p_{\mathrm{o}}=f(S_{gm}) \quad (7)$$

The constraint equation of saturation is expressed as follows:

$$S_{gm}+S_o=1 \quad (8)$$

When a condensate gas reservoir is injected with a large amount of dry gas, it will inevitably cause a change in reservoir fluid density. According to the molar mass ratio of dry gas and condensate gas and the molarity of dry gas, the density variation of mixed gas is deduced as shown below:

$$\rho_g=\rho_0+\left(C_mX_A-C_mX_{A0}\right)\left(\frac{M_B}{M_{\mathrm{A}}}-1\right) \quad (9)$$

where X_{A0} is the mole fraction of A at the reference point, ρ_0 is the density of mixed gas under the reference dry gas mole fraction (X_0), M_A is the mole mass of A (kg/mol), and M_B is the mole mass of B (kg/mol).

The constraint equation of the mole fraction of the components is represented as follows:

$$X_A + X_B = 1 \tag{10}$$

In the numerical simulation of cyclic gas injection in the condensate gas reservoir, the initial and boundary conditions are restricted. The formation pressure at the initial moment saturation of the mixed gas and mole fraction of dry gas are a known function, namely:

$$p\,(x, y, z)|_{t=0} = P_0 \tag{11}$$

$$S_{gm}\,(x, y, z)\Big|_{t=0} = S_{gm0} \tag{12}$$

$$X_A\,(x, y, z)|_{t=0} = 0 \tag{13}$$

At this moment, the boundary conditions are divided into internal and external boundary conditions. The internal boundary condition refers to the state of the producing or injection well. The injection and producing wells select the fixed injection and producing flow, fixed flowing bottom-hole pressure (FBHP), or mole fraction of the component according to actual situations. The specific internal boundary conditions are:

$$q|_{r=r_w} = q_{const} \tag{14}$$

$$p_{wf}\Big|_{r=r_w} = p_{const} \tag{15}$$

$$X_A|_{r=r_w} = \mathrm{X}_{const} \tag{16}$$

The external boundary condition is the state of edges of the gas reservoir. It can be further divided into boundary conditions, as shown below:

$$p|_{\Gamma} = p_{const} \tag{17}$$

$$\left.\frac{\partial p}{\partial n}\right|_{\Gamma} = F_q\,(x, y, z, t) \tag{18}$$

$$\left.\frac{\partial X_A}{\partial n}\right|_{\Gamma} = F_x\,(x, y, z, t) \tag{19}$$

where $(\partial p/\partial n)|_{\Gamma}$ is the derivate of the pressure on boundary Γ related with the external normal direction, $(\partial X_A/\partial n)|_{\Gamma}$ is the derivate of the mole fraction of A on boundary Γ related with the external normal direction, $F_q\,(x, y, z, t)$ is the determined function related with flow, and $F_x\,(x, y, z, t)$ is the determined function related with the mole fraction of dry gas.

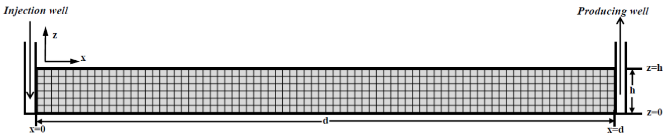

Figure 2: Meshing of the rectangular region

Table 1: Formation and fluid parameters

Parameter	Value
Initial formation pressure P_0, MPa	48
Formation temperature T, K	408
Initial gas phase saturation S_{gm0}, %	60
Porosity ϕ, %	15
Distance between the injection and producing wells d, m	800
Formation thickness h, m	60
Horizontal permeability K_x, $10^{-3}\mu m^2$	100
Vertical permeability K_z, $10^{-3}\mu m^2$	10
Mole mass of dry gas M_A, g/mol	16.5
Mole mass of condensate gas M_B, g/mol	44.2
Molecular diffusion coefficient D_{AB}^{M}, 10^{-8} m^2/s	3.9
Pressure diffusion coefficient D_A^{p}, 10^{-16} m^2/ s·Pa^{-1}	4.5
Thermal diffusion coefficient D_A^{T}, 10^{-12} m^2/s·K^{-1}	-11.8

3.4. Solving the model

The control equations of dry gas migration in cyclic gas injection of the condensate gas reservoir are formed by Equations (1), (3), and (4). The associated variables in the equations are eliminated from Equations (7)–(10); hence, the three independent variables, namely, p_{gm}, S_{gm}, and X_A, are unknown. By combining the initial and boundary conditions, the results can be calculated by using the finite difference method. First, the gas reservoir space is discretized by the block center difference grid. Second, the discrete equation is linearized by the improved IMPES method [31], thereby obtaining the linear control equations of pressure, saturation, and concentration. These linear control equations are solved in the programming manner by using the successive over-relaxation method [32]. The calculations of pressure and saturation are based on the initial concentration distribution. The calculated results can then be used to calculate the concentration distribution. In the calculation process, pressure, saturation, and concentration distributions can mutually serve as calculation conditions. Iterative computations are required in each step to solve the coupling problem of pressure, saturation, and concentration distributions. In addition, the matrix of coefficient that represents the characteristic parameters of formation must be corrected during the iteration of pressure, saturation, and concentration distributions.

4. Result analysis and discussion

The profile model between an injection well and a production well is analyzed in the Yaha condensate gas reservoir in Xinjiang, China. The distance between the injection and producing well is $800\,\mathrm{m}$. The profile model is $800\,\mathrm{m}\times10\,\mathrm{m}\times60\,\mathrm{m}$ rectangular region, as shown in Fig. 2. The injection well is at the left boundary of the rectangular region ($x = 0$), and the producing well is at the right boundary of the rectangular region ($x = d$). The grid size divided by the difference

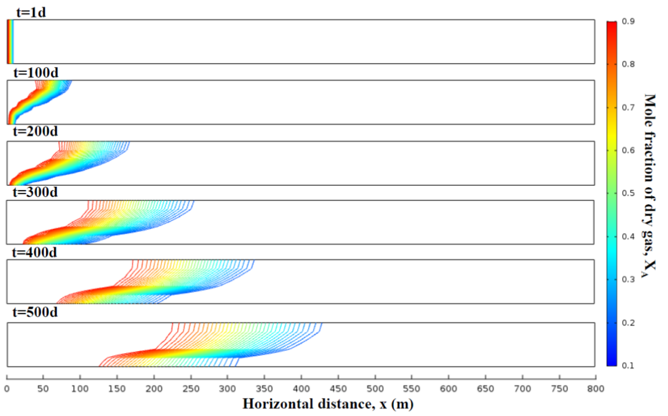

Figure 3: Isoline changes of the mole fraction distribution of dry gas in the rectangular region with time

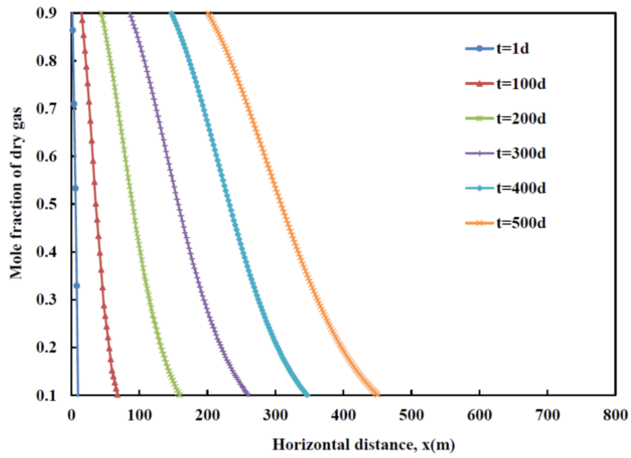

Figure 4: Variation curves of the mole fraction of dry gas at the middle position with the horizontal distance at different times

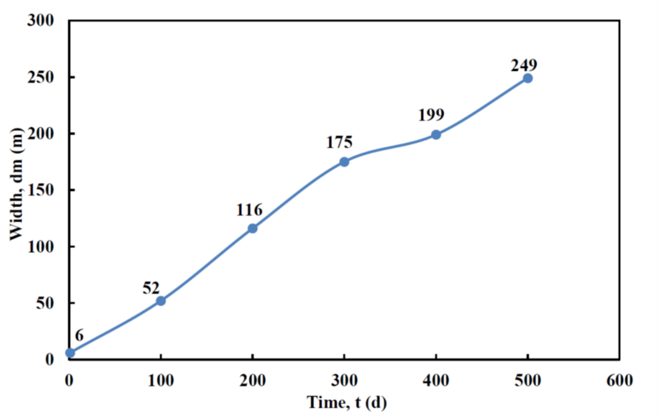

Figure 5: Variation curve of the width of the transition belt over time

method is $10\,\mathrm{m} \times 10\,\mathrm{m} \times 10\,\mathrm{m}$. Injecting dry gas into the formation through the injection well is used as the production control condition. The mole fraction of injected dry gas is 1.0. Different mole fractions of dry and condensate gases are collected from the producing well. In addition, $x = 0$ and $x = d$ (two ends of the rectangular region) are determined as the constant pressure boundary. The injection end pressure is 45 MPa, whereas the producing end pressure is 44 MPa. The formation and fluid parameters required in the numerical simulation are listed in Table 1.

4.1. Analysis of the transition belt of dry and condensate gases

When analyzing the underground formation where dry and condensate gases are mixed, the distance between the isoline with 0.1 and 0.9 mole fraction of dry and condensate gases is defined as the width of the transition belt (d_m), respectively. The previous calculation model and method indicate that the isoline of the mole fraction distribution law of dry gas in the rectangular region at different times (1, 100, 200, 300, 400, and 500 d) can be obtained, as shown in Fig. 3.

The injected dry gas drives the condensate gas toward the producing well on the $x - z$ plane over time. Moreover, the transition belt widens, which indicates that the dry gas does not mix with the condensate gas immediately due to their diffusion behavior. Instead, a large-scale transition belt is observed. The isoline of the mole fraction distribution law of dry gas in the transition belt is dense in the middle and sparse at the two ends. This finding reflects the considerable changes in the mole fraction in the center of transition belt and the small changes in the mole fraction at the two sides of the transition belt. This result conforms to the mixing law of dry and condensate gases.

Fig. 4 shows the variation curve of the mole fraction of dry gas at the middle position of the formation ($z = h/2$) with distance x at different times. Over time, the convective diffusion of dry and condensate gases develops from nothing and intensifies gradually, accompanied with the gradual widening of the transition belt. Fig. 5 shows the variation curve of the width of the transition belt over time. The width of the transition belt increases from 6 m to 249 m when time t increases from 1 d to 500 d (Fig. 5).

4.2. Analysis of the overlying of dry gas

The highest overlying degree should concentrate in the middle of the transition belt due to the distribution characteristics of dry and condensate gases in the transition belt. The variation range of the velocity field is mainly concentrated in the range near 250 m. Thus, a longitudinal cutting line perpendicular to the x-direction is drawn at $x = 250$ m, as shown in Fig. 6. The variations of the mole fraction of dry gas that runs through this cutting line and the overlying law of dry gas are investigated.

Suppose that one longitudinal cutting line exists in $x = x_0$ at $t = t_0$. The mole fraction of dry gas at the top formation ($z = h$) is X_{top}. The mole fraction of dry gas at the bottom formation ($z = 0$) is X_{bottom}. Therefore, the difference between the mole fraction of the dry gas at the top and bottom formations is defined as F, as expressed below:

$$F|_{x=x_0}^{t=t_0} = X_{top} - X_{bottom} \quad (20)$$

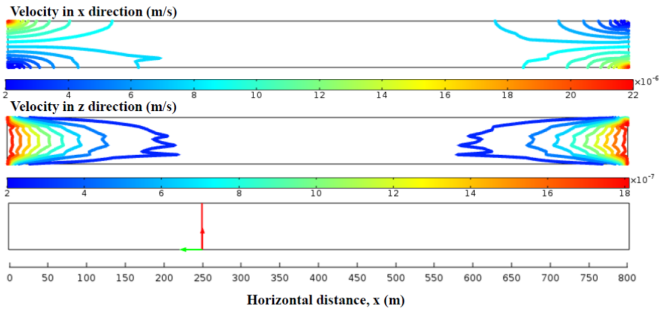

Figure 6: Isoline of velocity distribution on the x and z-directions in the rectangular region and the cutting line at x = 250 m

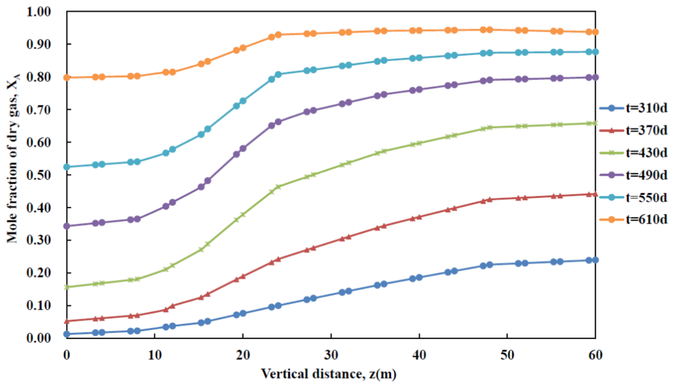

Figure 7: Relation curves of the mole fraction of dry gas and the vertical distance at different times

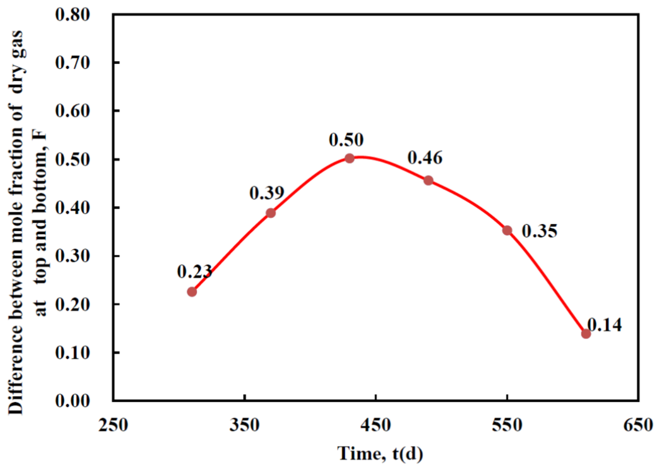

Figure 8: Variation curve of the value of F over time

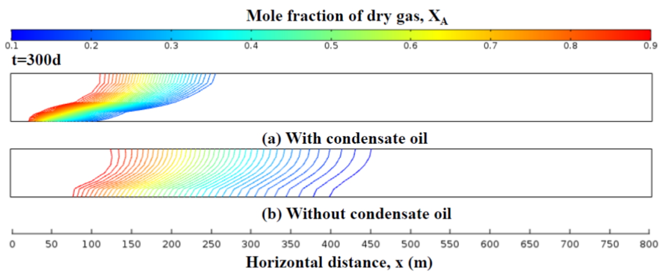

Figure 9: Isoline of the mole fraction distribution of dry gas in the rectangular region with and without condensate oil

The difference between the mole fraction of the dry gas at the top and bottom (F) formations can be used to characterize the overlying capacity of dry gas. A larger value of F implies a larger overlying of the injected dry gas. The variation curve of the mole fraction of dry gas that runs through $x = 250$ m at different times is shown in Fig. 7. The mole fraction of dry gas increases with the vertical distance. The variation curve of the F value over time at $x = 250$ m is shown in Fig. 8. The initial value of F is relatively low, which increases and then decreases with time. This result conforms to the distribution pattern of dry gas in the transition belt. The overlying degree of dry gas increases and then decreases with time.

4.3. Effect of condensate oil on the overlying of dry gas

Condensate oil can influence the saturation and velocity distribution of gas significantly. Fig. 9 shows the isoline of the mole fraction distribution of dry gas in the rectangular region with and without considering the condensate oil in the model ($t = 300$ d). If the condensate oil is neglected and only gas flows in the condensate gas reservoir, then the overlying degree of dry gas is low and the transition belt widens. Fig. 10 shows the histogram of the difference between the mole fraction of the dry gas at top and bottom (F) formations under different mole fractions of dry gas (X_{top}) with and without condensate oil ($x = 250$ m). The initial values of the gas saturation in the condensate gas reservoir are 0.6 and 1.0. The initial saturation value of the gas phase is 1 and the value of F is 0.18 at most. In view of the condensate oil, the initial saturation value of gas phase is 0.6 and the value of F is 0.5 at most. The value of F increases by 0.32; however, the width of the transition belt becomes narrower and the gas diffusion rate declines. Thus, the existence of condensate oil in the condensate gas reservoir is conducive to viscous fingering of gases and overlying of the dry gas.

4.4. Effect of perforation method on the overlying of dry gas

The perforation method has a great influence on the overlying of dry gas, including symmetric and top perforation of the reservoir. The top 30% of the reservoir is perforated under the top perforation method. Distributions of the mole fraction of dry gas in the rectangular region under the symmetric perforation and top perforation of the reservoir ($t = 500$ d) are shown in Fig. 11. The width of the transition belt (d_m) is 249 m and 270 m using the symmetric perforation and top perforation of the reservoir, respectively. The diffusion range of dry and condensate gases under the top perforation of the reservoir is wider than that under symmetric perforation.

Fig. 12 shows the histogram of the difference between the mole fraction of the dry gas at the top and bottom (F) formations with different mole fractions of dry gas (X_{top}) under the symmetric perforation and top perforation of the reservoir ($x = 250$ m). From the Fig. 12, the value of F initially

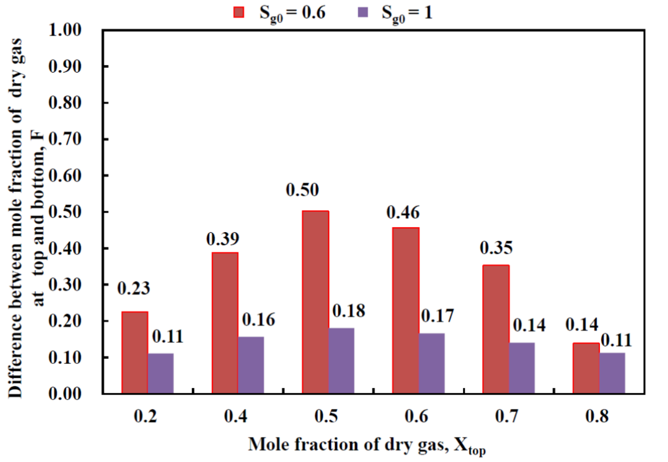

Figure 10: Histogram of the value of F with the mole fraction of dry gas at the top formation with and without condensate oil

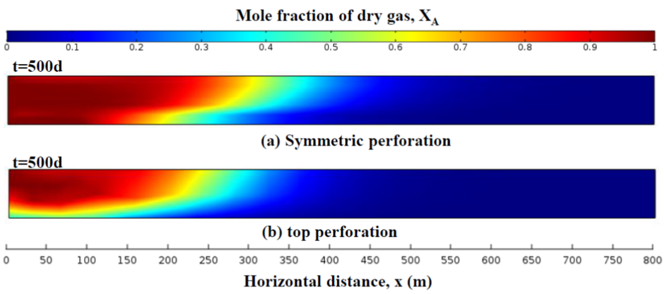

Figure 11: Mole fraction distribution of dry gas in the rectangular region under symmetric perforation and top perforation of the reservoir

increases and then decreases with the mole fraction of dry gas at the top formation under the symmetric perforation of the reservoir. The maximum value of F is 0.50. Under the top perforation of the reservoir, the maximum value of F is 0.55. Therefore, the top perforation of the reservoir can affect the overlying of dry gas significantly. When formulating the production scheme, the perforation method in the reservoir should be selected appropriately to increase the cyclic gas injection and recovery efficiencies of the condensate gas reservoir.

5. Conclusions

A mathematical model of dry gas migration was established based on the diffusion model considering gravity to investigate the distribution and overlying laws of dry gas under the gas injection mode of a condensate gas reservoir. The dry gas distribution and transition belt were analyzed in the condensate reservoir. The effects of condensate oil and perforation method on the overlying of dry gas were discussed. The following conclusions may be drawn:

1. The established mathematical model can predict the transition belt and overlying of dry gas and reflect the overlying law of dry gas on the condensate gas well.

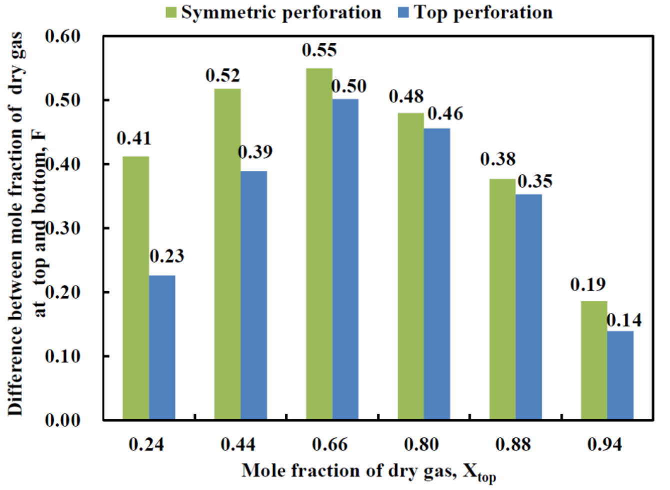

Figure 12: Histogram of the value of F with mole fraction of dry gas at the top formation under symmetric perforation and top perforation of the reservoir

2. The transition belt of dry and condensate gases widens gradually with time. In this transition belt, the mole fraction of dry gas is dense in the center and sparse at the two ends, which indicates the more violent changes of the mole fraction of dry gas in the center than those at the two sides.
3. If condensate oil is neglected and only the gas-phase movement in the condensate gas reservoir is considered, then the overlying degree of dry gas is low and the width of the transition belt increases. This phenomenon indicates that the existence of condensate oil makes overlying of dry gas easier but decelerates gas diffusion.
4. The effects of symmetric and top perforation of the reservoir on the overlying degree of dry gas are investigated. Under the top perforation of the reservoir, the transition belt widens and the overlying degree of dry gas increases. Selecting the appropriate perforation method should be considered when formulating the gas injection production.

In this study, the convective diffusion of dry and condensate gases, which can reflect the accurate distribution and overlying laws of dry gas, were analyzed comprehensively. These methods could provide theoretical references for the optimization of follow-up gas injection production of condensate gas reservoirs.

Given that the model was simplified, the phase-state changes of condensate oil were not fully considered. Moreover, the effects of heterogeneous conditions on the overlying degree of dry gas must be further explored. In future studies, the mathematical model of dry gas migration with consideration to phase-state changes might reflect the changes in the pressure and concentration fields in formation accurately. The results could help researchers understand the distribution and overlying laws of dry gas in the cyclic gas injection production of condensate gas reservoirs.

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