Study on cyclic injection gas override in condensate gas reservoir

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Abstract. Cyclic injection gas override in condensate gas reservoirs for the large density difference between injection gas and condensate gas has been studied, but no relevant mathematical models have been built. In this paper, a mathematical model of cyclic injection gas override in condensate gas reservoir is established, considering density difference between the injected gas and the remaining condensate gas in the formation. The vertical flow ratio and override degree are used to reflect the override law of injected dry gas. Combined with the actual data of Tarim gas condensate reservoir, the parameters of injected dry gas override are calculated and analysed. The results show that the radial pressure rises or falls rapidly and the pressure gradient varies greatly in the near wells. The radial pressure varies slowly and the pressure gradient changes little in the reservoir which is within a certain distance from the wells. In the near injection well, the injected dry gas mainly migrates along the radial direction, and the vertical migration is relatively not obvious. With the distance from the injection well, the vertical flow ratio and override degree of injected dry gas increases, and the vertical flow ratio reaches the maximum in the middle of the injection well and the production well.

1. Introduction

The condensate oil content in Tarim condensate gas reservoir is high, and the difference between formation pressure and dew point pressure is small. When gas reservoir is produced and the pressure drops a little, retrograde condensation occurs very quickly. The development of cyclic gas injection method can greatly improve oil recovery [1-4]. In the past 5 years, according to the profile test of the well, the gas oil ratio at the top of the gas well is higher than that at the bottom in positive rhythm reservoir, which is inconsistent with the previous gas injection passing through the high permeability zone to the gas well [5, 6]. So in the process of cyclic gas injection in condensate gas reservoir, the injected gas and formation fluid cannot be mixed into one phase immediately[7, 8], and the override of injected gas is caused by the difference of density between the two fluids. As the injection gas increases, more injected gas flows over the reservoir condensate gas.

By means of down-hole fluid component analysis apparatus, scanning tests are made on some gas producing wells in Yaha condensate gas field, and the vertical distribution characteristics and gravity differentiation of dry gas and condensate gas are further recognized [9].Through the study of injection gas displacement mechanism, it is found that the flow of injected gas in reservoir is affected by micro mixing, viscosity difference, gravity overlap and high permeability zone, and there is a mixing zone between injection gas and formation fluid at the front of gas injection [10]. Based on the dry gas and

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condensate gas diffusing experiment, the injected dry gas is discovered not to mix into one phase with the condensate gas immediately, when the test pressure is lower than dew point pressure, the following distribution phenomenon occurs from the top to bottom for the dry gas, the condensate gas and the condensate oil, but when the experimental pressure is higher than the dew point pressure, the dry gas is in upper part and the condensate gas is in deeper part [11]. The migration model of injected gas in the direction perpendicular to the reservoir has not yet been studied considering the difference of injected gas and condensate gas density.

2. Mathematical model of injection gas override

2.1. Assumptions of model

The model is assumed to consist of two wells in the condensate gas reservoir, including an injection well and a production well. In the condensate gas reservoir, the development of cyclic dry gas injection is implemented. In the model, it is assumed that gas injection well is produced at constant injection rates and production well is produced at constant gas production.

In view of the large density difference between the injected gas and the remaining condensate gas in the formation, the condensate gas is defined as wet gas relative to dry gas. The floating phenomenon of injected gas caused by density difference is considered. The effect of density difference on the injected gas overlap is taken into account in this model, while molecular diffusion is not considered in order to simplify the model in order to study the override law of injected gas.

2.2. Force analysis of injected dry gas

The down-hole fluid composition test shows that the injected gas cannot completely mix with the formation condensate gas. The overlap of injected dry gas mainly appears in vertical migration. In the front of gas injection, the dry gas is injected into the condensate gas in the form of gaseous micro particles. Because of the difference of density between dry gas and condensate gas micro particles, the dry gas micro particles are ascending upward by buoyancy. So the force acting on the vertical direction of the injected dry gas is analysed. In the vertical direction, the injected gas micro particles is subjected to buoyancy and its own gravity. Perpendicular to the reservoir direction, the gradient of resultant forces of the dry gas (F_{dv}) is expressed as follows:

$$F_{dv} = \frac{\partial p_d}{\partial z} = (\rho_w - \rho_d) g \tag{1}$$

Where ρ_w is the density of wet gas (kg/m^3), ρ_d is the density of dry gas (kg/m^3), and g is the gravitational acceleration (m/s^2).

The radial migration of injected dry gas is mainly caused by pressure difference between injection and production gas. The pressure distribution of a production well with time (t) in an infinite formation [12] is expressed as follows:

$$\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{1}{\chi}\frac{\partial p}{\partial t} \tag{2}$$

The coefficient of pressure (χ) is expressed as follows:

$$\chi = \frac{\varphi \mu C_t}{K_r} \tag{3}$$

The boundary and initial conditions are expressed as follows:

$$\lim_{r\to 0}\left(r\frac{\partial p}{\partial r}\right) = \frac{Q_p \mu}{2\pi K_r h} \qquad (r \to 0, t > 0) \tag{4}$$

$$p(r,t) = p_i \qquad (r \to \infty, t > 0) \tag{5}$$

$$p(r, t=0) = p_i \qquad (0 \le r < \infty) \tag{6}$$

Where φ is the rock porosity (%), μ is the gas viscosity (mPa·s), C_t is the comprehensive compressibility (MPa^{-1}), Kr is the radial permeability of reservoir (μm^2), h is the reservoir thickness (m), and Q_p is the well production (m^3/d).

In order to solve the equation, the Boltzmann transformation is used as follows:

$$u = \frac{r^2}{4\chi t} \tag{7}$$

The Boltzmann transformation is introduced into the governing equation, boundary condition and initial condition equation.When a production well is produced alone in an infinite formation, the pressure (p) at any point M in the formation is obtained as follows:

$$p(r,t) = p_i + \frac{Q_p \mu}{4\pi K_r h} Ei\left(-\frac{r_i^2}{4\chi t}\right) \tag{8}$$

Where r_i is the distance from M point to the production well (m), and E_i is a power integral function. The pressure drop (Δp_{pwell}) at any point M in the formation is expressed as follows:

$$\Delta p_{pwell} = p_i - p(r,t) = \frac{Q_p \mu}{4\pi K_r h}\left[-Ei\left(-\frac{r_i^2}{4\chi t}\right)\right] \tag{9}$$

If the well gas production (Q_p) is replaced by well gas injection (Q_j), the pressure distribution of an injection well in an infinite formation can be obtained by the Equation (11). Therefore, according to the superposition principle of potential, the radial pressure distribution between an injection well and a production well can be obtained as follows:

$$\frac{\partial p_d}{\partial r} = \Delta p_{pwell} + \Delta p_{jwell} = \frac{Q_p \mu}{4\pi K_r h}\left[-Ei\left(-\frac{r_i^2}{4\chi t}\right)\right] + \frac{Q_j \mu}{4\pi K_r h}\left[-Ei\left(-\frac{r_j^2}{4\chi t}\right)\right] \tag{10}$$

Where r_j is the distance from M point to the injection well ($r_j = d - r_i$), and d is the distance from an injection well to a production well (m).

Combining Equation (10), the radial pressure (p_d) between an injection well and a production well is expressed as follows:

$$p_d = p_i - \frac{Q_p \mu}{4\pi K_r h}\left[-Ei\left(-\frac{r_i^2}{4\chi t}\right)\right] + \frac{Q_j \mu}{4\pi K_r h}\left[-Ei\left(-\frac{r_j^2}{4\chi t}\right)\right] \tag{11}$$

2.3. Radial and vertical velocity equations of injected dry gas

According to Darcy's law, the vertical velocity (V_{dv}) and the radial velocity (V_{dr}) are expressed as Equations (12) - (13), respectively.

$$V_{dv} = \frac{K_v}{\mu} F_{dv} = \frac{K_v}{\mu} \frac{\partial p_d}{\partial z} \tag{12}$$

$$V_{dr} = \frac{K_r}{\mu} F_{dr} = \frac{K_r}{\mu} \frac{\partial p_d}{\partial r} \tag{13}$$

Where K_v is the vertical permeability of reservoir (μm^2), F_{dr} is the gradient of pressure of the dry gas between the injection well and the production well in the radical direction.

3. Evaluation parameters of injection gas override

Based on the vertical and radial seepage velocity of injected dry gas, two parameters that can mainly reflect the law and capacity of injection gas override are defined.

The vertical flow ratio f_v is defined as the ratio of vertical migration to total migration due to the upward migration of injected gas. This parameter can reflect the ratio of the vertical migration velocity to the total migration velocity, and indicate the extent of the gas injection override. The larger the f_v value is, the stronger the capacity of injected gas override is. The distance (d) between an injection well and a production well is divided into n segments. The vertical flow ratio (f) of i-th section is expressed as follows:

$$f(i,t) = \frac{v_{dv}(i,t)}{v_{dr}(i,t) + v_{dv}(i,t)} = \frac{k_v(\rho_w - \rho_d)g}{k_r \frac{\partial p_d}{\partial r}(i,t) + k_v(\rho_w - \rho_d)g} \tag{14}$$

The injection gas override degree A is defined as the ratio of cumulative migration gas along the vertical to the cumulative injection volume, in analogy with a method for evaluating the degree of steam overlap in thermal recovery of heavy oil [13]. The injection gas override degree (*A*) of *i*-th section is expressed as follows:

$$\mathrm{A}(i,t)=\left[1-\mathrm{A}(i-1,t)\right] f_{vi}+\mathrm{A}(i-1,t) \tag{15}$$

If the greater the *n* value is, the more accurate the injection gas override degree is calculated, but an excessive n value will lead to an increase in the amount of computation.

4. Results and discuss

The mathematical model of the injected gas override above in this paper is used to simulate the calculation combined with the actual data of Tarim gas condensate reservoir. The data of Tarim gas condensate reservoir are showed on Table 1. Taking a gas injection well corresponding to a gas production well as an example, the problem of injection gas overlap degree is discussed.

Table 1. Data of Tarim condensate gas reservoir.

Parameters	values	Unit
Initial formation pressure	56.1	MPa
Average Porosity	16	%
Average reservoir thickness	22	m
Temperature	409	K
Dew point pressure	52.1	MPa
Radial permeability	99	mD
Vertical permeability	20	mD
Dry gas density	248.4	kg/m^3
Condensate gas density	350.1	kg/m^3

4.1. Formation pressure distribution between gas injection well and gas well

The results of radial pressure (p_d) with time are shown in Figure 1. As can be seen from Figure 1, the radial pressure rises or falls rapidly and the pressure gradient varies greatly in the near gas injection well and gas production well. But in the reservoir which is within a certain distance from the wells, the formation pressure varies slowly and the pressure gradient changes little. With the increase of time, the bottom-hole pressure of the injection well rises, and the bottom-hole pressure of the production well drops. As time goes, the pressure in the middle zone of the two well changes violently, and the pressure gradient is larger. In addition, the pressure changes at each point in the formation tend to be stable after a period of production.

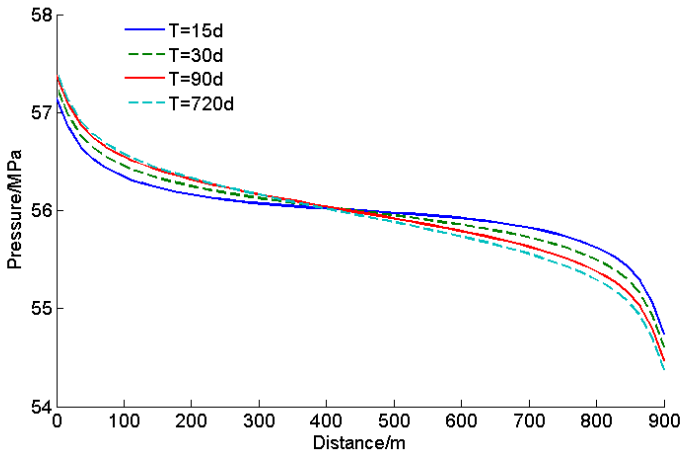


Figure 1. Formation pressure distribution between injection well and production well with time.

4.2. Vertical flow ratio

The results of vertical flow ratio (*f*) with time are shown in Figure 2.As can be seen from Figure 2, the radial pressure gradient is relatively large in the near wellbore area and the injected dry gas mainly migrates along the radial direction and the vertical flow ratio is small. With the distance from the injection well, the radial pressure gradient becomes small, and the vertical migration of dry gas cannot be neglected. The vertical flow ratio increased sharply, and the amount of vertical migration of injected dry gas increased. The vertical flow ratio reaches the maximum in the middle zone between the injection well and the production well. With the increase of time, the radial pressure gradient becomes larger in the middle zone. So the vertical flow ratio of injected gas becomes small and the capacity of vertical migration of injected gas is weakened.

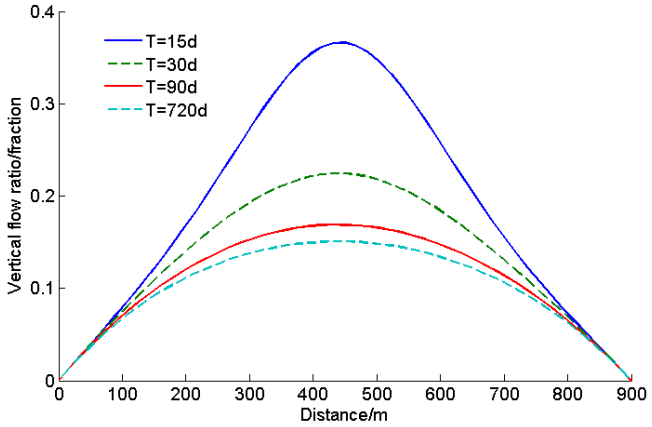


Figure 2. Vertical flow ratio between injection well and production well with time.

4.3. Override degree

The results of override degree (*A*) with time are shown in Figure 3.As can be seen from Figure 3, in the area near the injection well, the override degree of injection gas is close to zero. As the distance from the injection well increases, the override degree increases. From the near injection well to the middle of the injection well and the production well, the injection gas override degree increases rapidly. From the middle position to the near production well, the vertical flow ratio of injected gas decreases. So the override degree of injected gas increases slowly. As time increases, the radial pressure gradient becomes larger and the vertical flow ratio of injected gas decreases, so the amount of vertical migration of injected gas decreases.

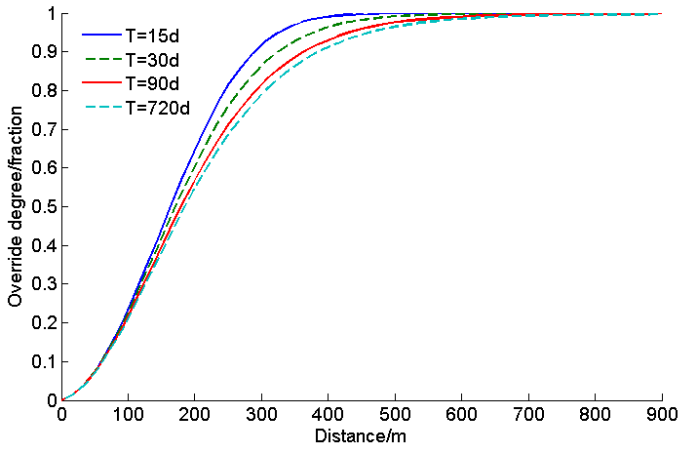


Figure 3. Override degree between injection well and production well with time .

5. Conclusions

In order to evaluate injection gas overlap, a mathematical model of cyclic injection gas override in condensate gas reservoir is established. The model mainly considers the buoyancy and gravity action of injected dry gas in the direction perpendicular to the reservoir, which is caused by the difference of density between injected dry gas and remaining condensate gas in the formation. The gas diffusion has not been taken into account in this model. In view of injection gas override, 2 parameters, including vertical flow ratio and override degree, are defined to indicate the vertical migration law of injected dry gas.

The example of application in Tarim gas condensate reservoir has shown that the radial pressure rises or falls rapidly and the pressure gradient varies greatly in the near wells. The radial pressure varies slowly and the pressure gradient changes little in the reservoir which is within a certain distance from the wells. In the near injection well, the injected dry gas mainly migrates along the radial direction, and the vertical migration is relatively not obvious. With the distance from the injection well, the vertical flow ratio and override degree of injected dry gas increases, and the vertical flow ratio reaches the maximum in the middle of the injection well and the production well. As time goes, the pressure in the middle zone of the two well changes violently and the vertical flow ratio becomes small. The position in which the override degree of injection gas is 100% is closer to the production well.

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