



A Method for Determining Reasonable Producing Pressure Drop of Gas Wells Considering Water Control Factors

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Abstract. Reasonable production of gas wells is the key to achieve efficient and sustainable development of gas reservoirs. Most of the developed gas reservoirs produced formation water. Water invasion leads to the decline of gas well productivity and gas reservoir recovery, the increase of production management and environmental protection risk, and the reduction of gas field development benefits. It is difficult to eliminate the negative impact of water invasion in the later stage of gas reservoir development. Therefore, in the early stage of gas reservoir development, it is necessary to consider the water control factors to determine the reasonable production rate of gas wells. Taking the Carboniferous gas reservoirs in eastern Sichuan Basin as an example, this paper analyses the water production performance, flow conditions of different types of formation water and their influences on the development of gas reservoir. A method is established to determine the reasonable producing pressure drop for controlling pore water invasion and edge-water invasion, which can guide the reasonable production proration of gas wells. Typical gas reservoirs show that the water invasion performance is not only related to the geological factors, but also to the production factors. When the producing pressure drop of gas wells meets the requirements of water invasion control, the recovery of gas reservoir can be increased by 10%–20%.

Keywords: Gas well · Reasonable producing pressure drop · Water invasion control · Pore water · Edge water · Carboniferous gas reservoir in eastern Sichuan

Nomenclature

F	= Buoyancy, MPa
$\Delta\rho_{gw}$	= Density difference of gas and water under formation condition, kg/m ³
g	= Gravity, 9.8N /kg
h_g	= gas column height, the vertical distance from top of gas reservoir to gas water interface, m
p_c^{gw}	= Critical capillary pressure of gas and water under formation condition, MPa
r_c	= Critical pore radius, μm

σ_{gw}	= Interfacial tension of natural gas and water under formation condition, mN/m
θ_{gw}	= Contact angle of gas and water under formation condition, degrees
Δp	= Producing pressure drop, MPa
v_w	= Seepage velocity of water, cm/s
t_w	= Water breakthrough time, s
μ_w	= Formation water viscosity, mPa.s
L	= Distance between gas well and edge water, cm
k_w	= Water permeability, μm^2
ϕ	= porosity, %
τ	= Tortuosity, %
Q_w	= Condensate production of gas well, m^3/d .
Q_g	= natural gas production of gas well, $10^4\text{m}^3/\text{d}$.
WGR	= Ratio of water productoin and gas production, $\text{m}^3/10^4\text{m}^3$
W_p	= Cumulative water production, m^3
G_p	= Cumulative gas production, 10^4m^3
p	= Reservoir pressure, MPa
S	= Content of sodium chloride, %
C	= Salinity correction factor, fraction
$OGIP$	= Original gas reserves in place, 10^8m^3

1 Introduction

Reasonable production of gas wells has always been the special concern of gas reservoir engineers, which is the key factor for the rational development of gas reservoirs. Conventional methods of gas production proration include empirical method, indicating curve method, nodal analysis method, etc. These methods are mainly based on the gas productivity equation of gas wells, and take into account the energy loss of natural gas flowing in reservoir and wellbore to allocate gas production rate, with less considering the control of water invasion.

Due to the existence of sealing water in sedimentary rocks, it is difficult to separate natural gas from formation water, so water production is common in the process of gas reservoir development. Most of gas reservoirs in China are affected by different degrees of water invasion, of which 40% to 50% are active or sub-active [1–5]. The activity of water invasion is not only to the geological factors, but also to the production factors. It is difficult to eliminate the negative impact of water invasion in the later stage of gas reservoir development, So it is necessary to consider the water control factors to determine the reasonable production of gas wells in the early stage of development.

Taking the Carboniferous gas reservoirs in eastern Sichuan Basin as an example, considering the main controlling factors of different water invasion, a method is established to determine the reasonable producing pressure drop for controlling pore water invasion and edge water invasion, which can guide the reasonable production proration of gas wells.

improve the percolation conditions of the reservoir, mainly small network fractures and micro fractures.

Aquifer Property: The Carboniferous gas reservoirs in eastern Sichuan Basin generally have edge water, with two typical gas-water distribution patterns.

① Edge water is located at the end of the long axis anticline: most of the gas reservoirs are long and narrow structures, and the two wings are trapped by faults. Only the end of the structure are connected with the edge water, and the water invasion path is relatively simple.

② Edge water is distributed along the long axis and the short axis: the contact range between gas area and water area is large, and when the exploitation of gas reservoir is unbalanced, it is easy to cause multi-point water invasion.

The aquifer size of Carboniferous gas reservoirs in eastern Sichuan Basin ranges from 0.4 to 5.0, and is generally less than 2, as shown in Fig. 2. Edge water often invades into gas reservoir along fractures, showing partial water drive characteristics.

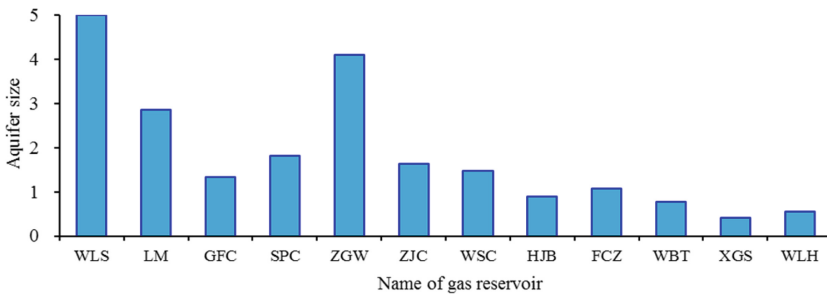


Fig. 2. Aquifer size of carboniferous gas reservoirs in eastern Sichuan Basin

3 Main Controlling Factors of Different Water Invasion

Water invasion is a key factor affecting the normal production and development of gas reservoirs. Once water phase invades the flow channel of gas phase, it will have a significant impact on gas reservoir development.

For the Carboniferous gas reservoirs in eastern Sichuan Basin, there are two types of formation water, one is water existing in the pore of gas formation, namely pore water, and the other is water existing in the edge aquifer. So there are two types of water invasion, one is pore water invasion and the other is edge water invasion.

3.1 Main Controlling Factors of Pore Water Invasion

Conventional structural gas reservoir is usually formed by secondary migration. Under the condition of hydrostatic pressure, the main driving force of natural gas migration is buoyancy and the resistance is capillary pressure [6–10], corresponds to Eq. 1 and Eq. 2, respectively.

Buoyancy is proportional to the height of gas column. The height of gas column is the vertical distance from top of gas reservoir to gas water interface as shown in Fig. 3. In the formation process of natural gas reservoir, when the buoyancy of gas phase is greater than capillary pressure of water phase, gas begins to expel water. The water in large pores is firstly expelled, then the water in smaller pores. When pore water can no longer be expelled, the buoyancy of gas phase is equals to the critical capillary pressure of water phase as shown in Eq. 3. In the initial water saturation of gas reservoirs, pores with radius less than r_c are filled with water.

$$F = \Delta\rho_{gw}gh_g \tag{1}$$

$$p_c^{gw} = \frac{2\sigma_{gw} \cos \theta_{gw}}{r_c} \tag{2}$$

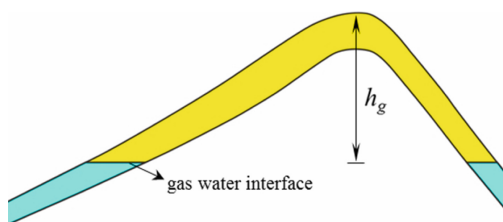


Fig. 3. Structural diagram of gas reservoir

$$\Delta\rho_{gw}gh_g = \frac{2\sigma_{gw} \cos \theta_{gw}}{r_c} \tag{3}$$

Pore water invasion is caused by the flowing of pore water. The mobility of pore water depends on the producing pressure drop Δp . During gas production, when producing pressure drop exceeds the capillary pressure of water phase, pore water is movable. Pore water is immovable as long as the producing pressure drop is less than the capillary pressure as shown in Eq. 4. The content of movable pore water is related to the initial water saturation, which is determined by pore size and the migration force during formation of gas reservoir.

$$\Delta p < \frac{2\sigma_{gw} \cos \theta_{gw}}{r_c} = \Delta\rho_{gw}gh_g \tag{4}$$

Interfacial tension of natural gas and water σ_{gw} varies with formation temperature and pressure, which can be taken according to the Schowalter’s Nomograph, as shown in Fig. 4 [6].

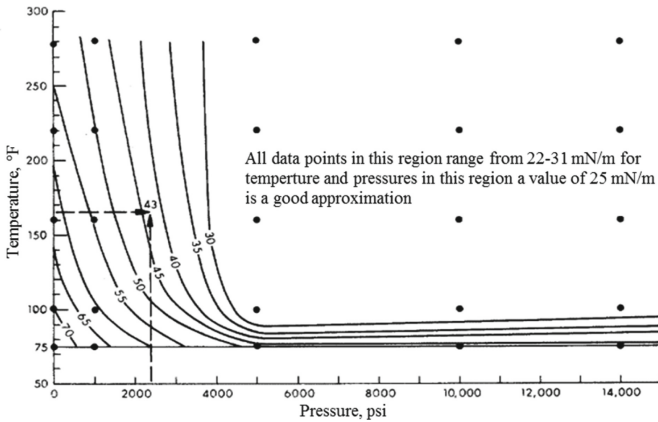


Fig. 4. Nomograph to estimate methane-water interfacial tension at different temperature and pressure (Schowalter [6])

According to Eq. 1 to Eq. 3, the curve of relationship of gas column height, critical producing pressure drop and critical pore radius is drawn as shown in Fig. 5. The larger the gas column height, the greater the critical producing pressure drop, the smaller the critical pores, and the lower the risk of pre water invasion.

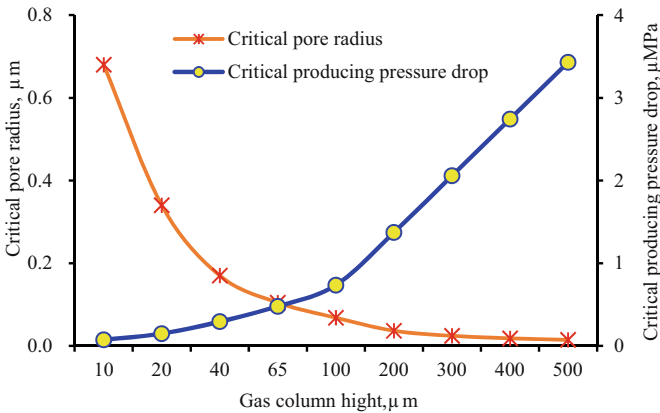


Fig. 5. Relationship of gas column height, critical producing pressure drop and critical pore radius

3.2 Main Controlling Factors of Edge Water Invasion

Edge water invasion is caused by the edge water flowing into the gas reservoir. Based on Darcy’s law, the equation of water breakthrough time of gas well in edge water gas reservoir is derived, as shown in Eq. 6. It can be seen from Eq. 5, the water breakthrough time of gas wells depends on producing pressure drop, distance between gas

well and edge water, water permeability, which are the main controlling factors of edge water invasion. Figure 6 is the curve of relationship of water breakthrough time and distance between gas well and edge water at different producing pressure drop.

$$V_w = \frac{k_w \Delta p}{\mu_w L} \times 10 \tag{5}$$

$$t_w = \frac{\phi L}{\tau V_w} = \frac{\mu_w \phi L^2}{k_w \Delta p} \cdot \tau \times \frac{1}{10} \tag{6}$$

Distance between gas well and edge water is one of important geological factor affecting the edge water invasion. The longer the distance between gas well and edge water, the longer the water breakthrough time of gas well is, and the longer the water-free gas production period of the gas well is. On the other hand, the smaller the area of edge water gas reservoir, the shorter the water breakthrough time of gas well, and the greater the influence of edge water invasion on gas production.

Heterogeneity is another important geological factor affecting the edge water invasion. The permeability of fracture is usually much higher than that of matrix. If the edge aquifer is connected with large fractures or faults in the gas reservoir, the water breakthrough time of the gas well will be greatly shortened.

If gas reservoir is homogeneous or apparent homogeneous, water breakthrough time of gas well can be effectively prolonged by controlling producing pressure drop. After setting the period of water-free gas production, the reasonable producing pressure drop of gas well can be calculated according to Eq. 7.

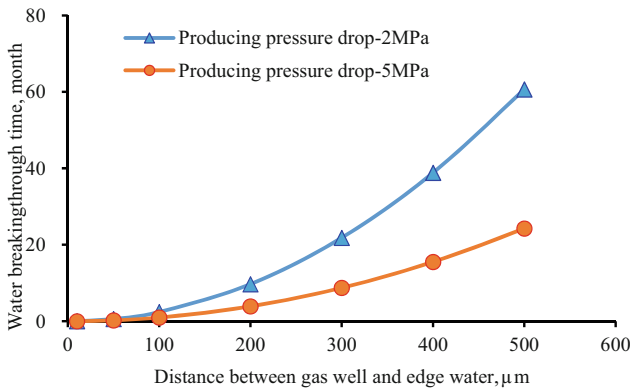


Fig. 6. Relationship of water breakthrough time and distance between gas well and edge water (WSC gas reservoir)

$$\Delta p \leq \frac{\mu_w \phi L^2}{k_w t_w} \cdot \tau \times \frac{1}{10} \quad (7)$$

4 Different Water Invasion Performance

During the development of Carboniferous gas reservoirs in eastern Sichuan Basin, there are two types of produced water, including condensate water and formation water. Condensate water exists in natural gas in the form of steam, which will not cause water invasion, and the production of formation water will cause water invasion.

The content of condensate water in natural gas depends on the temperature and pressure of gas reservoir. With the flow of natural gas from reservoir to wellhead, the pressure and temperature are changing, and the saturated water content is also changing. In the process of gas reservoir development, the temperature of gas reservoir is basically unchanged, and the influencing factors of saturated condensate water content are mainly reservoir pressure. With the decrease of reservoir pressure, the content of saturated condensate water increases gradually. The content of saturated condensate water can be measured in the laboratory or calculated by the following Equations [11].

$$Q_w = Q_g \times WGR \quad (8)$$

$$WGR = 1.6019 \times 10^{-4} A [0.32 \times (0.5625T + 1)]^B C \quad (9)$$

$$A = 3.4 + 148.0278/p \quad (10)$$

$$B = 3.2147 + 3.8537 \times 10^{-2} p - 4.7752 \times 10^{-4} p^2 \quad (11)$$

$$C = 1 - 0.4893S - 1.757S^2 \quad (12)$$

According to above Equations, the curve of content of saturated condensate water and reservoir pressure of SPC gas reservoirs in eastern Sichuan Basin is calculated, as shown in Fig. 7. The initial gas reservoir pressure and temperature SPC gas reservoir is 56 MPa and 106°C, respectively. Under initial formation condition, the content of saturated condensate water of SPC gas reservoir is 0.038 m³/10⁴ m³.

When water-gas ratio of a gas well exceeds the content of condensate saturated water, it means that the gas well produces formation water.

For Carboniferous gas wells in eastern Sichuan Basin, when pore water is produced, the WGR is generally between 0.1 to 0.3 m³/10⁴ m³, with chloride ion content of 2000 to 20000 mg/L; when edge water invades uniformly, the WGR increases slowly, generally between 0.3 to 5 m³/10⁴ m³, with chloride ion content more than 20000 mg/L. When edge water invades along large fractures, the WGR increases rapidly, generally more than 10 m³/10⁴ m³.

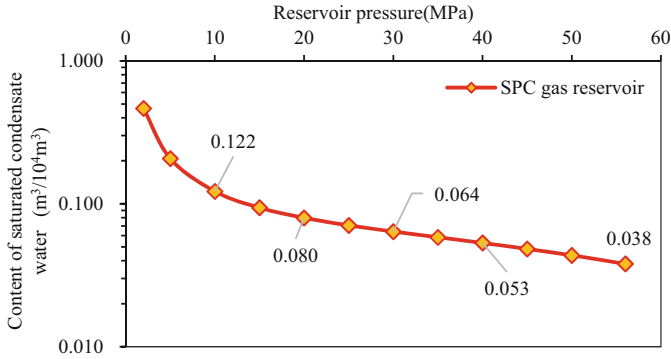


Fig. 7. Relationship of content of saturated condensate water and reservoir pressure (SPC gas reservoir)

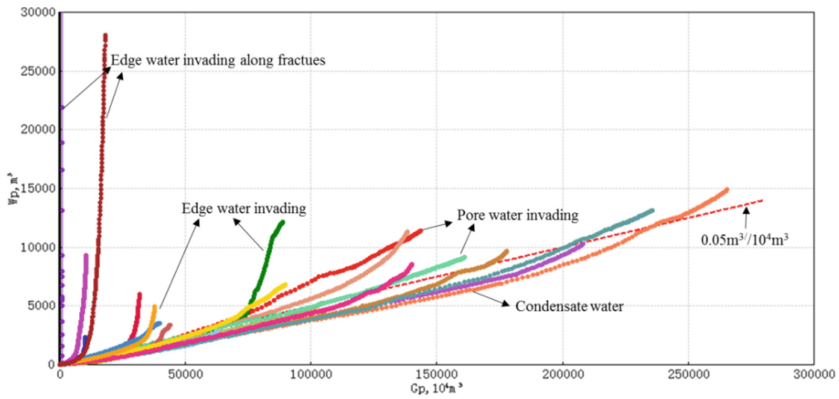


Fig. 8. Relationship of W_p and G_p of SPC gas wells in eastern Sichuan Basin

Figure 8 is the relationship of cumulative water production and cumulative gas production of gas wells in SPC gas reservoir, which shows different water invasion performance.

5 Typical Gas Field Examples

5.1 Influence of Pore Water Invasion

Generally, the pore water production of structural gas reservoir is relatively low, which is often ignored. However, sometimes the influence of pore water invasion on gas reservoir production cannot be ignored.

GDP Carboniferous gas reservoir is located in eastern Sichuan Basin, with structural-stratigraphic trap, without edge or bottom water (Fig. 9). The parameters of GDP gas reservoir are listed in Table 1.

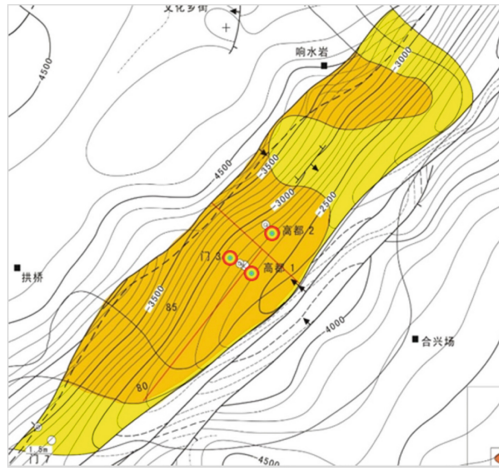


Fig. 9. Structural map of GDP Carboniferous gas reservoir in eastern Sichuan Basin

In June 2005, Due to the increase in gas production, producing pressure drop of GDP gas wells increased from 2–6 MPa to 4–11 MPa (as shown in Fig. 10), resulting in pore water flow, and WGR exceeding the content of saturated condensate water (as shown in Fig. 11). Although the water production is low, it can be seen from the FMB curve (Fig. 12) that dynamic reserves of GDP gas reservoir is obviously affected by pore water invasion, reducing by 3–410⁸ m³, accounting for 13–17% of OGIP.

Table 1. Parameters of GDP Carboniferous gas reservoir

Parameters	GDP gas reservoir
Original gas in place, 10 ⁸ m ³	23.4
Area of gas reservoir, km ²	11.5
Reservoir pressure, MPa	46.61
Initial content of saturated condensate water, m ³ /10 ⁴ m ³	0.014
Number of gas wells	3
Average Q _{aof} , 10 ⁴ m ³ /d	139
Gas production of individual well, 10 ⁴ m ³ /d	25–30
Gas recovery, %	73

5.2 Influence of Edge-Water Invasion

The Carboniferous gas reservoirs in eastern Sichuan Basin are mostly long axis anti-cline structures with edge water. The development practice of typical gas reservoir shows that reasonable producing pressure drop can effectively reduce the impact of water invasion. Gas reservoirs developed by “small producing pressure drop” model have 10 to 20% higher ultimate recovery than those developed by “large producing pressure drop” model.

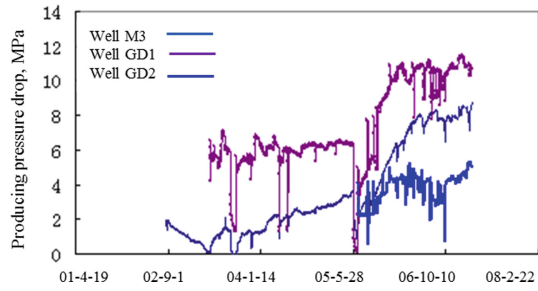


Fig. 10. Producing pressure drop of GDP gas wells

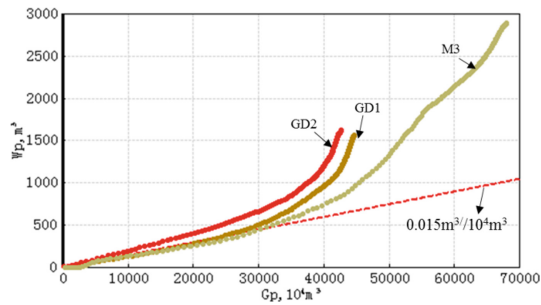


Fig. 11. Relationship of WP and Gp of GDP gas wells

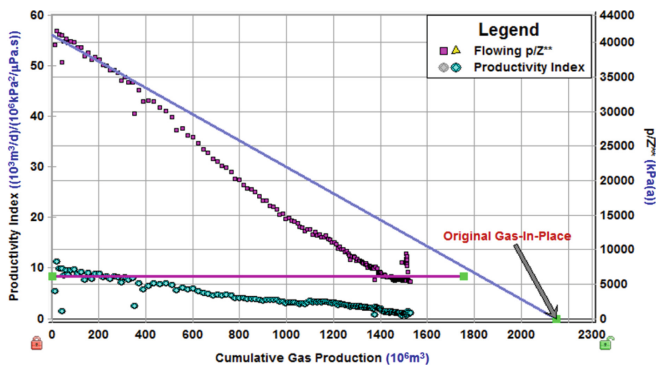


Fig. 12. Curve of flowing material balance (FMB) of GDP gas reservoir

WSC gas reservoir and SPC gas reservoir were developed by different models. Figure 13 shows the Gas-water distribution of these two reservoirs, and gas reservoir parameters are listed in Table 2.

WSC gas reservoir was developed by “small producing pressure drop” model, and water control factors are considered in determining gas production. Producing pressure drop of WSC gas wells range from 0.14 MPa to 1.8 MPa, as shown in Fig. 14(a). For

well CH6 located near the fault and edge water, the producing pressure drop is less than 0.8 MPa, which effectively delays water breakthrough time. Water-free gas production period of well CH6 is up to 81 months. The ultimate recovery of SPC gas reservoir is predicted to be 80–85%.

SPC gas reservoir was developed by “large producing pressure drop” model. In the early stage of SPC gas reservoir development, the producing pressure drop was 3–8 MPa. Since 2007, the production of gas reservoir has been increased, and the producing pressure drop was increased to 5–15 MPa, as shown in Fig. 14(b). Most of SPC gas wells produced formation water (Fig. 8), which had a great influence on gas production, and the final recovery is predicted to be 60% (Fig. 15).

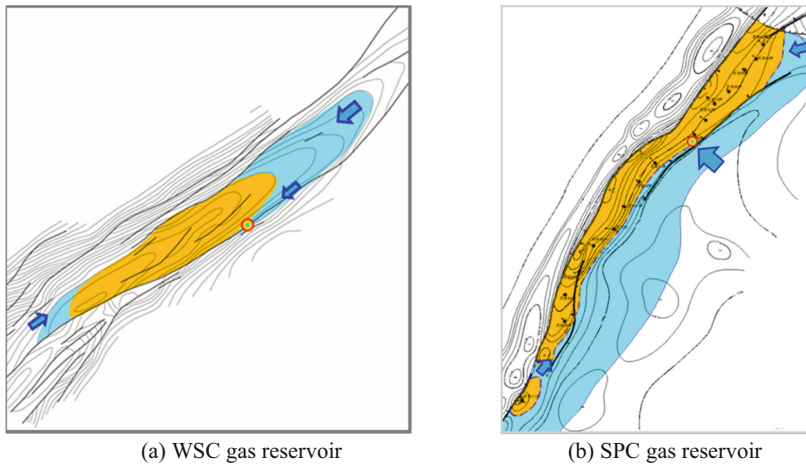


Fig. 13. Gas-water distribution of Carboniferous gas reservoir in eastern Sichuan Basin

Table 2. Parameters of Carboniferous gas reservoir with edge water

Parameters	WSC gas reservoir	SPC gas reservoir
Original gas in place, 10^8 m^3	71	337
Area of gas reservoir, km^2	27.3	70.6
Middle depth of gas reservoir, m	3353	4881
Reservoir pressure, MPa	38.4	56.2
Reservoir temperature, $^{\circ}\text{C}$	75	106
Aquifer size	1.47	1.81
Permeability of well test interpretation	3.7–105	0.3–13
Number of gas wells	7	22
Average Q_{aof} , $10^4 \text{ m}^3/\text{d}$	314	171
Gas production of individual well, $10^4 \text{ m}^3/\text{d}$	15–18	25–35
Producing pressure drop, MPa	0.14–1.8	3–15
Gas recovery, %	80–85	60–65

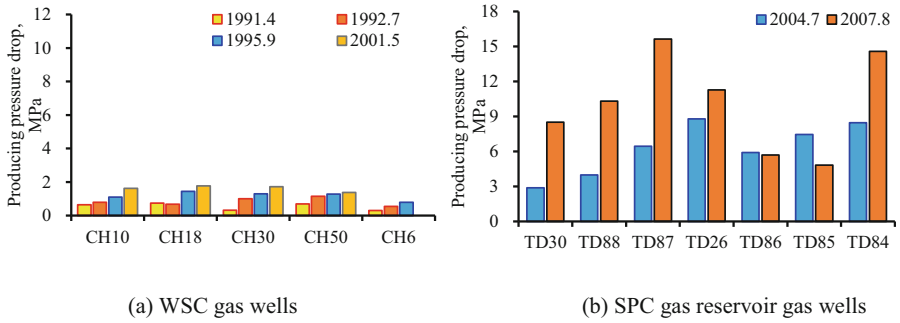


Fig. 14. Producing pressure drop of Carboniferous gas reservoir with edge water

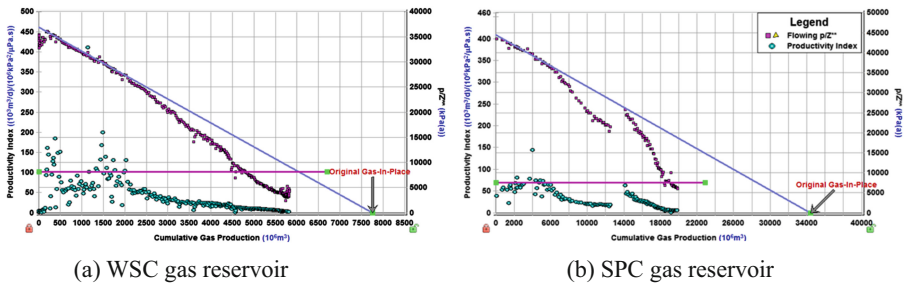


Fig. 15. Curves of flowing material balance of Carboniferous gas reservoir with edge water

6 Conclusions

Water invasion is a key factor affecting the development effect of gas reservoir. It is necessary to consider the water control factors to determine the reasonable production rate of gas wells. The key to determining the reasonable production of gas wells is to determine the reasonable production pressure difference, to prevent pore water invasion, and to delay edge water invasion. When the producing pressure drop of gas wells meets the requirements of water invasion control, the recovery of gas reservoir can be increased by 10%–20%.

References

1. Zhang, S., Li, X.: A discussion on development of water-drive gas reservoirs in Sichuan Basin. *Sino-Global Energy* **14**(4), 43–47 (2009)
2. Xia, C.: Ways and methods of enhancing recovery in various water-carrying gas reservoirs. *Nat. Gas Ind.* **22**(S1), 73–77 (2002)
3. Zhang, L., Mei, Q., Li, Y., et al.: The method of improving recovery efficiency of edge water drive gas reservoirs. *Nat. Gas Ind.* **26**(11), 101–103 (2006)

4. Feng, X., Zhong, B., Yang, X., et al.: Effective water influx control in gas reservoir development: problems and countermeasures. *Nat. Gas Ind.* **35**(2), 35–40 (2015)
5. Li, Q., Yang, Y., Peng, X.: Research on water intrusion mechanism and water control countermeasures of water-bearing gas reservoirs in Sichuan Basin. In: 2018 National Natural Gas Academic Conference held in Xiamen, China (2018)
6. Schowalter, T.T.: Mechanics of secondary hydrocarbon migration and entrapment. *AAPG Bull.* **63**(5), 723–760 (1979)
7. Liu, K.Y., Eadington, P.: A new method for identifying secondary oil migration pathways. *J. Geochem. Explor.* **78**(2), 389–394 (2003)
8. Bekele, E., Person, M.: Modeling secondary oil migration with core-scale data: viking formation, alberta basin. *AAPG Bull.* **86**(10), 55–74 (2002)
9. Li, W., Lv, Y.: The process of pulse secondary migration of natural gas. *J. Daqing Petrol. Inst.* **35**(2), 38–40 (2011)
10. Lin, J., Shao-bo, L., Feng, H.: Analysis of controlling factors of gas saturation in tight sandstone reservoir. *J. Southwest Petrol. Univ. (Sci. Technol. Ed.)* **33**(6), 121–125 (2011)
11. Li, X., Liu, Q., Sun, W., et al.: *Drill. Prod. Technol.* **24**(6), 30–32 (2001)