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RESEARCH ARTICLE-PETROLEUM ENGINEERING

Quantitative Evaluation Method for Gas Loss in Underground Natural Gas Storage Reconstructed from Abandoned Gas Reservoirs

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Abstract

Natural gas loss inevitably occurs during gas injection and production operation in underground gas storage. At present, the study of gas loss is only in the qualitative description stage and cannot meet the quantitative evaluation requirements for economical gas storage. Combining the theory of inventory analysis and the experimental study of the injection-production mechanism and aimed at the phenomena of microseepage, dissolution diffusion, abnormal gas leakage and macroscale gas leakage in the process of injection and production of underground natural gas storage, gas loss evaluation mathematical models are established to quantitatively evaluate the gas loss of underground natural gas storage. The results show that the gas loss in the macrodisplacement process is the main component of geological gas loss in gas storage, which decreases with increasing injection-production cycles. On this basis, a quantitative evaluation method for the natural gas loss of gas reservoir-type gas storage is established, and the accuracy and reliability of the method are verified by the gas loss calculation results of the Banzhongnanbei (BZNB) underground natural gas storage. The validation results show that the calculation error is very small, meeting the requirements of gas storage operation accuracy and providing high application value. This calculation method can effectively reduce the loss of natural gas in gas storage, provide an early warning of leakage risk, and improve the economic benefits and injection-production safety of gas storage.

Keywords Underground gas storage · Nature gas loss · Sealing evaluation · Operating efficiency · Storage volume calculation

1 Introduction

Compared with conventional fossil energy, natural gas is cleaner and plays an increasingly important role in human daily life [1, 2]. As an energy fuel, the demand for natural gas varies greatly in a year. Generally, the gas consumption in summer is small, but in winter, the use of natural gas increases significantly, even exceeding the supply capacity of natural gas, resulting in gas shortages in many large cities in winter [3, 4]. Therefore, the particularity of transportation and supply has become a bottleneck for the effective utilization of natural gas. Underground natural gas storage can effectively adjust the peak-valley difference of gas consumption, solve the problem of urban gas shortages, and facilitate a timely response to gas transmission pipeline emergencies. This type of storage plays an increasingly important role in the process of natural gas supply and demand [5].

The century of development history of underground gas storage shows that natural gas loss occurs in the process of injection production and is one of the inherent properties of gas storage [6–8]. Due to the water barrier, low sweep efficiency and serious gas channelling, a large amount of gas is lost during the injection and production process. For example, most sandstone underground gas storage in China exhibits gas loss phenomena [9–11]. However, through scientific operation and reasonable control, gas loss can be

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reduced, which can effectively reduce economic losses and safety risks [12–14]. There are usually two methods for reducing gas loss during the operation of underground gas storage. One is the design of reasonable control measures to reduce the loss of natural gas through the prediction and evaluation of the amount of natural gas loss and its trends to reduce the additional gas loss and improve the economic benefits [15, 16]. The other is the accurate prediction of the sealing capacity of faults and caprocks to obtain the amount of gas leaked through them in order to prevent major safety accidents caused by natural gas loss and ensure the safety of natural gas energy, life and property [17]. At present, the level of China's research on gas loss in underground gas storage is low and is only in its infancy. The loss of natural gas can be evaluated only qualitatively, not quantitatively. The calculation index of natural gas loss can only be calculated by the cumulative injection-production balance difference of the gas reservoir, which is very inaccurate [18]. Some researchers use monitoring data and numerical simulation methods to calculate the leakage of gas storage, but this is only a prediction method, and it has not been used in for actual gas storage operations [19]. These qualitative evaluations of the amount of natural gas loss cannot meet the requirements for the evaluation of the safe operation of underground gas storage, so it is necessary to carry out a quantitative study of natural gas loss in gas storage [20].

The gas loss of underground natural gas storage is the total amount of natural gas lost in the process of injection and production, and the loss rate is the ratio of the amount of gas lost to the amount of gas injected [21]. Natural gas loss can be caused by geological factors and engineering factors. Geological factors include the caprock and fault sealing ability, spill point position, microscopic flow, diffusion and dissolution of gas molecules. Engineering factors include the casing sealing of injection and production wells, ground venting of the gas injection and production system, and amount of gas carried by the condensate in the production separator. Under certain circumstances, the possible leakage of ground pipelines and equipment and natural gas leakage caused by sudden accidents are included in this category [22]. The loss caused by engineering factors is relatively small and can be accurately read with a ground flow metre. Geological factors are the main factors leading to gas loss in gas storage. In addition, the changes in the fluid properties, reservoir deformation and microfractures during high-speed injection and production can lead to gas leakage [23, 24]. This paper mainly focuses on the quantitative evaluation of natural gas loss caused by geological factors.

The main purpose of this paper is to establish a mathematical model of macroscale gas loss in underground natural gas storage to quantitatively characterize the gas lost through faults and caprocks. Starting with the formation mechanism of natural gas loss, first, the influence of trap sealing, wellbore sealing and reservoir microseepage on gas loss is analysed in this paper to determine the gas loss mode of water-invasion sandstone underground gas storage. Then, with multiple cycles of injection-production data analysis of the actual underground gas storage, the relationship between gas leakage and dynamic parameters is regressed to establish a mathematical model of gas loss. Finally, the established model is used to quantitatively evaluate the loss of the selected gas storage to provide effective guidance for preventing gas loss and improving injection-production operation efficiency.

2 Innovation and Method

At present, there are gas losses in the injection and production process of most of China's underground gas storage. Some of the lost gas can be recovered, but most cannot, which increases the uncertainty of underground gas storage operation and results in a serious waste of gas resources. The main reason why gas loss cannot be recovered is that the types of loss are complex. It is difficult to describe them clearly and calculate their volume; therefore, it is impossible to effectively tap their potential. In this paper, based on a large number of analysis results of underground gas storage operation, combined with experimental data of injection-production seepage mechanisms, a theoretical model of inventory analysis and prediction is established to predict the natural gas loss under the interference of multiple factors. The model can be used to analyse the mode and type of gas leakage of underground gas storage reconstructed from abandoned gas reservoirs and to accurately calculate the gas loss during operation. Therefore, the model can effectively reduce the gas loss of underground gas storage, give early warnings of gas leakage risks, and improve the economic benefits and injection-production safety of underground gas storage. This method has been applied to many underground gas storage systems and has achieved good results.

3 The Gas Loss Mechanisms Related to Geological Factors

The loss mechanism of underground natural gas storage is divided into macroscopic displacement loss and microscopic flow loss [25]. The macroscopic displacement loss is mainly composed of the leakage caused by trap and wellbore seal failure and the loss caused by gas injection to the marginal low-permeability zone or water body. The microscopic flow loss is mainly caused by the dissolution of natural gas in formation water and remaining oil diffusion and the closed gas in micropore throats. This part of natural gas is not truly

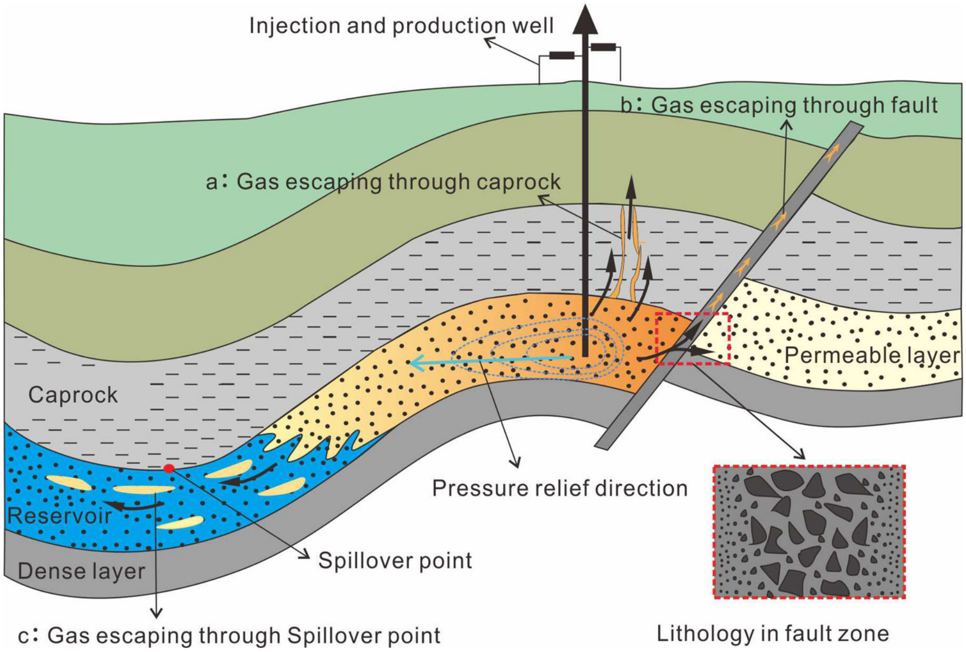


Fig. 1 Leakage mechanism of the multicycle trap sealing failure of gas storage

lost gas; it can be recovered during the gas storage operation process and can be defined as general natural gas loss [26].

3.1 Gas Loss Caused by Trap Seal Failure

There are three main ways for natural gas to diffuse and leak through caprock. First, gas molecules in the free state percolate out of the reservoir according to Darcy's law through unconsolidated areas in the caprock. Second, gas molecules dissolved in the pores of the capstone migrate under hydrodynamic conditions. Third, gas molecules diffuse and migrate through the pore space of the caprock layer. After a long time of accumulation and compaction, the possibility of gas migration through seepage is small, and the loss is mainly due to diffusion [27]. Although the diffusion rate is slow, the diffusion loss cannot be ignored during the 50-year cycle injection-production operation of gas storage (Fig. 1a). Trap faults play a decisive role in the lateral migration of fluids in the process of natural gas accumulation. In the process of gas reservoir development, as the formation pressure decreases, most of the faults are in a closed state [28]. However, after gas storage is rebuilt, due to the severe alternating loads during the periodical injection and production process, a large pressure difference is formed locally in the fault, and the sealing ability is gradually weakened, which may cause the fault to open and result in natural gas leakage (Fig. 1b). Leakage loss at the overflow point refers to the fact that the injected gas is rapidly directed to the nonpiston in the lower part of the structure and overflows from the structure when the gas rushes to the trap overflow point during the gas injection process of gas storage, affected by factors such as high gas injection pressure, limited structural trap height, and gentle structure. (Fig. 1c).

3.2 Gas Loss Caused by Wellbore Sealing Failure

In the process of injection and production, gas storage wells experience severe alternating loads, which causes slight elastic deformation of the inner wall of the wellbore or surrounding rocks (Fig. 2). The long-term effect of this alternating stress leads to a series of problems, such as cement sheath rupture, casing thread leakage, and casing corrosion damage, which causes gas leakage from the wellbore. Leaked natural gas can enter the sand layer and water layer it passes through until it reaches the ground and is lost to the atmosphere. This not only results in the loss of natural gas but also causes environmental accidents and even safety accidents [29].

3.3 Gas Loss Caused by Wellbore Sealing Failure

Under the action of the displacement pressure difference, part of the injected gas migrates to the well control external area, reservoir edge, low-permeability zone or gas–water transition zone and cannot always be recovered due to the limited well pattern control, small pressure gradient, and limited gas recovery time rate. This part of natural gas should be considered to be the loss of gas storage because from the operational and economic point of view, this part is excluded from the working gas, equivalent to the loss of natural gas [30]. The actual injection and production conditions of many underground gas storage facilities operating in eastern China

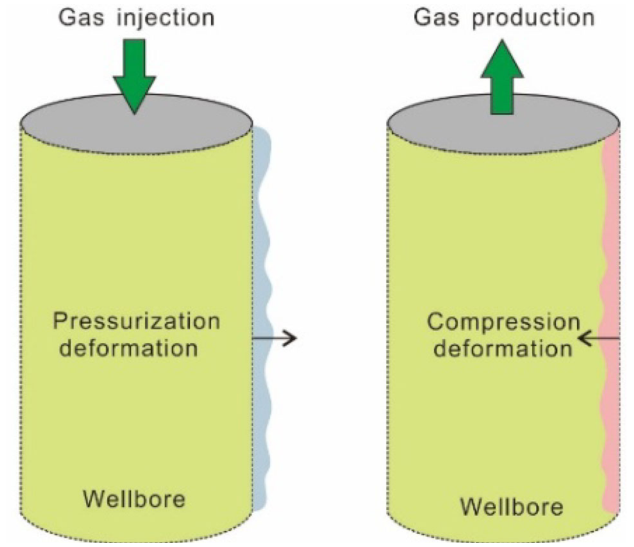


Fig. 2 Microdeformation of the wellbore in underground gas storage during injection and production

show that the loss of this kind of natural gas accounts for approximately 5% of the entire working gas volume and has resulted in extensive economic losses.

Figure 3 shows the generation mechanism and occurrence state of lost gas in sandstone underground gas storage. Five injection and production wells in the gas reservoir are in normal operation. There is no obvious gas invasion in monitoring wells J2, J4 and J5 during the injection and production process of underground gas storage, but there is an obvious gas channelling phenomenon in J3 and J1. The main seepage direction of the fluid is from northwest to southeast, and a high permeability channel is formed in this area. In this channel, the most likely locations of lost gas include gas in physically isolated areas. If the bottom hole pressure (BHP) of well J1 changes little during gas production, this indicates that there is no pressure response in this area and that it is a lost gas accumulation area.

3.4 Gas Loss Caused by Microscopic Dissolution and Diffusion

In gas storage that is converted from a water-containing gas reservoir or a gas-cap oil reservoir, the oil and water in the gas–water transition zone and the gas-oil transition zone are both undersaturated due to the influence of gas reservoir development or gas storage depressurization. During the gas injection process, natural gas molecules diffuse into the marginal waters or remaining oil. Due to the dissolution of natural gas in water and oil, the gas dissolves in the bound water and residual oil and is swept away, resulting in natural gas loss [31].

3.5 Gas Loss Caused by Microscopic Conditions

During the gas injection process, the gas at the top of the gas storage that is converted from a reservoir with edge water migrates downwards quickly, displacing the remaining oil and the edge water, thereby achieving the purpose of capacity expansion. Affected by factors such as the reservoir physical properties, capillary force, fluid type and wettability, injected gas flowing at a high speed forms a certain amount of water-entrained gas or oil-in-gas in the coexistence area of multiphase fluids. These gases have difficulty forming a continuous gas flow and cannot be produced during the gas production process, resulting in gas loss [32]. The visual displacement experiment of the glass etching model can intuitively reveal the interaction between fluids during the high-intensity injection-production process of underground gas storage. First, according to the pore characteristics, throat characteristics, clay mineral types and wettability of the core of the gas reservoir, the rock micropore structure model is established, and the pore and throat morphology are etched on the glass surface according to a computer model. Then, the three steps of water saturation, oil displacing water and water displacing oil are carried out. When the displacement efficiency is the same as that before the construction of underground gas storage, oil displacement stops, and the system is held until the fluid is stable; finally, gas injection and production experiments are carried out to observe the trend of the oil–gas-water triple-phase during and at the end of displacement. According to the experimental results, the types of lost gas are classified and characterized under microscopic conditions [33]. In the final state, part of the gas is blocked by oil to form lost gas, and the other part is blocked by water to form lost gas; both of these are microscale closed gases (Fig. 4).

4 Mathematical Model for Natural Gas Loss Prediction

First, based on the production and monitoring data of the multiperiod injection and production of gas storage, this paper analyses the microseepage, solution diffusion, abnormal leakage and macrodisplacement in the process of gas storage injection and production in detail. Then, by means of gas reservoir engineering, physical experiments and numerical simulations, a mathematical model of natural gas loss evaluation in the process of the injection and production of underground gas storage is established to realize the quantitative evaluation of gas loss in underground gas storage.

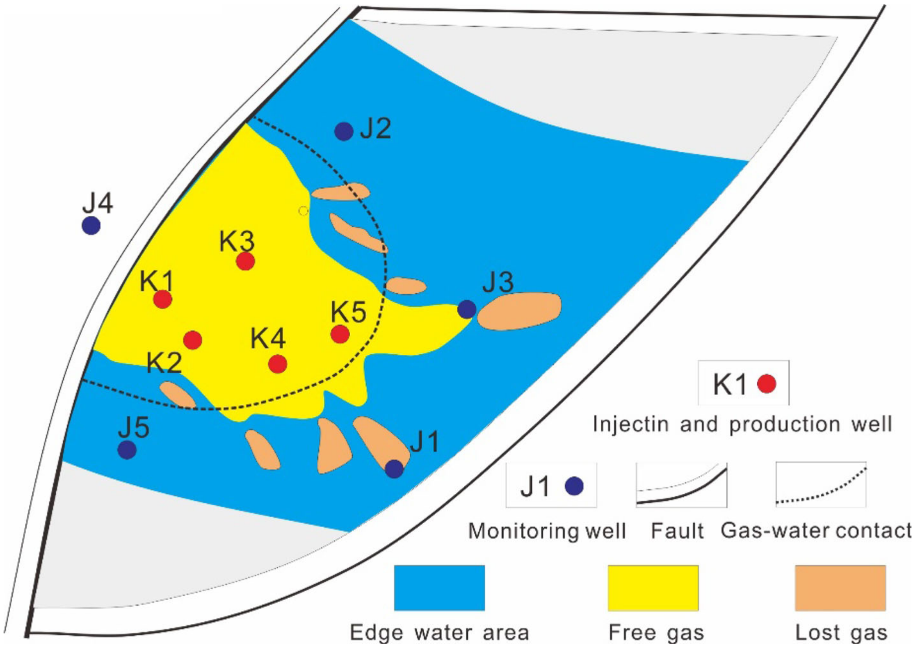
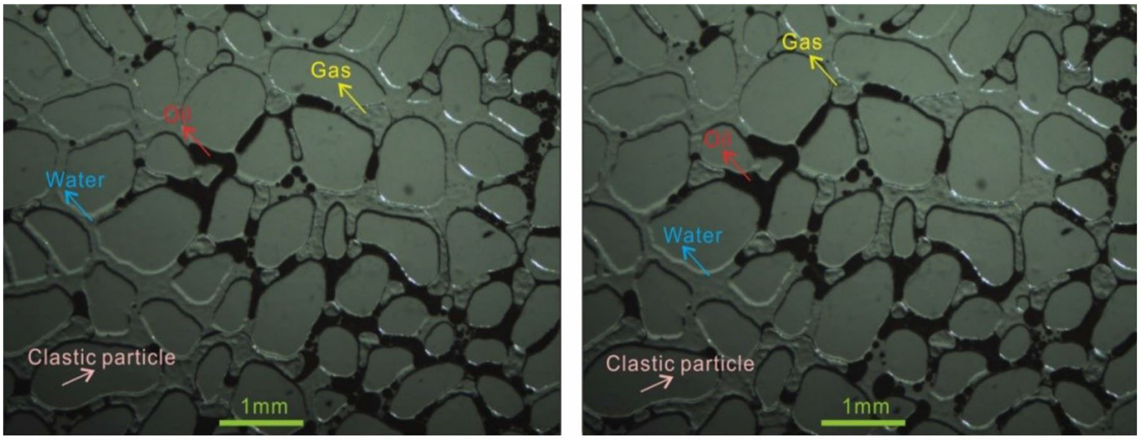


Fig. 3 Gas loss during the injection-production process and displacement



a Fluid distribution after 1 hour displacement **b** Fluid distribution after 5 hour displacement

Fig. 4 Fluid distribution trend in the multicycle injection-production gas storage experiment

4.1 Total Loss of Natural Gas

Based on the prediction method of the technical index of the gas storage inventory [34], the cushion capacity in a certain injection-production cycle of gas storage is calculated. The natural gas loss Q_{sh} is the difference between the cushion capacity of the two cycles, and the ratio of the cushion change to periodic gas injection is the loss rate $E_{sh(i)}$.

$$Q_{sh} = G_{min(i)} - G_{min(i-1)} \tag{1}$$

$$E_{sh(i)} = \frac{G_{min(i)} - G_{min(i-1)}}{Q_{(i)}} \tag{2}$$

where

$Q_{sh(i)}$: Total loss at the i-th cycle, 10^8 m^3; E_{sh}: Microscopic loss rate of the physical simulation;

Q_{sh}: Total loss, 10^8 m^3; $G_{min(i)}$: Whole working gas capacity of the i-th cycle, 10^8 m^3;

$Q_{(i)}$: Injection and production capacity of the i-th cycle, 10^8 m^3.

4.2 Gas Loss Caused by Microscopic Conditions

Through the measurement of the relative permeability of multiple rounds of gas–water mutual flooding in the laboratory and the analysis of movable fluid nuclear magnetic resonance, the trends of bound water $S_{wi(i)}$ and residual gas saturation $S_{gr(i)}$ during multiple rounds of gas–water mutual flooding are determined. Therefore, the efficiency of reservoir space utilization can be evaluated, and the microscale closed gas loss of natural gas can be calculated.

In cycle i, the gas storage pore space utilization rate $E_{P(i)}$ can be characterized as follows:

$$E_{p(i)} = \frac{1 - S_{wi(i)} - S_{gr(i)}}{1 - S_{wi}} \tag{3}$$

where

$E_{p(i)}$: The gas storage pore space utilization rate; $S_{wi(i)}$: Initial water saturation of the i-th cycle;

$S_{gr(i)}$: Residual gas saturation of the i-th cycle; S_{wi}: Initial water saturation.

According to the actual multiperiod gas injection-production dynamic data, the microscopic conditions of the gas loss $Q_{ws(i)}$ in the i-th period are:

$$Q_{ws(i)} = E_{p(i)} * Q_{in} \tag{4}$$

where

$Q_{ws(i)}$: Microscopic gas loss, 10^8 m^3; Q_{in}: Multicycle actual gas injection quantity, 10^8 m^3.

4.3 Microscopic Dissolution Diffusion Loss

Using numerical simulation technology, a 3D fine geological model of gas storage can be established to describe the gas–water mutual flooding in the process of gas injection and production and to quantitatively describe the water volume V_w of the multiperiod gas–water transition zone and the remaining oil volume involved in dissolution and saturation V_o changes. The dissolved gas loss of natural gas in water and residual oil can be characterized as follows:

$$Q_{wr(i)} = \frac{V_{w(i)} * R_w}{B_g} \tag{5}$$

$$Q_{wo(i)} = \frac{V_{o(i)} * R_o}{B_g} \tag{6}$$

where

$Q_{wr(i)}$: Gas volume dissolved in water, m^3; $V_{w(i)}$: Water volume of the i-th cycle, m^3;

R_w: Gas solubility in water, m^3/m^3; $Q_{wo(i)}$: Oil volume dissolved in water, m^3;

$V_{o(i)}$: Oil volume of the i-th cycle, m^3; R_o: Oil solubility in water, m^3/m^3;

B_g: Gas volume coefficient, m^3/m^3.

The solubility R_w of natural gas in water and the secondary solubility saturation in the remaining oil are based on laboratory test results.

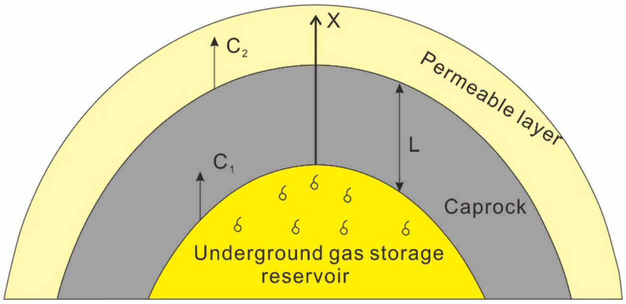


Fig. 5 Multicycle caprock diffusion mechanism of gas storage

4.4 Caprock Diffusion Loss

The diffusion loss process of gas through the caprock can be characterized as a mathematical formula, but a reference surface needs to be selected [35]. According to the nature of underground gas storage, the caprock nearest to the gas reservoir can be selected as the reference surface, and then the process can be simplified (Fig. 5).

After the reference surface at the top is selected, the gas diffusion process can be simplified as a one-dimensional problem, and the formula is as follows:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{7}$$

$$C = 0 \quad 0 < X < L,\ t = 0$$

$$C_{|x=0} = C_0 \qquad t > 0$$

$$C_{|x=L} = C_1 \quad t > 0$$

The above equation is solved, and the gas concentration due to diffusion at any point in the caprock layer is:

$$C = C_0 + \frac{1}{L}(C_1 - C_0)X + \sum_{n=i}^{\infty}\frac{2}{n\pi}\left[C_1(-1)^n - C_0\right] sin\left(\frac{n\pi X}{L}\right) e^{-n^2\pi^2 Dt/L^2} \tag{8}$$

According to the diffusion geological model and boundary conditions, the amount of natural gas lost from the caprock can be simplified as follows:

$$Q_{ck} = \frac{C_0 Dt}{L} + \frac{2LC_0}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\left(1 - e^{\frac{-n^2\pi^2 Dt}{4L^2}}\right) \tag{9}$$

where

Q_{ck}: Gas diffusion per unit area of caprock, m^3/m^2; D: Diffusion coefficient, cm^2/s;

C_0: Initial hydrocarbon concentration, m^3/m^3; t: Diffusion time, s; L: Cover thickness, m.

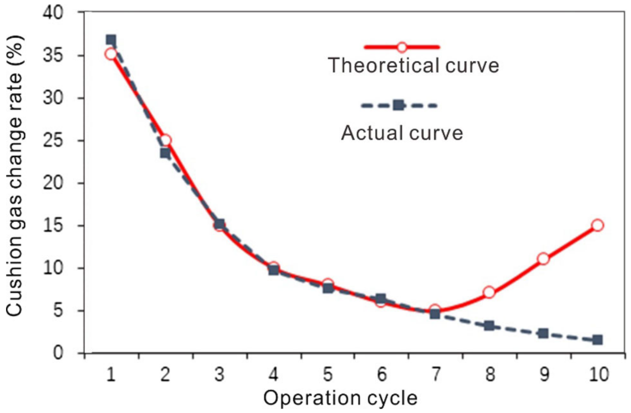


Fig. 6 Variation curve of the air cushion gas loss rate of gas storage

The diffusion coefficient D in the equation can be obtained through actual measurement, and the diffusion time and caprock thickness can be obtained according to the actual geological conditions. The initial interface concentration C_0 of the reservoir cap can be represented by the concentration of natural gas in the pore water of the caprock:

$$C_0 = C_g \bullet \varphi \tag{10}$$

4.5 Abnormal Loss from Caprock and Faults

The monitoring systems of domestic gas storage currently built are relatively backward, lack monitoring data, and use imperfect evaluation methods for natural gas leakage losses. Research on the operation of gas storage at home and abroad has shown that the change rate of gas storage and the operation cycle exhibit exponential decreases (Fig. 6).

Based on the inventory evaluation method of gas storage, the actual change rate of the cushion gas can be compared with the abnormal change in the theoretical curve, and the interpolation between them is the abnormal loss of natural gas. The formula is expressed as follows:

$$Q_{l(i)} = Q_{(i)} * \left(E_{sh(i)n} - E_{sh(i)}\right) \tag{11}$$

where

$Q_{l(i)}$: Abnormal gas leakage of the i-th cycle, 10^4 m^3.

4.6 Macroscopic Displacement Loss

In the process of high-speed and high-strength injection and production of gas storage, the control radius of the gas well is relatively small due to the limitation of the physical properties of the reservoir and the time rate of gas recovery. Therefore, the inventory in the uncontrolled area of gas wells cannot be converted into working gas, as it exists in gas storage in an unusable way. This gas is difficult to use under the current well pattern conditions, making it equivalent to the loss of natural gas from an operational management point of view. Generally, the reservoir heterogeneity in sandstone gas storage is very strong, and the well control radius of gas storage under high-speed injection and production is generally irregular. If the conventional gas reservoir engineering method is used to calculate the gas loss, the error would be large. In view of this, a new method to calculate the gas loss is proposed and used in this paper: the total amount control method. In the calculation process, the total loss Q_{sh} is deducted from the results of Formulas (4), (5), (6), (9) and (11). The new formula can be expressed as follows:

$$Q_z = Q_{sh} - Q_L - Q_{ws} - Q_{ck} - Q_{wo} - Q_{wr} \tag{12}$$

where

Q_z: Natural gas loss caused by gas injection, 10^4 m^3.

5 Application Examples

5.1 Overview of the Application Area

A representative underground gas storage (BZNB underground gas storage) was selected as an example to calculate the loss of natural gas using this new method. This underground gas storage was reconstructed from an abandoned edge water gas reservoir in 2003. The burial depth of the BZNB underground gas storage is 2890 m, its original formation pressure is 30.5 MPa, its reservoir average permeability is approximately 100.7×10^{-3} μm^2, and its average porosity is 17.4%. The designed reservoir capacity of the BZNB underground gas storage is 2.45×10^8 m^3, and the designed operating pressure ranges from 13 MPa to 30.5 MPa. Since the construction of the reservoir, it has experienced 15 injection-production cycles, with a total of 7.81×10^8 m^3 of gas injected and 6.77×10^8 m^3 of gas produced.

5.2 Natural Gas Loss Calculation

The mathematical model of this paper is used to calculate the natural gas loss of the BZNB underground gas storage in multicycle operation. The calculation results are shown in Table 1.

5.3 Natural Gas Loss Analysis

(1) Natural gas loss is an inherent attribute of gas storage and accompanies the entire life cycle. At the beginning of the construction of the gas storage, with the extrapolation of the gas flooding front, a large amount of injected gas enters the edges, the water areas, the low-permeability areas and the

Table 1 Statistical table of the prediction results of gas loss by multicycle geological factors

Cycle	Injection (10^8 m^3)	Total loss quantity (10^4 m^3)	Total loss rate (%)	Displaced (10^4 m^3)	Microclosed (10^4 m^3)	Dissolved in water (10^4 m^3)	Diffused through water (10^4 m^3)	Lost in fault (10^4 m^3)	Diffused through caprock (m^3)
2003 ~ 2004	1.59	6798	42.7	6420	355	0	20.3		3.1
2004 ~ 2005	4.54	10,753	23.7	9615	1011	118	8.4		1.3
2005 ~ 2006	5.17	8812	17.0	7851	900	54	6.4		1.0
2006 ~ 2007	2.69	8481	18.3	8022	374	79	5.4		0.8
2007 ~ 2008	4.53	3890	8.6	3279	562	44	4.8		0.7
2008 ~ 2009	6.07	4633	7.6	3988	607	33	4.3		0.7
2009 ~ 2010	5.54	1766	3.2	1197	554	10	4.0		0.6
2010 ~ 2011	6.28	2783	4.4	2128	628	23	3.7		0.6
2011 ~ 2012	6.15	8945	14.5	4281	615	45	3.5	4000	0.5
2012 ~ 2013	6.80	10,275	15.1	3741	680	50	3.3	5800	0.5
2013 ~ 2014	6.93	9085	13.1	3346	693	43	3.1	5000	0.5
2014 ~ 2015	5.96	9087	15.3	3244	596	43	3.0	5200	0.5
2015 ~ 2016	3.66	3800	10.4	1408	348	40	2.8	2000	0.5
2016 ~ 2017	6.06	5709	9.4	3571	606	28	2.8	1500	0.5
2017 ~ 2018	6.20	4771	7.7	2911	620	37	2.7	1200	0.5
合计	78.19	99,588	16.0	65,001	9149	647	79	24,700	12.3

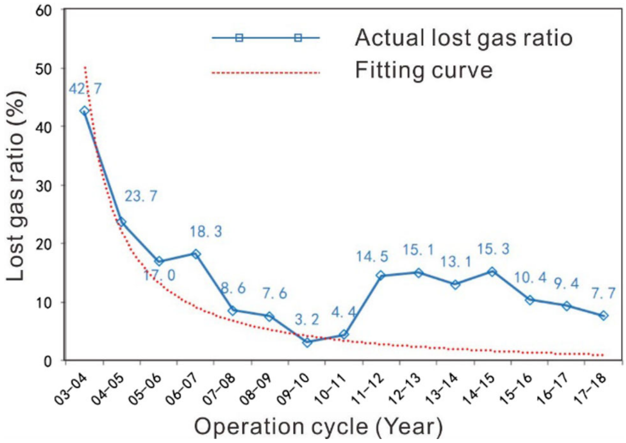


Fig. 7 Multicycle loss rate and loss rate trend of H gas storage

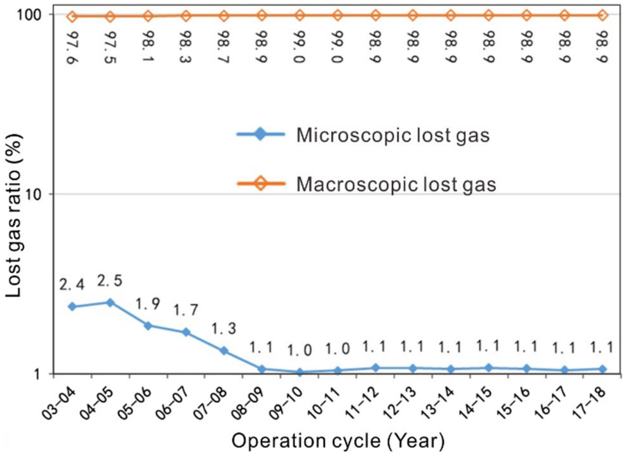


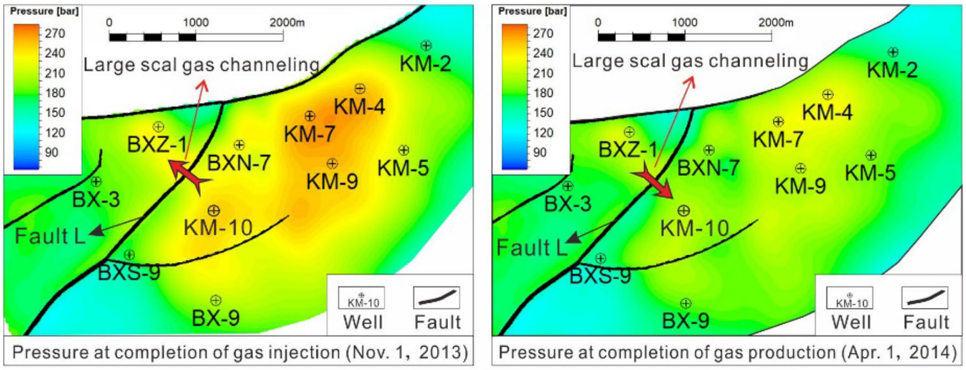
Fig. 8 Composition and proportion of multicycle losses in BZNB underground gas storage

fine pore throats. These parts of natural gas stay in the reservoir in the form of unused inventory and cannot be recovered, resulting in the loss of natural gas. As gas storage transitions from a rapid expansion period to a stable or even stagnant expansion period, the natural gas loss rate decreases rapidly as a power function and stabilizes at approximately 1% without abnormal gas leakage (Fig. 7).

(2) Macroscopic displacement loss is the main component of natural gas geological loss in gas storage. If there is no gas storage leakage, macrodisplacement loss mainly occurs in the gas storage capacity expansion period. As the injection-production well pattern is improved and the expansion speed slows, the loss decreases year by year. The amount of macroscopic displacement loss is relatively large, accounting for 98% to 99% of the total loss. The microscopic seepage loss is much lower, mainly due to the closed gas formed by the reservoir micropores, accounting for 1–2% (Fig. 8).

(3) There is some natural gas leakage through faults in BZNB underground gas storage, which has been verified by engineering verification methods. During the operation period from 2011 to 2012, the loss rate of BZNB underground gas storage increased significantly. Therefore, it is judged that it has abnormal trap leakage, and the periodic leakage vol-

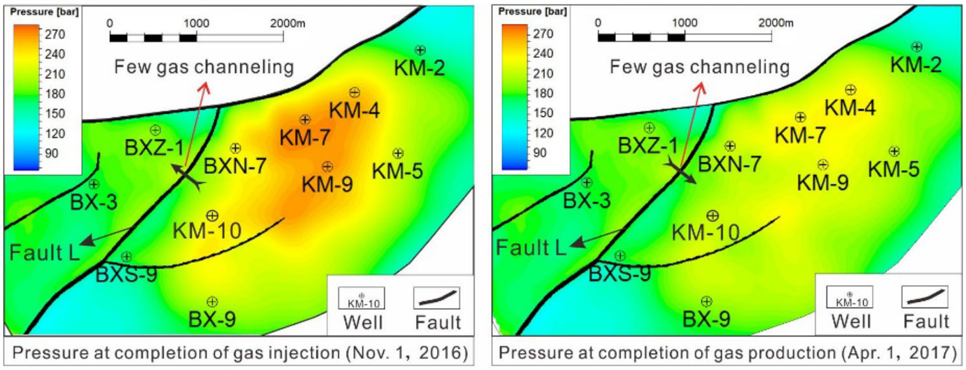
Fig. 9 Changes in pressure at different stages of BZNB underground gas storage



Pressure at completion of gas injection (Nov. 1，2013)

Pressure at completion of gas production (Apr. 1，2014)

a Pressure change law before the new scheme implementation



Pressure at completion of gas injection (Nov. 1，2016)

Pressure at completion of gas production (Apr. 1，2017)

b Pressure change law after the new scheme implementation

ume is calculated to be 40–5800 × 10^4 m^3 per cycle. Through the evaluation of the trap tightness, it is believed that fault L in the northwestern part of the gas reservoir may be open. Through the evaluation of the trap tightness, it is believed that the L fault in the northwestern part of the gas reservoir may be open.

The sampling test results of well BXZ-1 show that the gas in the well is injected dry gas, which is channelled through the fault gas. It is also verified that fault L is open; in addition, it can be seen from the pressure change pattern diagram (Fig. 9a) that the pressure changes on both sides of the fault during injection and production have a good correlation, indicating that the fault is very closed. During the period from 2015 to 2016, a new adjustment measure was implemented in this gas storage, that is, to reduce the gas injection intensity of the injection and production wells near fault L, control the injection pressure difference, and prevent gas leakage under high pressure. The pressure change pattern at this time (Fig. 9b) shows that the pressure change on both sides of the fault is significantly reduced, indicating that the amount of gas leaking through it has been reduced. The current gas leakage is only 12 × 10^4 m^3 per cycle, and the rate has dropped to 7.7%. This result shows that by adjusting the injection-production parameters of the well, the gas loss through fault L can be controlled, which reduces most of the gas loss of BZNB underground gas storage, improving its operation efficiency.

6 Conclusions

(1) Natural gas loss is an inherent characteristic of gas storage in the injection and production operation, accompanying the entire lifecycle and gradually decreasing with increasing operation cycles. There are two main mechanisms of gas loss: macroloss and microloss. The former is the main component of the natural gas geological loss of underground gas storage, accounting for more than 98% of the total gas loss in China. Preventing macrogas loss is the primary target for improving the operation efficiency of underground gas storage.

(2) Based on the basic theories of gas–water flooding and diffusion seepage, aimed at the phenomena of microseepage, dissolution diffusion, abnormal leakage and macroleakage in the process of injection and production of underground natural gas storage, a quantitative gas loss evaluation mathematical model is established to calculate the natural gas loss of the BZNB underground gas storage. The calculation result is accurate; there is little difference between the results and the actual statistical gas leakage, which proves that the accuracy and reliability of this model are very high and can meet the requirements of practical application.

(3) The research results provide a good way to treat gas loss in BZNB underground gas storage. This method can reduce the natural gas loss of underground gas storage, provide early warnings of leakage risk, and improve the economic benefits and injection-production safety of gas storage.

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