Research on Dynamic Evaluation Technology of Multi-period Injection-Production Technology in Gas Storage

Zhuo-cheng Yin(✉)

Jianghan Machinery Research Institute Limited Company, CNPC, Wuhan, China
yinzcdr@cnpc.com.cn

Abstract. For gas storage multi-cycle injection and production process dynamic evaluation technology, mainly including gas storage geomechanical test analysis, injection and production well completion process research, gas storage capacity and injection and production layer gas analysis, the numerical simulation of aquifer gas storage effect, the influence of gas storage on condensate gas reservoir rocks and fluids, etc. In addition, the analysis of cavity creation and injection and mining technology of deep salt hole gas storage, the simulation calculation study of the dynamic injection and mining process of salt hole gas storage, and the determination of the operating pressure limit and the cavity shape detection in the process of injection and mining operation were completed. Finally, innovative puts forward a kind of intelligent gas storage multi-cycle injection-mining process dynamic evaluation system, the artificial intelligence technology applied to underground gas storage injection-mining process dynamic evaluation system, can realize gas storage efficient repeated injection supplement inventory, complete from underground gas storage facilities in high speed repeated injection and gas ability optimization and intelligent operation management, to build safe and efficient, accurate monitoring, intelligent decision-making comprehensive wisdom of gas storage more cycle dynamic evaluation system and supporting system has far-reaching significance.

Keywords: Gas storage · Injection-production process · Dynamic evaluation · Intelligence

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1 Introduction

In recent years, with the world's economic and social high quality accelerated development, the global energy consumption growth surge year by year, lead to oil, coal, natural gas as the main body of the traditional fossil energy consumption and effective use reserves, at the same time the relationship between fossil energy supply and demand obvious seasonal periodic changes and regional mismatch inherent contradictions, so around the world to guarantee the stable energy supply, to adapt to the energy supply and demand, the sustainable development of new energy development and utilization of technology and methods of large-scale application imminent [1, 2].

Among them, the natural gas as a small environmental pollution, high energy storage density and development and utilization of high economic benefit of traditional high quality clean energy and energy storage carrier, can directly through combustion reaction, also can use the chemical catalytic reaction into hydrogen, benzene and other kinds of important chemical raw material products for energy storage and energy supply, so widely used worldwide. However, there is a significant mismatch between the development and application of natural gas, which is mainly reflected in the inconsistency between the seasonal periodic change of natural gas production volume and its application demand, as well as the regional differences between the area of large natural gas reserves and the gathering place of consumer demand. Therefore, in order to balance the contradiction between the peak and valley cycle difference of natural gas development and application and the significant regional imbalance, it is urgent to make full use of the large-scale natural gas reserve, gathering, transmission and transfer technology and adjusting the supply and demand balance technology represented by gas storage technology.

Underground gas storage technology can be developed at any time after compression gas into underground long-term storage, and can according to the application demand time quantitatively through the pipeline network to natural gas from underground storage transport supply, large-scale safe storage of natural gas, natural gas development and utilization peak valley cycle, unicom natural gas development and consumption of key areas, ensure the safe and stable supply of natural gas, and long-term economic and efficient recycling and many other advantages, to promote global energy structure green renewable energy low carbon transformation, power scale utilization and comprehensive global energy security stability is of great significance. However, to realize the underground gas storage, large and scale, commercial application, there are still a series of key technical problems to be solved, among them, as the underground gas storage capacity, production effect and peak load capacity and efficiency of gas storage multi-cycle dynamic evaluation technology behind seriously restricted the large-scale development and application of underground gas storage. Therefore, For the dynamic evaluation technology of multi-cycle injection and production process of gas storage, Systematically completed the geomechanical test analysis of gas storage, Study on injection and well completion process scheme, Analysis of gas storage capacity and injection and production cushion layer, Numerical simulation of the injection and extraction effect of the aquifer gas reservoir, Analysis of single-well injection and production nodes in gas storage, Study on the influence of gas injection on condensate gas reservoir rock and fluid; besides, Also analyzed the cavity construction and injection technology of deep salt hole gas storage, Simulation and calculation study of the dynamic injection and mining process of salt hole gas storage, Completed the determination of the operating pressure limit and the shape detection analysis of the cavity during injection and mining operation; last, innovatively proposed a dynamic evaluation system of multi-cycle injection and production process of intelligent gas storage, Applying the AI well technology to the dynamic evaluation system of the injection and production process of the underground gas storage reservoir, It can realize efficient and repeated injection and production and inventory replenishment of gas storage, complete the capacity optimization of high-speed repeated injection and extraction of natural gas from underground gas storage facilities, and intelligent operation management, It has far-reaching significance for the construction of the multi-cycle injection and production dynamic evaluation system and supporting system of the comprehensive intelligent gas storage reservoir with safe, efficient, accurate monitoring and intelligent decision-making.

2 Evaluation of Geology and Injection Production Characteristics of Gas Storage

Underground gas storage geological evaluation and injection and production effect evaluation is an important theoretical basis of scientific design and operation management, gas storage gas injection process is different from the single extraction process of gas reservoir, mainly divided into storage capacity of two stages of construction and injection and production operation, the geological evaluation requires comprehensive, system and fine, in addition to the reservoir fine description, 3D modeling, fluid distribution study, system to consider the closure of trap, fault and cover gas injection into the selected target layer of safe, no leakage, provide geological basis for injection and production operation scheme design and effectively control the cost.

Using deep salt mine cave for underground energy reserve is currently widely recognized in the world, and it is also the key deployment direction of China's strategic energy reserve. About geological mechanical model test of geotechnical engineering, the domestic related units conducted extensive research, and made some progress, but considering the rheomorphism of salt rock and the influence of alternating pressure risk, carry out the layer of underground gas storage operation process of 3D geomechanical model test study rare reports at home and abroad [3]. Due to the complicated deformation characteristics and destruction mechanism of the underground gas storage operation, the risk factors such as salt rock creep, injection and mining variable pressure and the change rate of the conventional macro geological analysis and the microscopic experiment of the static sealing evaluation method cannot meet the requirements of gas storage condition, under the alternating pressure is of great theoretical significance and engineering application value. Therefore, according to the operation process of salt rock underground gas storage, the three-dimensional gradient hydraulic load model test system, model test, intelligent control system, and similar materials of the change of atmospheric pressure on the safety and stability of storage operation, and provide a reliable test basis for the safety control of storage operation. In addition, according to the study showed that the natural gas into waste condensate gas reservoir storage will lead to gas relative permeability and condensate saturation changes directly affect the gas extraction production, because of condensate precipitation gas output to some extent by increase the injection production cycle recovery, in the first cycle of a large amount of gas, can prevent the formation of condensate, improve the gas index [4].

In addition, to determine the underground gas storage of urban gas system, the most basic design parameter is the design reserves of gas storage, that is, the total gas storage capacity of the storage, which is determined according to all kinds of gas demand in the market, mainly composed of two parts: injection and production gas and cushion gas [5]. Among them, the storage operation of injection (gas storage operation system diagram shown in Fig. 1) working gas including maintaining city load of gas and urban gas supply pipe network system emergency storage gas, peak injection gas is gas market supply and marketing system of all kinds of gas load change, determines the gas storage of gas. Therefore, in the storage planning and design, it is necessary to predict the residential gas load, heating and refrigeration power generation load and other commercial and industrial gas load. Emergency gas reserves in order to ensure the safety of gas supply reliability, must consider emergency accidents such as equipment overhaul, system failure, sudden large new users, etc., to have emergency accident emergency gas reserves, the size of the reserve gas and trunk gas pipeline length, number, standby unit type and number of many factors, usually according to experience, the additional effective accident emergency reserve for about 10% of the compensation season gas imbalance. To maintain the volume of gas storage, must ensure that part of the gas retention in the storage, this part of the gas called cushion gas, it is part of the underground gas storage gas, cushion gas is to ensure the minimum pressure of the reservoir, make the gas supply can provide enough transport speed, but gas storage in peak production operation, this part of the gas can not be produced. The larger the gas volume of the cushion, the higher the formation pressure of the reservoir, which can reduce the number of Wells in the gas

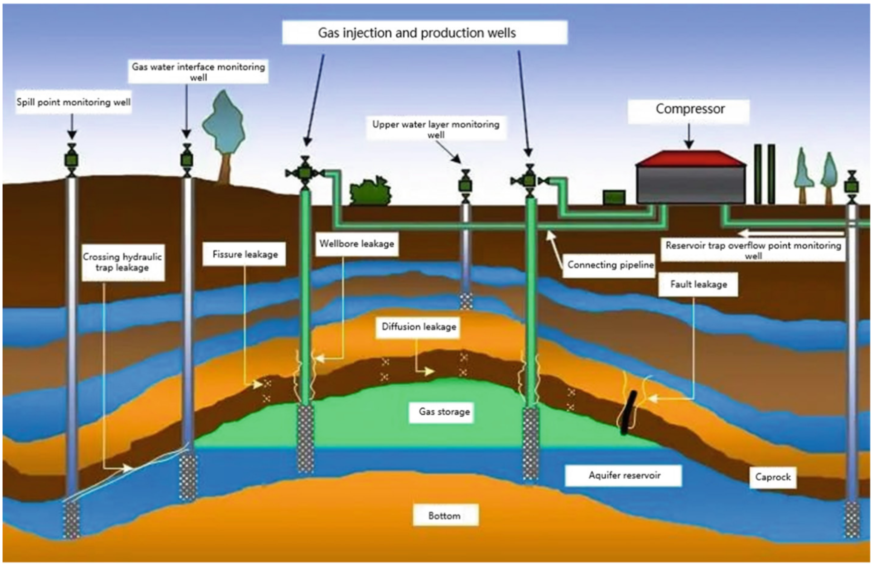


Fig. 1. Schematic diagram of gas storage injection and production operation system.

well and provide high pressure energy for the gas production. Therefore, the cushion gas is the basic parameter to ensure the normal injection and production operation of the gas storage and determine the design of the gas storage, so it needs to be fully calculated and determined.

In all kinds of underground gas storage type, aquifer gas storage is injected into the confined aqubearing strata, the water compression or displacement to the storage surrounding artificial gas reservoir, with large storage, easy to located near large and medium-sized cities from oil and gas area, suitable for urban gas peak shaving, application prospects, and many other advantages, so the following quifer gas storage as the main research object for analysis, other types of gas storage can also be used for reference simulation calculation. Aquifer type underground gas storage is for the purpose of gas storage. The compressor is artificially pressurized to inject the natural gas into the ground through the gas well, discharging the water from the pores of the rock layer in the aquifer, and the gas storage site is directly formed under the non-permeable water-bearing cover. For aquifer, the initial reservoir pore space is completely filled by water, in the process of gas injection, due to the homogeneity of the reservoir, the gas will first drive the water in the rock with large permeability, with the increase of injection, gas gradually drive for dense low permeability water, gradually become gas, gas storage area gradually expanded, being open water in the form of side water or bottom water, as the boundary of the reservoir plays a sealing role, when reaching the predetermined injection, well, and back when needed. For new storage, cushion gas is a great investment, especially for aquifer storage. Usually, cheap inert gas replaces natural gas as cushion gas for injection and production operation, which has important economic significance.

Therefore, the inert gas as the cushion gas, based on the geological data of the underground aquifer gas storage pressure, water saturation and gas concentration distribution. In the applied calculation model, the seepage process is regarded as an isothermal process, and the gas-water seepage conforms to Darcy's law, the gas and water are insoluble, and the influence of capillary pressure is considered, which ignores the compressibility of rock. Because the thickness of the aquifer is very small compared with its area, it can be considered as a two-dimensional problem. The continuity equation of gas-water two-phase seepage flow, equation of motion, saturation balance equation, capillary force equation and gas state equation [6]:

$$\begin{cases} \nabla \cdot \left(a_g \nabla P_g\right) + Q_g = d_g \dfrac{\partial P_g}{\partial t} - e_g \dfrac{\partial S_w}{\partial t} \\ \nabla \cdot \left(a_w \nabla P_g\right) - \nabla \cdot (b_w \nabla S_w) + Q_w = d_w \dfrac{\partial P_g}{\partial t} + e_w \dfrac{\partial S_w}{\partial t} \end{cases} \tag{1}$$

In the equation: $a_g = H\frac{KK_{rg}}{B_g\mu_g}$, $d_g = H\frac{\Phi}{B_g}(1 - S_w)C_g$, $e_g = H\frac{\Phi}{B_g}$, $a_w = H\frac{KK_{rw}}{B_w\mu_w}$, $bw = H\frac{KKrw}{Bw\mu w}p'_c$, $d_w = H\frac{\Phi}{B_w}S_wC_w$, $e_w = H\frac{\Phi}{B_w}\left(1 - S_wC_wp'_c\right)$, $Q_g = \frac{H\delta q_g}{\rho_{gs}}$, $Q_w = \frac{H\delta q_w}{\rho_{ws}}$.

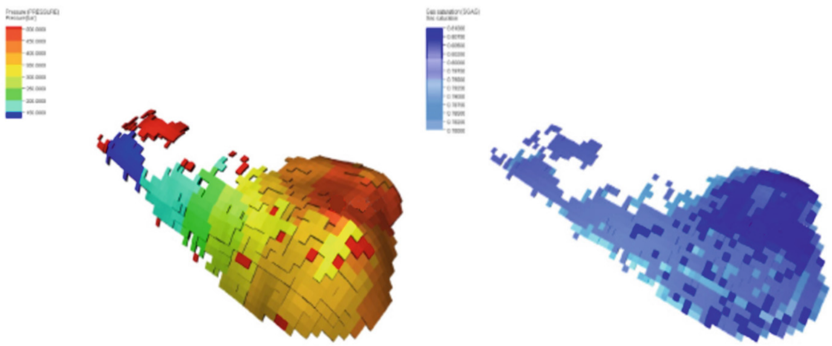
Due to the mixing between inert gas and natural gas, there is a gas convection diffusion model for each gas:

$$\nabla \cdot \left(f \nabla p_g\right) + \nabla \cdot (g \nabla C) + Q_c = u\frac{\partial C}{\partial t} - v\frac{\partial S_w}{\partial t} \tag{2}$$

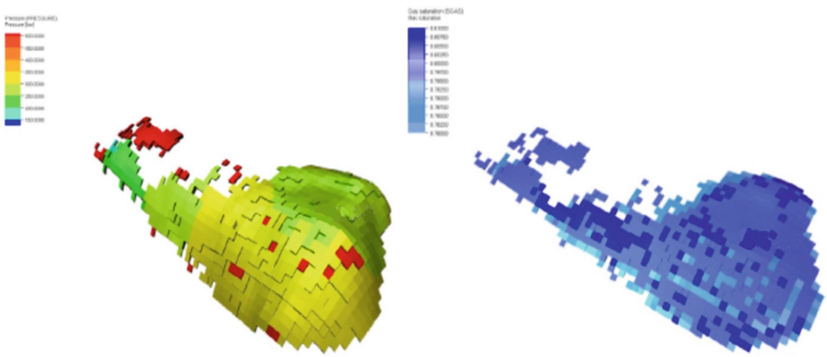
In the equation: $f = HMC\frac{KK_{rg}}{\mu_g}$, $g = H\Phi MD_{AB}(1 - S_w)$, $u = H\Phi M(1 - S_w)$, $v = H\Phi MC$, $Q_c = H\delta q_c$.

In the boundary condition setting, the outer boundary condition is considered as a closed aquifer reservoir, i.e.: $\frac{\partial p}{\partial n} = 0$, $\frac{\partial S}{\partial n} = 0$. The inner boundary condition is that the well radius is very small compared to the storage area, so the well point is considered as a point source or sink. The initial condition is to simulate starting from the initial construction of the reservoir, with an initial water saturation of 1 and a gas concentration of 0 [7].

Using the theoretical numerical calculation model established above, and based on the actual geological and physical properties information and operating parameters of the gas storage reservoir, the spatial area of the gas storage reservoir is divided into grids in the numerical simulation software, and the condition attributes and boundary conditions are set. By using the simulation software, the multi cycle injection and production simulation calculation of the gas storage reservoir can be completed, and the formation pressure of the injection and production wells under different injection and production conditions can be obtained The dynamic simulation results such as gas saturation were used to



a. Formation pressure after injection. b. Gas saturation after injection.



a. Post production formation pressure. b. Post production gas saturation.

Fig. 2. Cloud chart of simulation of gas storage operation during a certain injection production cycle.

analyze the injection and production characteristics evaluation parameters of the gas storage reservoir, as shown in Fig. 2.

3 Research on Injection and Production Technology of Gas Storage

Gas storage is an important means for natural gas peak shaving, balancing pipeline networks, and strategic energy reserves. Quantitative calculation and qualitative analysis of the reliability of gas storage injection and production, and guidance on the operation of the gas storage system based on the calculation results, can help deepen the research on gas storage injection and production technology. Using underground salt caverns to store natural gas to solve the problem of day night and seasonal peak shaving of urban natural gas has many advantages, such as good economic benefits, small environmental impact, high recovery rate, and high injection and extraction rate. Combining rock salt mining with the construction of strategic resource gas storage depots not only saves resources, but also achieves resource recycling, truly achieving low-carbon and green development. Building and developing more underground salt cavern natural gas storage depots has become an important development direction for global strategic gas storage development. Therefore, the following mainly focuses on the research of underground salt cavern gas storage injection and production technology, as well as related technical analysis, Elaborate on the commonly used key technologies involved in the construction of various injection and production processes for deep salt cavern gas storage, such as drilling and completion, dissolution cavity, gas injection and brine removal, and gas injection and production. Provide targeted recommendations for deep salt cavern construction and on-site injection and production operations.

3.1 Analysis of Injection and Production Construction of Salt Cavern Gas Storage

Before the construction of salt hole gas storage, a straight well needs to be drilled, and the well slope must be strictly controlled during drilling. Salt hole gas storage is to dissolve the cavity in stages by lifting the column and making the cavity, and measure the cavity at each stage of the cavity making. If the oblique control is not proper, the upper and lower pull string and logging equipment will be blocked and unable to continue drilling. When constructing the salt hole gas storage is built in the salt layer with a depth of about 2000m, it is suggested to control the full angle change rate within 1.5°. After the gas storage, the formation pressure test is required to test the sealing of the formation. During the pressure test, the method of stratified pressure test is adopted, and the pressure test level is the cover layer, salt layer, salt layer, salt layer and bottom rock layer. The pressure of the formation pressure test shall be subject to the highest pressure of the gas storage injection and mining operation, and the pressure test value shall be 1.1 times of the maximum operating pressure of the gas storage reservoir. A large amount of gas cushion is needed in the process of deep salt hole gas storage to ensure that the pressure in the gas storage meets the requirements of gas stability in the later stage of gas recovery.

During the cavity making construction of salt hole gas storage, the workover machine will be used in the lower lumen making string, accident treatment and well opening operation. In order to ensure the normal construction of cavity, the safety level of the workover machine in different depths of salt layer is different. The pressure of the ground injection pump is the pressure generated by the flow friction resistance in the pipe column, the difference between the internal and external concentration of the lumen column, and the pressure loss of the ground pipeline and the brine pressure of the wellhead. With the increase of salt layer depth, the column flow friction increases, and the pressure generated by the concentration difference between the internal and external columns of brine and fresh water cavity also increases. Compared with the shallow salt layer, the pressure level of the ground injection pump is large, the salt layer at different depths, and the pressure level of the ground injection pump is different, so the safety of the salt hole gas storage construction is very important. Corresponding safety measures must be taken at the wellhead to ensure that the water injection displacement and brine extraction rate of the lumen and annmeet the design requirements, and the casing head, casing, oil pipe, tree and corresponding accessories should also meet the pressure requirements of gas storage. The design principle of lumen column of salt hole gas storage is to choose the lumen tube first, then comprehensively analyze the cyclic pressure consumption results of different lumen column combinations, and finally select the outer tube of salt hole gas storage.

After the cavity construction of the salt hole gas storage is completed, the brine injection and drainage operation can start, and the purpose of the operation is to discharge the brine from the cavity by injecting natural gas. The design of the injection and production pipe column should not only meet the needs of gas injection and drainage in the gas storage reservoir, but also meet the requirements of gas injection and production operation. After the injection and drainage of the gas column, there is no need to take out the halogen pipe column after gas injection and production, and the oil pipe injection and production method is used in the injection and production well. The injection and production operation pressure of deep salt layer gas reservoir is large, the performance requirement of injection and production pipe string is high, and the change of alternating pressure of injection and production operation must be met. Therefore, large size pipe string should be selected within the allowable range, which can reduce the construction pressure during gas injection and halogen discharge and ensure the construction safety. In the process of no well pressing after the injection of halogen discharge, the high pressure of the deep salt layer gas reservoir increases the technical difficulty of no well pressing operation, and the non-well pressing equipment and process requirements are high.

Finally, it is difficult to determine the operating pressure of salt hole gas storage, which must take comprehensive factors and cannot be determined by subjective experience alone. When determining the maximum operating pressure of salt hole gas storage, the sealing of gas should be satisfied first. This is because the pressure in the cavity is too large, if the breakthrough pressure, the gas will leak, forming a safety hazard. When determining the minimum operating pressure of gas storage, the influence of cavity stability should be mainly considered. This is because the pressure in the cavity is too small, and the halite creep will further reduce the volume of the cavity, and the volume loss of the cavity volume may cause the volume of the cavity to collapse. Therefore, in the process of injection and production of gas storage, the operating pressure range of gas storage should be reasonably controlled, and the pressure of salt hole gas storage is different during the operation [8].

In addition, the sonar detection technology is a shape detection technology commonly used in the process of salt hole gas storage. Due to the creep characteristics of the salt hole, the sonar detection of the salt hole gas storage should be conducted every certain years after the completion of the cavity, so as to find the underground faults as soon as possible and ensure the safety of the salt hole gas storage. In addition, the current injection and mining operation scheme can be optimized according to the detection results. Due to the different properties of salt layers for gas storage in different regions in China, the buried depth and design form and size of gas storage are different, the existing research results cannot be directly applied to the construction and operation of all underground salt cave gas storage. Based on this, in order to avoid the adverse effects of the inappropriate operating pressure limit on the gas storage stability, long-term safety and economic operation, it is necessary to study the specific real stratum and shape data of the gas storage to determine the optimal operating limit pressure of the gas storage [9].

3.2 Dynamic Operation Analysis of Injection Production Process

Based on the dynamic operating characteristics of the injection and production process of salt cavern gas storage, a typical injection and production well construction model of salt cavern gas storage, as simulated in Fig. 3, was constructed. It consists of a gas reservoir, production casing, operation casing, surface wellhead equipment, and supporting operation tool system. The production casing is equipped with an injection and production pipeline system connected to the ground manifold system. Assuming that the temperature and pressure of the gas inside the salt cavern are uniform, the salt layer is at a constant temperature, and the wellbore is outputting reactive power, ignoring the kinetic energy loss of the wellbore airflow, the dynamic parameters of the salt cavern gas storage and production process are simulated and calculated [10].

Control Volume Equation in Gas Storage

Considering Δt Within time t, the conservation equation of the system control body mass should be:

$$\frac{P_n}{Z_n T_n} = (1 - \frac{G_d}{G} dt) \frac{P_{nI}}{Z_{nI} T_{nI}} \tag{3}$$

In the equation: P_n, Z_n, T_n—Actual parameters inside the gas storage chamber, P_{nI}, Z_{nI}, T_{nI}—The initial parameters of injection and extraction, G—Gas storage capacity in storage (standard state), G_d—Daily injection and production volume in gas storage.

Similarly, considering Δt Within time t, the energy equation of the system control volume should be:

$$\Delta m U_E = m_I U_{EI} - m H_E + Q$$

In the equation: U_{EI}—Initial internal energy, m_I—ρsc, $m = \rho sc G_d$—Injection volume, $\Delta m = m + m_I$ (Injection), $\Delta m = m_I - m$ (Extracted), Q is convective heat transfer value between the gas and the salt wall in the gas storage tank.

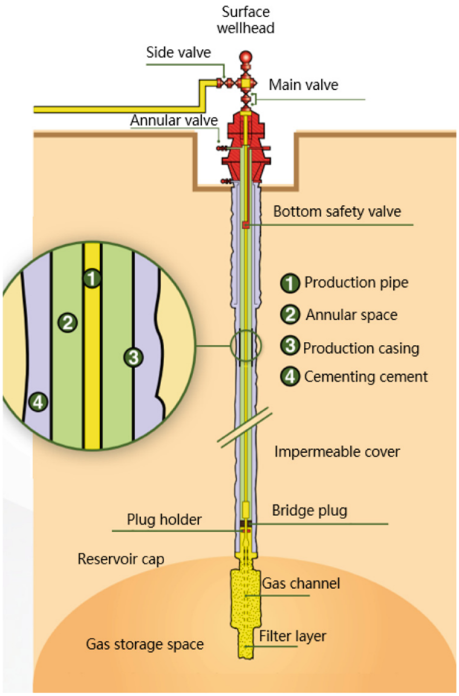


Fig. 3. Schematic diagram of gas storage injection and production well structure.

Due to the cooling effect of salt during the salt washing process, the temperature of the salt cavity wall is lower than the temperature of the surrounding salt layer. If the temperature of the salt cave wall is TW1 and the temperature of the surrounding salt layer is T_{W2}, then:

$$q = \frac{T_{W1} - T_{W2}}{\frac{1}{2\pi\lambda}\ln\frac{r_2}{r_1}}$$

At the wall:

$$-\lambda\frac{\partial T}{\partial n}|_{w} = \alpha(T_W - T_n)$$

Can obtain: $Q = \pi dh\frac{T_{W1}-T_n}{\frac{1}{2\pi\lambda}\ln\frac{r_2}{r_1}+\frac{1}{2\pi r_1\alpha_1}}$ $Q = \pi dh\frac{T_{W1}-T_n}{\frac{1}{2\pi\lambda}\ln\frac{r_2}{r_1}+\frac{1}{2\pi r_1\alpha_1}}$.
To obtain H_E, use the thermodynamic differential equation:

$$dH_E = C_d dT - [V - T(\frac{\partial V}{\partial T})P]dP$$

According to Bertrand's equation of state:

$$\frac{PV}{RT} = 1 - \frac{9P_n}{128T_n}(\frac{6}{T_n^2} - 1)$$

After substituting and organizing, we can obtain:

$$V - T(\frac{\partial V}{\partial T})P = -\frac{9RT_C}{128P_C}(\frac{18T_C^2}{T^2} - 1)$$

$$H_E = \int_0^{T_n} C_d dT + \int_0^{P_n} \frac{9RT_C}{128P_C}(\frac{18T_C^2}{T^2} - 1)dP$$

$$H_E = C_d T_n + \frac{9RT_C}{128P_C}(\frac{18T_C^2}{T^2} - 1)P_n$$

Due to continuous daily injection and production, the temperature change is not significant, so C_d is almost constant.

And because $U_E = H_E - PV$, By Bertrand's equation of state:

$$PV = RT - \frac{9T_C P}{128P_C T}(\frac{6}{T_r^2} - 1)RT$$

Obtained:

$$U_E = (C_d - R)T_n + \frac{9RT_C}{128P_C}(\frac{24T^2C}{T^2} - 2)P_n$$

Substitute all the above into the original equation to obtain:

$$\begin{aligned} &\Delta m[(C_d - R)T_n + \frac{9RT_C}{128P_C}(\frac{24T_C^2}{T_n^2} - 2)R_n] = \\ &m_I U_{EI} - m[C_P T_n + \frac{9RT_C}{128P_C}(\frac{18T_C^2}{T^2} - 1)P_n] + Q \end{aligned} \tag{4}$$

Wellbore Flow Equation

Based on the assumed conditions, the energy equation for stable gas flow can be obtained:

$$\frac{dP}{\rho} + gdH + \frac{fu^2 dH}{2d} = 0$$

In the formula: H - pipe length; F - friction coefficient; U - gas flow rate in flowing state; D - Inner diameter of the oil pipe.

$$u = \left(\frac{G_P}{86400}\right)\left(\frac{T}{293}\right)\left(\frac{0.101325}{P}\right)\left(\frac{Z}{l}\right)\left(\frac{4}{\pi}\right)\left(\frac{1}{d^2}\right)$$

$$\rho = \frac{PM_g}{ZRT} = \frac{28.97\gamma P}{0.008314ZT}$$

After sorting, separate the variable integrals to obtain:

$$P_w^2 = P_{ne}^{2-2s} - \frac{1.324 \times 10^{-18}(G_P\overline{TZ})^2 f(1 - e^{-2s})}{d^2} \tag{5}$$

In the equation: $\overline{T} = \frac{T_W + T_n}{2}$, $\overline{P} = \frac{P_W + P_n}{2}$, $\overline{Z} = g(\overline{T}, \overline{P})$, $s = \frac{0.03416\gamma_g H}{\overline{TZ}}$.
G_d is positive during injection G_d is negative during extraction.

Solving Mathematical Models

According to the injection and production operation modes in the gas storage injection and production process. When injecting, under any initial condition, PW, TW (wellhead parameter), and Gd (daily injection amount) are known, and the constraint conditions is $P_n \leq P_{n\max}$ (Maximum allowable pressure during storage design); At the time of extraction, under any initial condition, Gd (daily extraction amount) is known, and the constraint condition is $P_w \leq P_{w\min}$ (minimum allowable wellhead pressure).

By using the N-R iterative method, we can obtain:

$$\frac{\partial F_{MB}^k}{\partial P} \Delta P_R^{k+1} + \frac{\partial F_{MB}^k}{\partial T} \Delta T_R^{k+1} = -F_{MB}\left(P_R^k, T_R^k\right)$$
$$\frac{\partial F_{EB}^k}{\partial P} \Delta P_R^{k+1} + \frac{\partial F_{EB}^k}{\partial T} \Delta T_R^{k+1} = -F_{EB}\left(P_R^k, T_R^k\right)$$

Control conditions: $\Delta P \leq 10\text{kPa}$, $\Delta Tn \leq 1°\text{C}$, Obtained Pn and Tn values.

The solution of wellbore parameters:

$$T_R = \left(\frac{P_R}{P_W}\right)^{\gamma - 1/\gamma} T_W,$$

$$T_R = (\frac{P_R}{P_W})^{\gamma - 1/\gamma} T_W$$

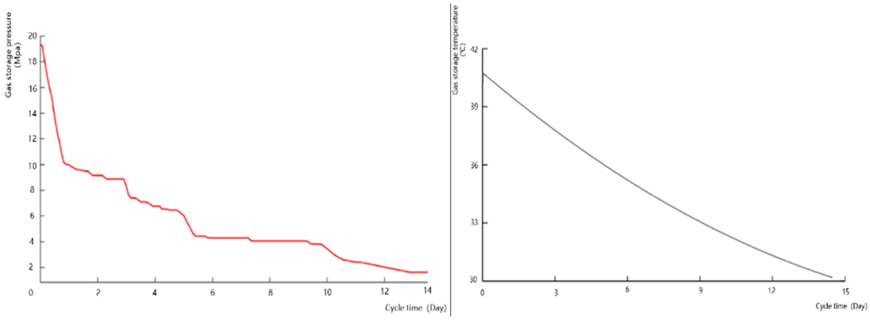
Calculated:

$$\overline{T} = \frac{1}{2} T_W [(\frac{P_R}{P_W})^{\gamma - 1/\gamma} + 1]$$

Obtain the nonlinear equation for PR and still use the N-R iterative method:

$$P_b^{k+1} = P_b^k - \frac{F(P_b^k)}{F'(P_b^k)}$$

Based on the simplified mathematical model proposed above for the injection and production dynamic process of salt cavern type gas storage, the model can predict the changes in natural gas pressure and temperature during any continuous injection and production cycle. Based on the actual bottom diameter D, bottom height H, initial temperature T_n, initial pressure P_n, salt layer temperature T_{W1}, and convective heat transfer coefficient of the salt cavern gas storage α、 By combining the maximum design pressure P_{nmax}, minimum design pressure P_{nmin}, minimum wellhead allowable pressure P_{Wmin}, pipeline inner diameter d, pipeline length h, pipeline friction coefficient f, and natural gas physical parameters, as well as the theoretical numerical calculation model constructed above, the multi cycle injection and production simulation calculation of the gas storage can be completed, and accurate dynamic simulation results of pressure, temperature changes, and other changes in the gas storage under different injection and production conditions can be obtained, Complete the calculation of characteristic evaluation parameters in the gas storage, as shown in Fig. 4. This model can be used for the design and planning of gas storage facilities, the comparison of various gas storage operation plans, and the determination of the hazardous range of hydrate formation.



a. Pressure variation curve of gas storage. b. Temperature variation curve of gas storage.

Fig. 4. Calculation results of pressure and temperature in gas storage.

4 Intelligent Gas Storage Multi Cycle Injection Production Process Evaluation System

In the process of construction, operation and management of gas storage, the traditional manual monitoring, data induction and analysis decision-making methods have obvious shortcomings such as low efficiency and poor accuracy. Supporting the construction of advanced automation control systems and intelligent analysis and decision-making systems covering the entire process will be an important research direction for achieving large-scale operation of gas storage in the future. Therefore, in the future, artificial intelligence technology will be integrated into the dynamic evaluation system of gas storage injection and production processes, fully relying on the collection, transmission, and output data of the gas storage monitoring system to establish a new production management mode of automatic control, simulation prediction, and intelligent decision-making. This can achieve efficient cyclic injection and production of gas storage, optimize the ability to repeatedly inject and extract natural gas at high speed from underground gas storage facilities, and achieve intelligent operation management, which is crucial for building a safe and efficient The comprehensive intelligent multi cycle injection and production dynamic evaluation system and supporting system for gas storage with precise monitoring and intelligent decision-making have profound significance.

The multi cycle injection and production process of gas storage is a key focus in the research of gas storage operation. It should focus on integrated numerical simulation and based on the research results of gas reservoir engineering, comprehensively analyze and optimize the injection and production operation of gas storage from market peak shaving demand, block pressure difference, energy efficiency, and other aspects. Design an injection and production optimization model for gas storage from the aspects of safety, energy efficiency, and peak shaving requirements. Based on simulation models or multi-objective evolutionary algorithms, adjust the injection and production plan and surface processes of the gas storage to ensure efficient and safe operation of the gas storage. The basic structure diagram of the gas storage is shown in Fig. 5.

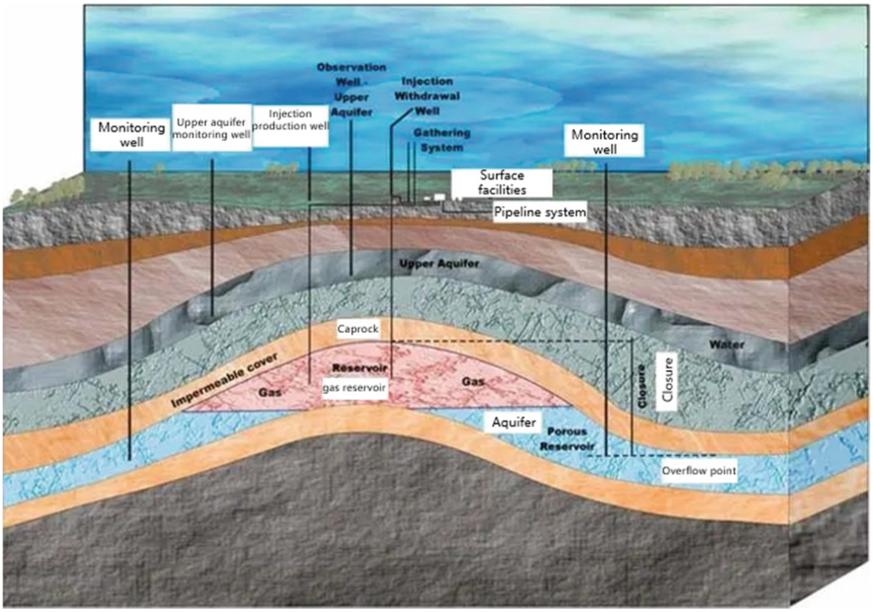


Fig. 5. Schematic diagram of basic structure of gas storage.

The research direction of gas storage injection and production operation is mainly based on nodal analysis, comprehensively considering the internal and external constraints of the injection and production system to coordinate the gas injection and production volume, building a three-dimensional integrated numerical simulation model of "geology wellbore surface", simulating the production performance of the entire production system, and completing the optimization of gas storage production allocation and injection based on it. Based on an integrated simulation model, with the energy consumption of ground equipment and the pressure of each manifold node as the objectives for the economy, stability, and safety of the gas storage, and taking into account the requirements of each season, an objective function is designed and relevant constraint conditions are formulated. A gas storage injection and production optimization model is constructed, which can achieve multi-parameter target monitoring and control optimization simulation of injection and production plans such as the number of injection and production wells and single well injection and production gas volume in the gas storage [11, 12].

By establishing an intelligent gas storage multi cycle injection and production process evaluation system to obtain continuous high-frequency measurement data of the gas storage, the high-frequency measurement data is collected and output in real time from various storage well monitoring systems, data acquisition systems, and supporting facilities at certain time intervals. The system flow diagram is shown in Fig. 6. In the first step of the evaluation system's processing process, the software system will confirm the connectivity of the data flow collection and transmission, and immediately notify the operators if the connection fails. After confirming the validity of the connection, the software system will input, filter, quality check, and summarize high-frequency data at longer intervals to reduce the size of the dataset. Before data aggregation, the software automatically removes sensor errors and transmission errors, and generates statistical reports to enable engineering personnel to evaluate the accuracy of the information. In order to automate the aforementioned routine tasks and improve data transmission speed, artificial intelligence technology has been developed. Key performance indicators can be obtained using newly collected data, which can be used to simulate and predict ongoing operations.

After the processing steps of the first level intelligent system are completed, the filtered data will be input into the software module to verify whether the system is operating normally. Through processing programs, external applications with data exchange capabilities can be integrated, including reservoir simulation software, production system analysis software, and various modules. The program can automatically perform historical fitting for trend analysis, provide well condition information for each well, and determine production and storage capacity limitations. Current and future injection and recovery volume requirements. The data input to the scheduling module will be transferred to another module of the software and all necessary assessments and predictions will be completed to ensure that the gas storage has enough storage volume to meet the scheduling requirements. The evaluation results were compared with the measured results through an automated monitoring system. If the information provided by the alternative model indicates that the performance of a certain well or surface facility has not met expectations, an event alarm will be triggered and staff will be notified. After

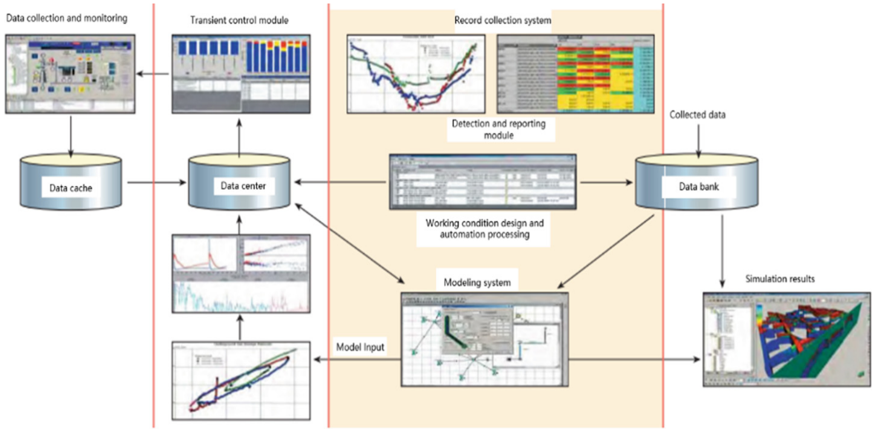


Fig. 6. Flow diagram of intelligent gas storage multi cycle injection production process evaluation system.

collecting and organizing data for processing, intelligent systems will run comprehensive simulation models in various dynamic modules. The system needs to be calibrated according to standards and generate a complete job health report using a deterministic model, which can be transmitted and recorded, and can monitor scheduled automated tasks or alarm triggered tasks. The intelligent gas storage multi cycle injection and production process evaluation system is a higher level of intelligence than monitoring and control, and is a key part of achieving digital oil fields. It can provide people with a high-level automation, simulation modeling, rapid intelligent decision-making tool, and innovative methods for monitoring and feedback on details.

5 Conclusion

The large-scale application of underground gas storage technology is of great significance for promoting the green and low-carbon transformation of the global energy structure, promoting the large-scale utilization of renewable energy, and ensuring global energy security and stability in all aspects. However, the research on the multi cycle injection and production dynamic evaluation system for gas storage is still in its early stages, and the entire system digital simulation, multi-party linkage optimization operation, safety warning and other system platforms are still blank. To this end, we will build and promote an intelligent gas storage multi cycle injection and production process evaluation system application platform with integrated simulation as the core, achieving real-time simulation calculation, online risk warning, and intelligent decision support synchronous connection, which can lay the foundation for future intelligent peak shaving, digital operation, and integrated control of gas storage. It has profound significance for building a comprehensive intelligent gas storage evaluation system and supporting systems that are safe, efficient, precise monitoring, and intelligent decision-making.

Future research on intelligent gas storage should: strengthen data governance, improve data quality, optimize learning algorithms, achieve the integration of "data modeling prediction", find out the adaptability and application boundaries of intelligent technology in all business links, and improve the reliability of artificial intelligence technology landing on the site; Strengthen the localization research and development of core software, establish a unified cloud platform to complete integrated construction; Strengthen the panoramic situational awareness and control of the physical operation of gas storage, and explore the method of combining mechanism models and machine learning models on this basis to improve the interpretability of the model and the credibility of decision-making, truly realizing the visualization, autonomy, and intelligent management of the entire lifecycle of gas storage.

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