Influence of natural gas thermodynamic characteristics on stability of salt cavern gas storage

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Abstract. The good creep characteristics and damage repair characteristics of salt rock make it a high-quality stratum resource for the construction of underground natural gas storage. During the operation of salt cavern gas storage, the creep of salt rock is mainly concentrated in the steady creep stage. Stress and temperature have a great influence on the creep properties of salt rock. When the salt cavern gas storage is in operation, the injection and production cycle alternates, the gas flow is large in a short time, and the internal pressure and temperature of the salt rock cavern are constantly changing. The thermal and stress states of the gas storage are constantly changing, which directly affects the creep characteristics of the underground cavern of the gas storage, and thus affects the shape change of the cavern and the volume convergence characteristics. This paper is based on the characteristics of natural gas flow and heat transfer when the gas is injected and mined, through the fitting of experimental data and the application of classical creep constitutive equations, the characteristics of the cavern volume convergence during the ultimate gas recovery operation and emergency peaking operation of the gas storage are studied. The results showed that the temperature change in the gas storage cavern had a significant effect on the creep of salt rock. The influence of temperature should be considered when analyzing the stability of gas storage. The volume convergence of the cavern gas storage cavern is mainly concentrated in the large-rate gas production and low-pressure gas storage stages. Increasing the internal pressure and shortening the gas production running time have a significant inhibitory effect on the volume reduction of the cavern. While meeting the demand for natural gas, the emergency gas production time should be shortened as much as possible to avoid the long-term low-pressure gas storage state of the gas storage, which can meet the stability requirements of the salt rock cavern volume convergence.

1. Introduction

The underground natural gas storage is used to adjust the balance between supply and consumption, to coordinate the change of supply and demand, and to coordinate the strategic reserve. There are four main types of underground gas storage in natural gas: gas storage rebuilt upon the depleted oil and gas reservoirs, gas storage in aquifer, salt cavern gas storage and discarded pit gas storage [1, 2]. As a
special kind of soft rock, salt rock has the characteristics of low permeability and easy water solubility mining, and has good creep characteristics and damage repair characteristics. It is a high quality geological resource for the construction of underground storage. Salt cavern gas storage in thicker salt rock has many advantages, such as good sealing and mechanical stability, flexible and efficient injection production operation modes, strong throughput capacity of single cavern, and so on. It is especially suitable for using as short term peak gas storage [3]. China's natural gas demand is increasing year by year, and the contradiction between supply and demand is becoming increasingly prominent. The construction of gas storage is the key task of the development of China's natural gas industry. The demand for natural gas in China has increased rapidly year by year, and the conflict between supply and demand has become increasingly prominent. The construction of gas storage is a key task for the development of natural gas industry in China. In order to cope with the“West-to-East Gas Transmission” project, CNPC Jiangsu Jintan Gas Storage and Liuzhuang Gas Storage has begun to operate in 2007. At present, 26 salt caverns have been put into operation. The external gas storage of Pingdingshan, Huai’an Zhaoji, Chuzhou, and Yunying are stepping up, and the feasibility study has been completed. At the same time, in the Jintan, the“East Sichuan Gas Transmission”gas storage area and the national oil reserve reservoir area were also planned [4].

Salt rock creep test studies show that the initial creep stage of salt rock is short, and it quickly transitions to the steady-state creep stage. The two factors of stress and temperature have a great influence on the creep characteristics of salt rock [5]. Domestic and foreign scholars have done a lot of research on the stability of salt cavern gas storage. Yin Xueying et al. used FLAC3D software to numerically simulate the stability of the old cavern and the creep of the cavern in Jintan, and the results show that when the operating pressure range of the gas storage is 6-14.5 MPa, the shrinkage rate of the solution cavern is within 22% [6]. Chen Feng used three-dimensional numerical simulation methods to study the stress state and volume deformation of solution caverns at four gas extraction caverns in Jintan under different gas production rates, and find that the maximum gas pressure drop rate of the gas storage should be less than 0.55 MPa/day [7]. Yang Chunhe et al. conducted numerical simulations on the cave shape, stability and long-term stability of deep underground salt caverns using Jintan Salt Mine as the research object and analyzed the changing law of the volume of the solution cavern under different pressures [8]. Zhang Qiangyong, Liu Dejun, and Duan Kang developed a three-dimensional geomechanical model testing system for salt rock underground gas storage, performed physical model tests on the safety of gas injection and gas production in gas storage, and obtained the force and deformation laws of the reservoir cavern and wellbore casing [9-11]. Wang Su et al. used Flac3D software to simulate the reservoir mechanical properties of the injection and production process, and obtained the influence of salt rock properties, stability of pillars, and the stability of the cavern on the operation of gas injection and production [12].

At present, the research on the stability of salt cavern gas storage is based on the perspective of rock mechanics. And most of the research work focuses on the stress factor, while ignoring the influence of temperature changes in the gas storage cavern on creep. The natural gas injection and production process of salt cavern gas storage is characterized by frequent alternation of gas injection and gas production cycles, large pressure difference changes, fast flow rate, the amount of short-term gas flow is large, The flow of natural gas is accompanied by the transfer of heat, and the thermal and stress conditions of the gas storage are constantly changing, directly affects the stability of gas storage. This article starts from the point of view of natural gas flow and heat transfer in the salt cavern gas storage and operation, and analyzes the influence of changes in the thermal state of the salt cavern gas storage on its stability to provide references for the development of gas storage injection operation strategy.
2. Salt rock creep and volume convergence characteristics of solution cavern

2.1. Creep properties of salt rock

The operation of the salt cavern gas storage generally does not enter the salt rock accelerating creep (creep damage) stage, and does not consider the creep damage of salt rock. Numbers of test data verify the applicability of Carter's creep constitutive model in underground salt rock natural gas storage cavern engineering and nuclear waste storage cavern engineering. It is believed that this constitutive model can well describe the steady-state creep of salt rock. Assuming that the salt rock medium is homogeneous and isotropic, based on the Carter steady-state creep constitutive model [13], a basic constitutive equation describing the creep (transient and steady-state creep) of salt rock can be obtained:

\[ \varepsilon = A_1 \left(1 + e^{-\alpha t}\right) + A_2 \exp\left(-\frac{Q_r}{R_0 T}\right) \left(\frac{\Delta \sigma}{\sigma^*}\right)^{n_r} t \]  

(1)

In equation (1), \( \varepsilon \) is creep rate for salt rock; \( A_1 \) is salt rock transient creep parameters (MPa\(^{-5}\)·h\(^{-1}\)); \( A_2 \) is salt rock steady-state creep characteristic parameters (MPa\(^{-5}\)·h\(^{-1}\)); \( Q_r \) is salt rock creep activation energy (kJ/mol); \( T \) is the temperature of salt rock (K); \( \Delta \sigma \) is stress difference (MPa); \( \sigma^* \) is unit stress (MPa); \( \alpha \) is salt rock material parameters; \( n_r \) is salt rock creep stress index.

Salt rock creep test studies show that the initial creep stage of salt rock is short, and it quickly transitions to the steady-state creep stage. The two environmental factors, stress state and temperature, have a greater response to the creep characteristics of salt rock. Based on the test data of salt rock mechanics parameters and the triaxial creep experimental data of Jintan Salt Mine [14], equation (1) was used to study the law of creep of salt rock with confining pressure and temperature, as shown in Figure 1.

![Figure 1](image_url)

**Figure 1.** Variation of creep strain of salt rock with confining pressure and temperature.

The relationship between creep strain and time of salt rock can be divided into two phases: initial stage and steady-state stage. The initial creep stage of salt rock is very short, and it quickly enters the steady-state creep stage. With the same axial pressure condition, the creep strain of salt rock increases with the increase of deviatory stress and temperature; and as the deviatory stress and temperature increase, the creep strain rate of salt rock gradually increases. Figure 1 shows, the steady-state creep strain rate of salt rock depends on the deviatory stress and temperature change, and the increase of temperature makes the steady-state creep rate of salt rock increase obviously and quickly. Therefore, the influence of the temperature change in the salt solution cavern caused by natural gas flow and heat transfer in the gas storage tank on the stability of the gas storage cannot be ignored.

2.2. Volume convergence characteristics of salt cavern

During the operation of the salt cavern gas storage, the salt rock creep causes the volume of the gas storage cavern to gradually converge, and the transient creep of salt rock is maintained for a short time, and it is mainly in the steady state creep stage. Considering that the horizontal principal stress of the strata in the viscous formation is approximately equal to the stress of the overlying stratum, based on
the steady-state creep constitutive equation (1), referring to the empirical equation for the volume convergence of spherical cavern [15], and the mathematical model of the creep volume converging of cylindrical cavern is expressed as equation (2).

\[
\frac{\Delta V}{V} = \left( \frac{2}{\sqrt{3}} \right)^{n+1} \left\{ \frac{3}{2} A_2 \exp \left( -\frac{Q_r}{R} \right) \left[ \frac{3}{2n} (P_\infty - P_t) \right]^{n} \right\} t
\]

(2)

Where the salt rock creep coefficient \( A_2 \) is 0.18MPa\(^{-5}\) d\(^{-1}\), \( Q_r \) is 12.9kcal/mol, \( n = 5 \).

Figure 2. The law of the volume convergence of salt cavern changing with internal pressure and gas production rate.

The salt rock creep results in the volume converging of the salt solution cavern and the thermal state and operation strategy of the solution cavern have a direct impact on the volume convergence. Figure 2(a) shows, it can be seen that with the decrease of internal pressure in the solution cavern, the volume of the solution cavern is significantly faster. When salt rock temperature is 50°C and formation pressure is 17 MPa, salt solution cavern internal pressure reaches 6 MPa. After 25 years, salt solution cavern volume converges about 37.13%; when the internal pressure is 10.5 MPa, the volume of the salt solution cavern converges to about 8.91% after 25 years; when the internal pressure is 13.5 MPa, the salt solution cavern volume converges about 1.34% after 25 years.

If the average operating pressure of the gas storage is 10.5-12 MPa, the salt solution cavern volume will converge by less than 10% after 25 years, the gas storage can meet the requirements for long-term operation, increasing the internal pressure has a significant inhibitory effect on the cavern volume reduction. Therefore, during the operation of the gas storage, the operating time of the gas storage at low pressure should be reduced as much as possible in order to prolong the service life of the gas storage. In the literature [16], the volume strain of the salt solution cavern should not exceed 3% during each cycle of the salt cavern gas storage, with an average of no more than 0.0082% per day. In Figure 2(a), the internal pressure of the cavern is constant at 6 MPa, and the volume of the cavern is an average of 0.0041%/d. Gas storage gas production run time does not exceed 1/3 of the operating cycle, in order to ensure that the volume of the solution cavern in a salt cavern gas storage does not exceed 0.0082%/d, the volume concentration rate of the solution cavern during the gas injection and storage phase should not exceed 0.0041%/d and the volume concentration rate of the solution cavern during the gas production stage should not exceed 0.0164%/d.

Figure 2(b) shows, the larger the gas production rates of the gas storage, the more obvious the convergence tendency of the solution cavern. When the gas pressure drop rate was 0.54 MPa/d, the volume of salt solution cavern converged to 0.4124% after 25 days, and the average convergence rate was 0.0165% /d; When gas pressure drop rate was 0.68 MPa/d, the volume of salt solution cavern converged to 0.981% after 25 days, and the average convergence rate was 0.0392%; When the pressure drop rate of gas production was 0.82 MPa/d, the volume of salt solution cavern converged to about 2.052% after 25 days, and the average convergence rate was 0.0821%/d. Under the conditions of this formation, the upper limit of the rate of the volume concentration of the solution cavern in the gas production stage of the salt cavern gas storage is constrained to 0.0164%/d, and the upper limit of the gas pressure rate in the gas storage is constrained to 0.54 MPa/day. At present, using the data of Jintan,
the maximum gas production rate of the salt cavern gas storage is recommended as a pressure drop rate of 0.55 MPa/day [11], it shows that the empirical formula used in paper is feasible and the result is reliable.

During the operation of the gas storage, increasing the gas production and depressurization rate of the gas storage and shorting the operating time under low pressure can effectively ensure the safe operation of the gas storage and prolong the service life of the gas storage.

3. Volume convergence analysis of solution cavern for gas storage injection and production operation

During the operation of injection and production operation in the salt cavern gas storage, the pressure, the temperature, and the wall temperature in the solution cavern change with the injection and production operation time. The change of the thermal state of the solution cavern redistributes the stress field and temperature field of the salt rock, the creep of the salt rock and the volume convergence of the solution cavern also changes. At present, the scholars focus on the influence of the extreme gas production rate of gas storage on the stability of reservoirs and the volume convergence of the solution cavern in view of the creep mechanical properties of salt rocks, and propose that the limit rate of gas production for salt caverns is 0.54 MPa/day. Based on the salt solution cavern volume convergence equation (2), according to the results of thermodynamic simulation of the operation of limit gas production and emergency gas supply of the salt cavern gas storage [17], the volume convergence process of the gas storage solution cavern in the two operating modes was simulated.

3.1. Analysis of thermodynamic state and volume convergence of solution cavern in extreme gas production rate

With the cavern volume is $25 \times 10^4 \text{ m}^3$, wellbore length is 1000m, the cavern initial pressure is 17MPa and the initial temperature is 50 $^\circ$C, gas production is performed at a rate of 0.54 MP/day. After 20 days of gas production, the pressure in the solution cavern reaches the minimum operating pressure of the solution cavern of 6MPa. During the gas production process, the gas production volume, the temperature of the solution cavern, and the wall temperature of the solution cavern with the time of the gas production change in the gas storage are shown in Figure 3.

![Figure 3. Relationship between daily gas mining in the gas storage, cavern temperature, and cavern wall temperature with gas production time.](image)

When gas storage operation is adopted to control the pressure drop in the solution cavern, the daily gas production will gradually increase. The daily gas production increased from $85.65 \times 10^4 \text{ N m}^3$ to $135.95 \times 10^4 \text{ N m}^3$, and after 20 days of gas production, the cumulative natural gas production was approximately $23 \times 10^6 \text{ N m}^3$. At the beginning of gas production, the temperature of the solution cavern was equal to the wall temperature of the solution cavern. As the gas production proceeded, the temperature of the solution cavern and the wall temperature of the solution cavern also decreased, and the temperature of the solution cavern dropped to about 20$^\circ$C at the end of the gas production. The temperature dropped to about 30$^\circ$C.
Based on the empirical equation, the volume convergence rate of the solution cavern with the change of thermal state is shown in Figure 4. The volume convergence rate of the solution cavern gradually increases with gas production. At the initial stage of gas production, the pressure and temperature salt cavern did not change much, and the creep of the salt rock was not obvious at this time, as the thermal state of the solution cavern gradually changed, the tendency of salt rock creep became more and more obvious, the volume of the solution cavern continuously converged, and the convergence rate was accelerated. At the end of the 20 days of gas production, the volume convergence rate of the solution cavern approached 0.06%. It can be seen that the change of the thermal state of the solution cavern directly affects the creep rate of the salt rock and the volume convergence rate of solution cavern and with the progress of gas production, the impact becomes more obvious.

![Figure 4](image-url)  
**Figure 4.** Relationship between volume convergence rate and thermal state of gas storage in extreme gas production operation.

3.2. Analysis of Thermal State and Volume Convergence of the Solution cavern during the Full Year Cycle of Emergency Air Supply

Although some research results have given the limitation of gas storage gas production limit rate, in the actual operation of gas storage, when the user demand surges, emergency gas supply operation must be performed within a short time. In order to meet the needs of users, the emergency gas production rate is often greater than the limit gas production rate. At this time, the emergency time is controlled to meet the volume convergence restriction conditions of the salt solution cavern.

When the salt cavern gas storage emergency conditions are in operation, a single cavern will complete two emergency injection and production cycles each year. In each emergency cycle, the number of emergency days is 10 days, and the emergency gas production rate is $2.6 \times 10^6$ Nm$^3$/day. After the emergency gas production, the gas storage will be adjusted for less than 2 months, followed by 4 months of gas injection operation and the following 1 month of gas storage stage. The annual cycle injection and production operations are shown in Figure 5. In the figure, 1 and 5 are gas production stages, 3 and 7 are gas injection stages, and 2, 4, 6 and 8 are gas storage stages.

![Figure 5](image-url)  
**Figure 5.** Relationship between emergency gas mining and injection gas volume, cavern pressure, solution cavern temperature and wall temperature of the cavern with running time.
During the entire annual emergency cycle injection and production operation, the curve of the thermal state parameters (pressure, temperature) of the gas storage underground solution cavern with the running time is shown in Figure 5. Gas storage for emergency gas production for 10 days, cumulatively produced natural gas of 26×10⁶ Nm³/day, and the pressure in the solution cavern quickly dropped from the initial 17MPa to 8.6MPa. The temperature of the solution cavern quickly decreased from the initial 50°C to about 22.5°C, and the temperature of the solution cavern decreased to about 29°C, at the end of the emergency gas production stage, the temperature of the solution cavern was significantly lower than the wall temperature of the solution cavern. In the subsequent gas storage phase, the pressure in the solution cavern and the temperature in the solution cavern have a slowly rising trend, and then the pressure, the temperature and the wall temperature in the solution cavern gradually increase with gas injection. Throughout the whole year cycle, the pressure in the solution cavern varies from 8 MPa to 17 MPa, the temperature in the solution cavern varies from 22.5°C to 59°C, and the wall temperature in the solution cavern varies from 29°C to 57°C.

When the gas storage is operated in emergency gas production mode, the gas production rate is relatively high, the thermal state of the solution cavern changes significantly in a short time, which will certainly have a greater impact on the creep characteristics of the salt solution cavern. Based on the empirical equation, the volume convergence of the salt solution cavern during the injection and production operation of the emergency gas production throughout the year is shown in Figure 6, during the emergency gas production operation of the gas storage and low-pressure gas storage, the volume of the salt solution cavern converged quickly and the convergence rate gradually increased, the emergency gas recovery was 10 days, and the volume of the solution cavern converged by 0.001%; At the end of the first gas storage phase, the volume of the solution cavern converged by approximately 0.15%; With the gas injection operation, the pressure and temperature of the solution cavern gradually increased, and the volume of the solution cavern significantly slowed down, tending to be gentle until the start of the next emergency gas recovery cycle. It can be seen that the volume converge of the salt solution cavern mainly occurred during the emergency gas production process and the low pressure gas storage phase throughout the entire cycle. Throughout the whole year cycle, the volume of the gas storage solution cavern converged by about 0.7%, and the average convergence rate was 0.0002%/day, which fully satisfied the limited requirements of the existing research results on the volume convergence of the salt solution cavern [11].

4. Conclusions
(1). When salt cavern gas storage salt solution cavern creep is in the steady-state creep phase, the thermal state parameters (pressure and temperature) of the solution cavern have a direct impact on its creep characteristics. As the temperature rises, the creep rate of the salt rock increases obviously and rapidly. Therefore, the influence of the temperature change of the gas storage on the stability of the gas storage during the injection and production of natural gas cannot be ignored.

(2). Based on the salt rock properties of Jintan gas storage, under the condition of salt rock temperature of 50°C and formation pressure of 17MPa, the empirical equation was used to calculate
the volume convergence of the solution cavern. The upper limit of the pressure drop rate of gas production from gas storage was 0.54 MPa/day is approximately equal to the existing three-dimensional numerical simulation results.

(3). The volume convergence of the gas storage cavern mainly concentrates on the large-scale gas production and low-pressure gas storage. Increasing the internal pressure and shortening the gas production time have a significant inhibitory effect on the cavern volume reduction. While meeting the demand for natural gas, the emergency gas production time should be shortened as much as possible to avoid the long-term low-pressure gas storage state of the gas storage, and it can meet the stability requirements of the salt solution cavern volume convergence, effectively ensure the safe operation of gas storage and prolong the service life of gas storage.

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