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The Influence of the Water Injection Method on Two-Well-Horizontal Salt Cavern Construction

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Abstract

With high construction efficiency and large usable volumes, underground TWH caverns in rock salt formations provide optimal storage for large-scale compressed natural gas. Previous studies of SWV cavern construction indicate that different water injection methods will result in different leaching rates and will therefore form different cavern geometries. Therefore the influence of the water injection method on the TWH cavern construction process and geometries were thoroughly evaluated in this study. Based on the leaching numerical simulation code TWHS MC V2.0, we conducted a series of simulation experiments. The results illustrate that under the same water injection rate, the cavern construction speed of the alternate injection method is faster than the unidirectional injection method. Using the unidirectional method will form asymmetrical triangular pyramidal caverns. In contrast, using the alternate method will form symmetrical elliptical cone caverns. Under repeated alternating “Injection” and “Withdrawal” operations, the larger the flow rate, the shorter the cavern construction time, and the smaller the H/L ratio coefficient, as well as the closer the cavern geometry is to the horizontal cavern. Thus, during construction of a TWH-cavern in thinly-bedded rock salt (halite) deposits, repeated and alternating injections and withdrawals with high flow rates are necessary.

Keywords:

Compressed natural gas; Salt cavern; Two-well-horizontal; Water injection method; Injection direction; Flow rate

Abbreviations

TWH: Two-well-horizontal; TWV: Two-well-vertical; SWV: Single-well-vertical; CNG: Compressed natural gas; CAES: Compressed air energy storage; SWOB: Single-well-oil-blanket; SIMPLE: Semi-Implicit Method for Pressure-Linked Equations; VOF: Volume of Fluid; TWHS MC: Two-well-horizontal solution mining cavern; N-S: Navier-Stokes

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1. Introduction

Underground large-scale energy (CNG and CAES) storage is widely used in industrial gas grids [1, 2]. It acts as a buffer to balance out temporal differences between the production and consumption of gas, and has been successfully employed around the world for many decades [3, 4]. It is a key element of the present natural gas infrastructure worldwide. Underground gas storage can be divided into porous and cavern storage types. Porous storages typically consist of depleted natural gas or crude oil reservoirs. However, sometimes they can also be deep saline aquifers [5-8]. In contrast, cavern storages are usually artificially created salt caverns. The salt cavern is deeply buried in the ground at hundreds of meters to kilometers. The mechanical properties of rock salt are stable and its pressure bearing capacity is strong, which can adapt to the alternating changes in storage pressure. At the same time, the rock salt has a certain plasticity under high pressure, has the ability of self-healing, and has low permeability, which can ensure that the cavity is airtight. In addition, there are further advantages to using salt caverns for large-scale underground gas storage:

1) Economy—A CAES salt cavern cost is about $6 \sim 10 \text{ USD}/(\text{kW} \cdot \text{h})$ [9], and its investment is only about 1/10 of traditional surface tanks.

2) Space management—surface installations of UGS salt caverns are relatively minor. For example, when constructing a salt cavern with volume of $3 \times 10^5 \text{ m}^3$, the surface installation area does not occupy more than 100 m^2 ; in contrast, traditional surface tanks with a volume of $5 \times 10^4 \text{ m}^3$ need to occupy about $8 \times 10^4 \text{ m}^2$.

3) Mature technology—as a conventional large-scale gas storage technology, the salt cavern construction technology is well established and its construction method is simple and reliable. Moreover, the structural shape of a salt cavern can be controlled accurately to meet stability requirements.

4) Good sealing performance—rock salt has very low permeability and good creep properties, which can ensure cavern tightness. The gas leakage is only on the order of $10^{-6} \sim 10^{-5}$ of the total gas storage.

5) High storage pressure capacity—salt cavern gas storage is buried deep in the ground at hundreds of meters to kilometers, and can withstand higher gas storage pressures. The maximum gas storage pressure for the salt caverns of the Huntorf power station in Germany and the McIntosh power station in the United States are 10 MPa and 7.5 MPa, respectively. At present, the storage pressure of the Jintan salt cavern in China reaches 16.8 MPa. In addition, the rock salt does not react chemically with the compressed air and thus does not dissolve. It therefore does not affect the quality of the storage medium (air) [10].

6) Safety of storage—rock salt has stable mechanical properties and has a self-healing ability, which can adapt to variable storage pressure. Take the salt cavern of the Huntorf power station in Germany as an example, (beginning operation in 1978). After successfully running for more than 20 years, the shapes of the two salt caverns were determined in 2001. It was found that there had not been a significant change in shape since 1984 [11]. In this case, the volume shrinkage rate was $0.15\% / \text{a}$, the average sedimentation rate was 3.24 mm/a , and no gas leakage has been found. This fact fully demonstrates salt caverns reliability for compressed air energy storage.

During salt cavern construction using one or more wells, fresh water is injected into the rock salt formation in order to dissolve it. Brines are then pumped out, and a cavern gradually develops. The SWOB method is widely used across Europe to construct SWV and TWV caverns in thick rock salt deposits (for example, $\Delta Z > 500$ m in Germany) (as shown in Figures 1 and 2). However, China's bedded rock salt deposits are generally relatively thin (about 80–300 m), containing high impurities and interlayering. When using the SWV or TWV methods to construct a cavern, the span limit and height limit pose a great influence on cavern volumes. Therefore, a new salt cavern storage construction method, applying water solution mining with the TWH cavern method has been proposed [4, 12–14].

The TWH-cavern construction method adopts a two-well system (Figure 3) to dissolve the salt formation. The excavation process consists of (i) drilling vertical and horizontal well till the salt formations as well as inserting casing cement and inner tubing; (ii) connecting the two wells with directional installation technology; (iii) injecting fresh water through one inner tubing and extracting brine from another. The working mode of a TWH cavern (height $\ll$ length) is: when gas is withdrawn from Well A, a certain volume of brine is injected from Well B; when gas is injected from Well A, it withdraws a volume of brine from Well B. This is carried out in order to maintain a constant maximum cavern pressure. Because the internal pressure of the cavern is kept constant during the operation, the stress state of the cavern is similar to the static stress state of the host rock. Under the original stress state, potential risks can be avoided, such as volume loss of the cavern, the seepage caused by the large deformation, or the shear stress that may occur due to the large horizontal span of the cavern roof.

Figure 1. Schematic of SWV cavern constructed in salt domes

Figure 2. Schematic of TWV cavern constructed in salt domes

Figure 3. Schematic of TWH cavern constructed in bedded salt layer

The two-well system has been used in the past for the production of brine, regardless of the geometry of the resulting caverns. Of late, scholars have proposed this method to salt cavern construction engineering [15, 16]. The TWH-cavern construction method is a new technology in the field of salt cavern construction engineering, and is also one of the main technologies for new salt cavern construction going forward. Its advantages are as follows: i) short construction time—during the construction process, it has a larger injection/withdrawal flow rate and a higher efficiency. ii) large storage volume—it can form a larger volume cavern, plus the utilization efficiency of the salt mine formation is higher. iii) cavern geometry control—the

directional well can be a horizontal well or an inclined well, and the cavern shape control will be more flexible. Because the two-well system of salt mining focuses on excavating the salt resource, but the TWH cavern system focus on cavern construction, there will be operational differences. At present, TWH cavern construction technology draws on two-well system mining technology. Appropriate construction and operational parameters should be provided to guide on-site TWH cavern construction.

There have already been some studies on horizontal gas storage caverns. For example, Wei Xing studied the stability of a horizontal gas cavern in a Jintan salt mine. However, cavern geometry was not reported [14, 17]. Liu Wei built the framework and feasibility criteria to evaluate gas storage salt caverns by obtaining TWH-cavern shape using physical simulation tests. Nonetheless, they did not calculate the concentration nor the velocity fields [12]. Yang Chunhe developed a 3D geomechanical model of horizontal caverns, but did not provide information on the process of salt cavern construction [13]. These works revealed many important characteristics of horizontal caverns, while promoting their use. Still, key information on the its construction process, geometry expansion, and operation parameters were not reported, or were barely sufficient. To that end, the presently available technologies and theories are not established well enough to guide implementation of TWH-caverns in thinly bedded rock salt deposit regions.

There are two ways to inject water with the SWOB method [18]: (a) Direct brine circulation (as shown in Figure 4), where water is injected through the tubing while brine is removed through the annular space between the tubing and the final casing. In this method, the cavern geometry is more of a cylindrical shape with a slightly expanded lower section. (b) In the Reverse-circulation method (shown in Figure 5), water enters the cavern through the annulus, while brine is removed through the corresponding tubing. In this case, the cavern is typically wider at its top than at its base (which is often called “morning glory”). A history of constructing SWV caverns informs us that different water injection methods will result in different leaching rates and will form different cavern geometries. TWH cavern construction technologies with higher efficiencies are expected to play a critical role toward establishing cavern construction methodologies. In order to effectively explore the potential of this technology, it is necessary to study the influence of the water injection method on TWH cavern construction.

Figure 4. Direct circulation

Figure 5. Reverse circulation

Since the TWH cavern method has no practical applications to date, the influence of the water injection method on the TWH cavern is still unclear. Moreover, due to the difficulty of the actual measurement, in most cases, it is not enough to optimize the construction and operation. Lab experiments and numerical simulation techniques can be used to further explore the issue. While attempts have been made to unravel the law of cavern volume expansion by lab experiments [19, 20], lab experimental conditions are greatly affected by the environment; and data reproducibility and accuracy are both related to the experimental environment. Lab experiment approaches still pose some serious limitations when it comes to getting a precise brine concentration distribution and the cavern expands. The numerical simulation results are highly repetitive and not affected by the environment. Therefore, the comparative analysis of numerical simulation schemes ensures correspondence between process parameter changes and the resulting in flow/concentration changes [13, 21].

Based on a VC++ computer program (TWHSMC V2.0) [4], this paper conducts simulations under different water injection methods to investigate brine concentration changes, the construction rate, and the development of the cavern geometry. The simulation results reveal the influence of the water injection method and provide theoretical constraints for TWH salt cavern storage construction.

2. Theory and method

Application of dynamic analysis to describe 3D convection and diffusion processes, we obtained a viable mathematical model of solute transport for fluid flow solution mining processes. We achieved this by combining the basic theories of chemical kinetics and thermodynamics as well as fluid mechanics.

2.1. Assumptions

We propose the following general assumptions:

- (1) The influence of microstructure anisotropy on rock salt dissolution (e.g., stratigraphic dip, bedding, salt crystal direction, etc) was neglected.
- (2) Rock salt is considered to be free of cracks and fractures
- (3) Insolubles are considered fully precipitated. Therefore, their influence on diffusion is neglected.
- (4) Effect of the temperature differential is neglected.
- (5) There are anisotropic dissolution rates for the cavern wall.

Table 1. Anisotropic cavern dissolution rates in the [22]

Concentration(in g/l)	Dissolution rate(in $kg/m^2 \cdot h$)	
	Upper	Side
0	41.4	21.2
112	26.0	14
250	4.1	2.5

According to experimental results described above, dissolution rate formula for different directions was obtained by fitting corresponding formulas for the rates of upper (i) and side (ii) solutions as shown below:

$$\text{i) } \text{flux}|_{G_i} = -0.1496C + 41.88$$

$$\text{ii) } \text{flux}|_{G_i} = -0.0751C + 21.632$$

2.2. Fluid flow and mass transfer equations

(1) Continuity equation

According to the law of mass conservation and the Reynolds equation, the continuity equation can be expressed as

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

where $\mathbf{u}$ is the velocity vector.

(2) Momentum equation

The Navier-Stokes (N-S) equation formulates the fluid momentum as

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = \mathbf{f} - \frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{u} \quad (2)$$

where ν is kinematic viscosity, ∇P is pressure gradient, P is average dynamic pressure, and $\mathbf{f}$ is a unit mass force vector.

When the gravity is the only mass force, Equation (2) can be written as

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -g \nabla h - \frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{u} \quad (3)$$

where h is a vertical coordinate with the up-direction being a positive value.

(3) Concentration equation

Salt diffusion process in a solution can be explained by the convection-diffusion equation.

$$\frac{\partial C}{\partial t} + (\mathbf{u} \cdot \nabla) C = \nabla \cdot (D \nabla C) \quad (4)$$

where C is the molar concentration, and D is a diffusion coefficient.

(4) Auxiliary equation

During rock salt dissolution, as a result of the brine flow and solute diffusion, flue system concentration is always in flux—meaning that its density is also in flux. Thus, the relationship between density and concentration is expressed as

$$r = r_w + CM \left(1 - \frac{r_w}{r_s} \right) \quad (5)$$

where r_w and r_s are distilled water and rock salt densities, respectively, and M is rock salt molar weight.

2.3. Definite conditions

Equations 1–5 can only be solved by knowing the proper initial and boundary conditions, defined as follows:

(1) Initial conditions

Prior to the dissolution of rock salt, aqueous solution in at the rock salt boundary is stationary, thus, initial conditions can be defined as

$$V|_{t=0} = 0, C|_{t=0} = C_0 \quad (6)$$

(2) Boundary conditions

In the cavern wall Γ_1 , no-slip boundary condition is needed,

$$V|_{\Gamma} = 0 \quad (7)$$

the bottom surface of the cavern is impermeable,

$$\left. \frac{\partial C}{\partial n} \right|_{\Gamma_2} = 0 \quad (8)$$

the solution mining system is at constant formation temperature,

$$T|_{\Gamma=0} = T_0 \quad (9)$$

where C_0 is molar concentration of the aqueous solution in its initial state. and Γ_2 is bottom surface of the cavern.

In summary, the set of differential solution equations for rock salt dissolution model is obtained:

$$\begin{cases} \nabla \cdot u = 0 \\ \frac{\partial u}{\partial t} + (u \cdot \nabla)u = -g \nabla h - \frac{1}{\rho} \nabla P + \nu \nabla^2 u \\ \frac{\partial C}{\partial t} + (u \cdot \nabla)C = \nabla (D \nabla C) \\ \rho = \rho_w + CM \left(1 - \frac{\rho_w}{\rho_s} \right) \\ V|_{t=0} = 0; C|_{t=0} = C_0 \\ V|_{\Gamma} = 0; \left. \frac{\partial C}{\partial n} \right|_{\Gamma_2} = 0; T|_{\Gamma=0} = T_0 \end{cases} \quad (10)$$

2.4. Software implementation toward a numerical solution

Equation 10 shows the theoretical formulae for the cavern leaching process. Given the technical parameters and the values of the initial control variables, the cavern expansion boundary movement is solved by the VOF algorithm [23]. The velocity and concentrations field can be solved by the SIMPLE algorithm [24]. The CNPC Engineering Technology R&D Company (China) developed numerical simulation application code

called “TWH solution mining cavern” (TWHSMC V2.0) in order to provide a numerical solution to model TWH caverns [4]. Written in the VC++ language, TWHSMC V2.0 employs the finite volume method. Figure 6 shows the independent operation interface. There are five function modules in this code: i) formation information input, ii) input of technical parameters as well as calculations of iii) flow/concentration in the field, iv) cavern boundary and v) insoluble sediment.

Figure 6. Graphical User Interface of TWHSMC

3. Leaching scheme and primary factor analysis

In order to explore the influence of the water injection method for TWH cavern solution mining technology, in this section we simulate and analyze some cases regarding the construction of horizontal salt caverns in bedded salt formations.

3.1 Basic parameters

To study the influence of the water injection method under the premise of controlling variables, an idealized TWH cavern model is assumed. The typical basic parameters for the geometrical and physical properties are adopted, as shown in Figure 7 and Table 2.

Figure 7. Schematics showing calculation simulations

Table 2. Basic parameters of numerical calculations related to formation and construction

Formation parameters		Construction parameters		
Thickness	200 m	interwell distance	115 m	
Density	2,160 kg/m ³	Initial well depth	550 m	
Insoluble percentage	2%	Casing diameters	outer	244.5 mm,
			inner	177.8 mm

3.2 Water injection direction

In simulations 1 to 3, flow rate of 300 m³/h was chosen, the unidirectional injection method was conducted, where A is the injection well, and B is the withdrawal well. For Simulations 4 - 6, a flow rate of 300 m³/h was chosen, and the alternate injection method was conducted; meaning repeatedly alternating between “Injection” and “Withdrawal” operations. Technological parameters of the simulations are shown in Table 3.

Table 3. Technological parameters of the injection direction

Simulation No.	Injection direction	Injection rate (m ³ /h)	Alternate “Injection” and “Withdrawal” operations period (day)	Tubing/oil-blanket lifting period (day)
1	Unidirectional: A → B	300	0	30
2		300	0	50
3		300	0	100
4	Alternate: A ⇌ B	300	30	30
5		300	50	50
6		300	100	100

Notice: “A → B” indicates that A is the injection well, and B is the withdrawal well.

“A ⇌ B” indicates repeatedly alternating “Injection” and “Withdrawal” operations.

Figure 8 and Figure 9 show that when constructing a cavern with an objective volume of 300,000 m³ under an injection flow rate of 300 m³/h, the leaching time of Simulations 1, 2, and 3 (unidirectional method) are 386 days, 377 days, and 392 days, respectively; while the leaching time of Simulations 4, 5, and 6 (alternate method) are 339 days, 342 days, and 364 days, respectively.

Figure 8. Comparison of cavern volume expansion between unidirectional method and alternate method

Figure 9. Comparison of leaching time between unidirectional method and alternate method

The maximum leaching time of the alternate method is 13 days shorter than the minimum leaching time of unidirectional method under the same conditions, the difference between the two methods being thereby obvious. Because the repeated operations of alternate water injection direction make the brine concentration more uniform, this accelerates rock salt dissolution. Therefore, the cavern construction speed under the alternate method is faster than the other. The alternate method should be adopted in actual engineering, and the alternate frequency would be determined according to the working conditions. The alternate method is the option chosen for the present article.

3.3 Water injection rate

In simulations 7 - 14, flow rates of 100~500 m³/h were chosen and the alternate method was used. Water was injected from Well A to Well B for a period of 30 days, then the direction of water injection was reversed, and water was injected from Well B to Well A for 30 days. Technical parameters of the simulations are shown in Table 4.

Table 4. Technical parameters injection rates

Simulation No.	Injection direction	Injection rate (m ³ /h)	Alternate "Injection" and "Withdrawal" operations frequency (day)	Tubing/oil-blanket lifting frequency (day)
7	Alternate: A↔B	100	30	30
8		150	30	30
9		200	30	30
10		250	30	30
4		300	30	30
11		350	30	30
12		400	30	30
13		450	30	30
14		500	30	30

In the case of the alternate method shown in Figure 10, we can see that the cavity volume expands over time. In the initial stage, the cavern is filled with saturated brine. The brine concentration decreased corresponding to the injection of water; the surface area of the cavern also increased, thus the volume expansion rate increases over time. In the latter stage, the brine concentration tends to be stable (as shown in Figure 12), as well as the rate of cavern expansion.

Figure 10. Expansion of the cavern volume with the alternate method under different injection flow

Figure 11. Comparison of leaching time for different injection rates

In Figure 11 we also see that for the higher the water injection flow rate, the lower is the brine concentration in the cavern, and the shorter is the cavern construction time—as well as the faster the cavern volume increases. This indicates that the cavern volume development is sensitive to injection flow rate—the volume expansion rate increases proportional to the flow rate.

4. Evolution laws in leaching process

In this chapter we analyze brine concentration, cavern volume, cavern shape, and other results in numerical experiments. Next, the evolution laws of the leaching process are discussed, and some practical suggestions are given based on the geological setting of thinly-bedded rock salt deposits in China.

4.1. Analysis of brine concentration

We obtained the brine concentrations of the outlet and the concentration distribution in the cavern during the entire process. The results of Simulation 4 were taken as an example to analyze the changes of concentration distribution in the cavern.

Figures 12 and 13 show the concentration of the outlet at the end of each cycle under different injection methods. Figure 12 indicates that the concentration of the outlet using the alternate method is higher than using the unidirectional method. The injection direction is fixed under the unidirectional method; the high concentration of brine accumulates at the outlet of the withdrawal well, resulting in a relatively high concentration. Figure 13 shows that under the alternate method, the smaller the flow rate, the higher is the brine concentration. When the flow rate is 100 m³/h, the concentration is close to the saturation concentration for the whole process.

Figure 12. Comparison of instantaneous concentration between unidirectional method and alternate method

Figure 13. Instantaneous concentration of alternate method under different injection flow

Figure 14. Instantaneous concentration of Simulation 4

We can see that the variations of the concentration curves shown in Figure 12 and Figure 13 are very similar. Before the injection/withdrawal operation was carried out, the cavern was filled with a saturated brine (Figure 15—Day 0). When the injection/withdrawal operations were carried out, the injection of fresh water greatly reduces the brine concentration (from Day 0 to Day 30). After Day 30, the concentration continues to rise until it reaches saturation. From Day 30 to Day 120, the concentration of the outlet at the end of each cycle increased quickly. After Day 120, the concentration of the outlet growth trend slowed down (as shown in Figure 14). With the alternate operation, the average brine concentration in the cavern is low in the early period, leading to a high dissolution rate, so the brine concentration grows faster at first. In the latter period, the average brine concentration in the cavern is high after a long leaching duration, so the dissolution rate is suppressed.

Figure 15. Concentration distribution of Simulation 4

In accordance with the concentration distribution shown in Figure 15, near the injection well the brine concentration is very low because of the fresh water injection. With brine flows through the horizontal channel, the rock salt becomes progressively dissolved, meaning that the brine concentration correspondingly increases. At the wellhead of the withdrawal well, the solution tends to be saturated.

4.2. Analysis of cavern geometry

Figures 16 and 17 show the TWH cavern geometry results from numerical simulations under the unidirectional method. It is symmetrical at the beginning, and as the unidirectional method injection proceeds, the shape becomes more and more asymmetrical. Taking the final Figure 17 as an example, the injection well is 28.56 m wider than the withdrawal well in the bottom latitudinal direction, and 18.4 meters higher in the longitudinal direction. The cavern being dissolved is large near the water injection well. Dissolution at early stages occurs mainly around its sides. At later stages, dissolution starts to move up. Geometry of the injection/withdrawal well cavern becomes pyramid-like: wider at the bottom and narrower towards the top. Near the brine withdrawal well, the cavern construction rate is quite slow, which makes the cavern small. As a result, cross-section of the horizontal part gradually decreases.

Figure 16. Cavern profile of Simulation 1

Figure 17. Cavern profile of Simulation 3

After a long period of unidirectional injection, excessive dissolution may occur near the injection well. At the same time, solution cavern width may exceed its limit. This could provoke geological hazards such as ground subsidence or even complete collapse. Therefore, during TWH cavern construction, the cavern shape, oil-blanket depth, as well as the flow rate and concentration should be constantly monitored in real time. Moreover, operations related to withdrawal and injection should alternate based on the working conditions to create a dissolution cavern shape as even and optimum as possible.

Figure 18 and 19 show the TWH cavern geometries of the numerical simulations under the alternate injection method. Our simulations showed that TWH cavern shape on both sides of the injection/withdrawal wells is near symmetrical, and all have an elliptical cone geometry. In Figure 18, the average vertical height and length of cavern are 57.56 m and 162.56 m, respectively, so the height-to-length ratio (H/L) is 0.35. In Figure 19, the average vertical height and length of the cavern are 49.38 m and 168.14 m, respectively, making the height-to-length ratio (H/L) 0.29. Therefore, the higher the injection flow rate, the smaller the H/L ratio coefficient, which means that the cavern is closer to the horizontal.

Figure 18. Cavern profile of Simulation 4

Figure 19. Cavern profile of Simulation 14

It is also seen in Figure 18 Figure 19 that at higher flow rates the cavities at the injection and withdrawal wells tend to be symmetric. Also the height of the horizontal channel gets closer to the height of the cavern on both sides of the injection/withdrawal well. The reason is that the larger the flow rate, and the more uniform the concentration in the cavern, the closer is the degree of dissolution of rock salt on all sides, and the closer the cavity is to the horizontal.

4.3. Engineering recommendations

Unlike the thick salt domes and thickly bedded rock salt formations in Europe and USA [25], the rock salt stratum in Jintan Salt Mine (Jiangsu Province, China) mainly consists of thinly bedded rock salt layers [14]. Following nearly ten years of experience of salt cavern gas storage construction in Jintan area, we know that the salt layer thickness for the SWV-cavern construction must be >120 m [12]. Salt strata in Jintan region with thicknesses below 120 m occupy ~ 12.9 km², which accounts for 56% of the total region area. Therefore, performance of the SWOB method, which is more adequate for homogenous salt formations, gradually deteriorates. This method, in fact, might be even unsuitable for the thin salt rocks like those in Jintan region.

Based on the cavern geometry formation dynamics results obtained in this paper, which use alternating withdrawal and injection operations at 300 m³/h flow rate, the highest point of the cavern is 72.26 m (Figure 18). If the flow rate increases to 500 m³/h, the highest point of the cavern becomes 58.20 m (Figure 19). The height of the cavern is much smaller than the thickness of the salt rock. Therefore, a horizontal cavern, whose length is much greater than its height, is more effective and more profitable. Thus, it is applicable to the specific geological condition of thinly-bedded rock salt deposits in China [14].

5. Conclusions

The main results and conclusions obtained in the study can be summarized as follows:

1. Under the same water injection rate, the cavern construction speed of the alternate injection method is

faster than the unidirectional injection method.

2. Under the unidirectional injection method, the asymmetrical triangular pyramidal caverns are present on both sides of the injection/withdrawal wells; under the alternate injection method, the symmetrical elliptical cones caverns are present on both sides of the injection/withdrawal wells.

3. Under the alternate injection method, the larger the flow rate, the shorter the cavern construction period, and the smaller the H/L ratio coefficient, as well as the closer the cavern geometry is to the horizontal cavern.

Our results demonstrated that during TWH-cavern construction in thinly bedded rock salt regions, frequent alternations of withdrawal and injection operations, in addition to a high flow rate, are recommended.

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Highlights

In this article, we have summarized three highlights.

- 1) Based on the leaching numerical simulation program code TWHSMC V2.0, a series of numerical simulation were set up to investigate the influence of the water injection method for the first time. The concentration field and the 3D boundary movement of cavern expansion were solved.
- 2) The asymmetrical triangular pyramidal caverns are formed under the unidirectional injection method; while the symmetrical elliptical cones caverns are formed under the alternate injection method.
- 3) It was first discovered that cavity shape is sensitive to the water injection rate. Under the alternate injection method, the larger the flow rate, the closer the cavern geometry is to the horizontal cavern.