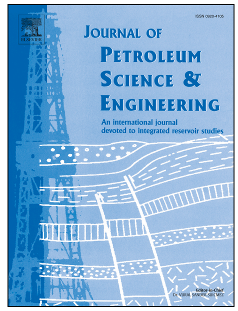

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Numerical Model and Program Development of TWH Salt Cavern Construction for UGS

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Abstract

Underground TWH caverns in salt rock have high construction efficiency and large usable volumes and provides an ideal space for large-scale natural gas storage. In this study, the solution mining process of TWH cavern is thoroughly analyzed. Applying basic principles of the Navier-Stokes equation method and reasonable assumptions, we established a new 3D mathematical model which includes flow and mass transfer and boundary movement for TWH salt cavern construction. Then, the velocity field and the concentration field can be solved by the SIMPLE algorithm, while the boundary movement of cavern expansion can be solved by the VOF algorithm. We developed a new VC++ computer code program TWHSMC for solution mining and herein we present the numerical results. Finally, the simulation cavern shapes results by program are compared with the experimental ones. The results indicate that our model successfully and accurately predicts the cavern shape and demonstrates the reliability and applicability of the model.

Keywords:

Underground gas storage; Two-well-horizontal cavern; Numerical model; Program development; Cavern expansion

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Abbreviations

UGS:	Underground gas storage
TWH:	Two-well-horizontal
TWV:	Two-well-vertical
SWV:	Single -well-vertical
2D:	Two dimensional
3D:	Three dimensional
SIMPLE:	Semi-Implicit Method for Pressure-Linked Equations
VOF:	Volume of Fluid
TWHSMC:	Two-well-horizontal Solution Mining Cavern
CFD:	Computational Fluid Dynamics
N-S:	Navier-Stokes

1. Introduction

Because of its low permeability and good self-healing capacity, salt rock is recognized as an ideal medium for large-scale energy high capacity storage (Yang et al., 2015) such as strategic petroleum reserves (SPR) (Liu et al., 2016; Zhang et al., 2017), compressed air energy storage (CAES) (Aghahosseini and Breyer, 2018; Budny et al., 2015; Wang et al., 2016; Wang et al., 2018), hydrogen energy storage (Le Duigou et al., 2017; Ozarslan, 2012; Slizowski et al., 2017b),and particularly natural gas storage (Liu et al., 2018; Wang et al., 2013).

The usage of natural gas resources strongly fluctuates according to the season, while the gas well production is stable(Arfaee and Sola, 2014; Lawal et al., 2017). To balance the mismatch in gas supply and demand, in recent years, some countries have addressed the construction of large-scale storage caverns in salt rock formations (Evans and Chadwick, 2009; Le Duigou et al., 2017; Michalski et al., 2017; Parkes et al., 2018; Shi et al., 2017; Slizowski et al., 2017a). An appropriate leaching method is the key to successful construction of salt cavern gas storage. As it determines whether the cavern can meet the requirements of underground gas storage as well as the construction time of the salt cavern UGS, so it always the primary considered issues.

When the conventional single-well-oil-blanket method was used for the construction of a SWV cavern in salt formations, the construction efficiency is low and the usable volume of the cavern is small. To overcome the restrictions of SWV-cavern, two-well leaching method is proposed to cavern construction in the thinly bedded salt rocks. Based on the connecting method and the interwell distance, the two-well system leaching technology can be divided into TWV cavern technology and TWH cavern technology(Ban, 2017),as shown in Fig. 1 and Fig. 2.

The TWV cavern consists of two vertical wells. The wells are connected by the leaching method. This technology has already had engineering cases, such as the TA&TB UGS in Manosque, France (De Laguérie and Cambon, 2010) and the Zuidwending UGS in the Netherlands(WILKE et al., 2011).In contrast to the SWV cavern method, the construction rate of TWV cavern method is faster in the early stage. In the later stage, the cavern construction rate of these two methods are similar. Moreover, it is difficult to control the cavity shape with the TWV cavern method, especially for thinly-bedded salt formations with a low halite purity; and it is also difficult to build a larger volume cavity using the TWV cavern method (Jiang et al., 2016a).

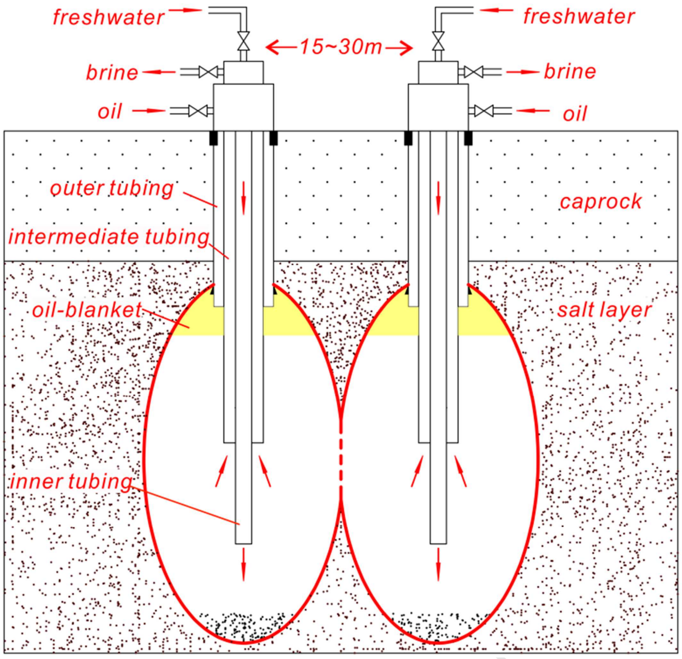


Fig. 1. Two-well-vertical (TWV) cavern

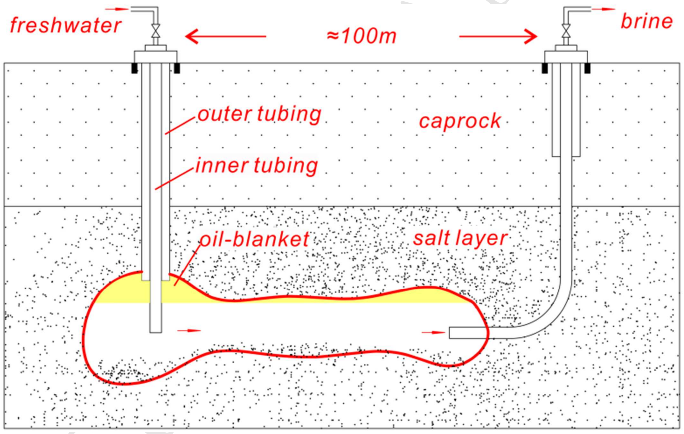


Fig. 2. Two-well-horizontal (TWH) cavern

The TWH cavern is constructed using a two-well system. The process consists of the following steps: (i) drilling a vertical well and a horizontal well to the target salt formation, plus casing cementing and the installation of the inner tubings. Then, directional installation technology is used to connect the two wells; (ii) injecting fresh water from one inner tubing and extracting brine from the other (Liu et al., 2018). The TWH cavern method can fully utilize the salt formation and allows for the construction of a larger cavity. In contrast to SWV cavern and TWV cavern, TWH cavern has several distinct advantages, such as higher adaptability to thin-bedded salt rocks, faster rate for cavern construction, higher flexibility of operation, and lower stock of cushion gas. This method was predominantly adopted for salt mining. In recent years, scholars have proposed the application of this method to UGS construction (Bowen and Priestly, 1967; Russo, 1995). Until now, the sonar surveying technique has been unable to measure a horizontal cavern's shape. Some researchers have conducted physical simulation experiments to study the process of cavity expansion, but it is difficult to get a precise distribution of the velocity field and brine concentration field (Jiang et al., 2016a; Jiang et al., 2016b). Therefore, numerical simulation becomes an alternative way to obtain the solution mining process for TWH caverns.

Since the 1960s, great progress has been made in the field of numerical simulation of solution mining for UGS (Kunstman and Urbanczyk, 2000). For instance, a series of commercial cavern leaching simulation codes have been developed. The algorithm can be divided into two categories: floating plume (SANSMIC) (Russo., 1983) and balance principle(WinUbro) (Kunstman and Urbanczyk, 2009).

Floating plume: In the floating plume method, the dissolved area is divided into four regions by the floating plume algorithm according to the flow characteristics (boundary layer region, main dissolution region, floating plume region, and dead water region). Concentration distribution and cavern expansion in each region are calculated by different mathematical models. In the algorithm turbulence is taken into account, the concept of floating plume is introduced, and the calculation is simplified when combined with the engineering. However, the region division is too dependent on experience, it is more arbitrary, and with the change of the cavern shape, the region division needs to be manually adjusted.

Balance principle: In the balance principle method, the brine concentration field is simplified into a horizontal layered distribution according to the balance principle algorithm. The cavern shape is corrected through the mass conservation equation. Cavern expansion calculation can be quickly achieved, and the results are corrected by a solution mining balance calculation. However, here the concentration field is simplified and a large number of experimental data are in fact needed for solve the cavern expansion.

Table 1 Differential salt cavern leaching simulation codes

Algorithm	Floating plume	Balance principle	N-S equation
Representative code	SANSMIC (For 2D SWV)	WinUbro (For 2D SWV)	Did not exist before
Development team	Sandia	Chemkop	Did not exist before

Computing method	1) The cavern is divided into four regions according to its flow characteristics. 2) Each region is calculated by a different mathematical model.	1) The concentration field is simplified into a horizontal layered distribution. 2) The cavern shape is corrected using the mass conservation equation.	1) Classical calculation method for fluid mechanics. 2) Based on the basic physical principles.
Advantages	1) Turbulence is taken into account. 2) Combined with engineering, the calculation is simplified.	1) The cavern expansion calculation can be quickly achieved. 2) Results are corrected using balance calculation.	1) With the good generality, the flow-mass transfer in each area and stage can be described effectively and uniformly. 2) Beside the basic physical parameters of rock salt, no empirical data are required. 3) Can provide more refined results for more variables.
Disadvantages	1) Region division is too dependent on experience. 2) With the cavern shape change, region division needs to be adjusted manually.	1) Concentration field is simplified and a lot of experimental data are needed to solve the cavern expansion.	1) Geometric modeling and meshing are more complicated. 2) A dense grid and more complex equations lead to greater computing resource consumption and longer calculation time.

As shown in the Table 1, the existing commercial codes based on the floating plume method and the balance principle method are only applicable to the 2D simulation of the SWV cavern working condition. However, during the leaching process of the TWH cavern in thin salt beds, both the geometry and the mass transfer process are more complex, thus, until now there has been no commercial code applicable to the leaching process of TWH caverns.

The N-S equation method is the classical calculation method for fluid mechanics. Based on basic physical principles, the flow mass transfer phenomenon is described for the entire cavern in the actual 3D area without artificial zone division. The 3D calculation ability and the uniform processing of this method in space avoid deviations from geometric simplification and geometric partitioning. It can effectively describe the flow and mass transfer for each area and stage effectively and uniformly. The N-S equation method is based on the basic principle of flow and mass transfer, thus the physical picture of the calculation is clearer. And no empirical data is required, while more refined results for more variables can be provided. In principle, we can use the N-S equation to describe flow and mass transfer as well as the boundary movement problem without any constraints. At the same time, the 3D computational domain and 3D discretization required by the method lead to complicated geometric modeling and meshing. And there are a large number of equations need to be solved, so more computing resource and longer calculation time is required.

During the construction of salt cavern UGSs, the shapes of the caverns are always the primary issues considered. However, FLUENT, CFX and other CFD codes (Fluent, 2012) are professional commercial software packages based on the N-S method, only used in the flow simulation under a fixed cavity shape. Thus, these CFD codes cannot describe the movement of the boundary of the cavern, they are not competent to simulate the cavity dissolution process.

For the further development of the TWH salt cavern gas storage, in this study, based on the basic principles of the N-S equation method and using some reasonable assumptions, we established a 3D mathematical model of the flow-mass transfer and boundary movement. We developed a VC++ computer code program (TWHSMC) that provides a numerical solution of the model, in addition to the velocity field, brine concentration field, cavern volume and cavern shapes. We selected an engineering case and the leaching process is simulated by the developed program. The comparison of the simulation results with the experimental data demonstrates the validity and accuracy of the proposed model. This study reveals the characteristics of the TWH cavern leaching process and supplies theoretical useful guidance for TWH salt cavern storage construction.

2. Methodology

The dissolution process of rock salt is the transport process of solute in the solvent flow system. This process is a complex fluid dynamics and chemical kinetics process. Based on the dynamic analysis of the 3D convection and diffusion process, combined with the basic theory of fluid mechanics, chemical kinetics, and thermodynamics principles, a mathematical model of solute transport and fluid flow in the process of solution mining can be established. In this way the mechanism of dissolving rock salt can be studied.

The dissolution process of rock salt is actually the diffusion process of rock salt molecules in water. The diffusion effect was produced by gradient change in concentration. The molecules spread from the high concentration area to lower concentration area depending on thermal motion, and finally tend to wards equilibrium. The diffusion occurs even when there is no macro flow.

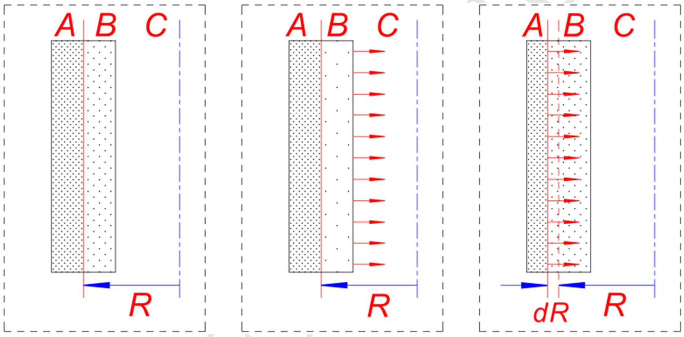
The dissolution process and diffusion process of salt in brine is consistent with the dissolution mechanism of rock salt. For convenience, the dissolution process of salt rock can be simplified as follows: As shown in Fig. 3, the salt molecules dissolve from the solid rock salt into the diffusion zone through the boundary layer, and the total amount of substances in the boundary layer has always maintained the dynamic balance between dissolution and diffusion.

As such, the dissolution process can be divided into the following 3 steps:

(1) The rock salt molecules in the boundary layer diffuse into the flow field, decreasing the concentration of the boundary layer.

(2) The solid rock salt wall's surface dissolves, and the rock salt molecules then enter the boundary layer to replenish its substantial loss, so such the concentration of the boundary layer is compensated by rising again.

(3) Due to the dissolution of salt solid wall, the wall (along with the attached boundary layer) recedes a small distance dR.



A. solid salt wall B. boundary layer C. diffusion region

Fig. 3. Sketch of salt rock dissolving process

In this section, the control equations of fluid flow and mass transfer are derived, as well as the equations for the development of the cavern boundary. In this way, we propose the definite solution conditions and solving algorithm of the mathematical model. Based on the model and the algorithm, we created a software program for TWH solution mining.

2.1. Assumptions

In previous studies on numerical simulations of solution mining for UGS, the problem was simplified for the calculation, and the assumptions have generally been proposed as follows(Ban et al., 2006; Zhicheng et al., 2004):

(1) The influence of microstructure anisotropy (stratigraphic dip, salt crystal direction, bedding,

etc.) on the rock salt dissolution process is neglected.

(2) Insolubles are 100% precipitated and their effect on diffusion is neglected.

(3) The influence of temperature difference is neglected.

(4) The cavern structure is axisymmetric and a two-dimensional model is adopted.

(5) The concentration of the boundary layer is saturated.

(6) Concentration and density are the unary functions of height.

In the simplification of this mathematical calculation, each additional assumption increases the deviation from reality. In order to enhance the practicability and accuracy of the program, the mathematical model of this study minimizes these assumption, and only assumptions (1)–(3) are retained. Every cancellation of an assumption is therefore relatively progressive and innovative.

In this study, a 3D model was used to achieve a true geometric simulation, and the distributions of the velocity field and the concentration field were solved directly. Assumptions were corrected as follows.

(1) The influence anisotropy on the microstructure on the rock salt dissolution process is neglected, such as stratigraphic dip, salt crystal direction, bedding, etc.

(2) Insolubles are 100% precipitated and their effect on diffusion is neglected.

(3) The influence of temperature difference is neglected.

2.2. Fluid flow and mass transfer equations

The governing equations of flow, mass transfer and dissolution during the solution mining process are as follows:

(1) Continuity equation

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

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

Where u is the speed vector.

(2) Momentum equation

According to the N-S equations, the fluid momentum equation can be written as

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

where ν is the kinematic viscosity, ∇P is the pressure gradient, P is the average dynamic pressure, and f is a unit mass force vector.

When the mass force is only gravity, equation (4.2) can be written as

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

where h is the vertical coordinate (upward is positive).

(3) Concentration equation

The dissolution process of rock salt is actually the diffusion process of rock salt molecules in solvent. It can be described by the convection-diffusion equation.

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

Where C is the molar concentration, and D is the diffusion coefficient.

(4) The diffusion can be described by Fick's first law of diffusion,

$$J=D\frac{\partial C}{\partial \vec{n}} \tag{5}$$

Where J represents the diffusion flux. That is, the mass flow of matter through a unit area perpendicular to the normal direction. $\vec{n}$ is normal vector.

(5) Auxiliary equation

In the dissolution process of rock salt, due to the flow of brine and solute diffusion, the concentration of the fluid system is constantly changing—so the density is also changing. The relationship between density and concentration can be thus written as.

$$\rho=\rho_w+CM\left(1-\frac{\rho_w}{\rho_s}\right) \tag{6}$$

Where ρ_w represents the density of distilled water. The variable ρ_s represents the density of rock salt, and M represents the molar mass of rock salt.

2.3. Mathematical model of boundary movement

As the rock salt dissolves, its boundaries move toward the interior of the solid domain(away from the solution). The dissolution rate model in this section relates the dissolution rate and the rock wall direction to the brine concentration. Based on the model, the moving speed of rock salt wall boundary can be quantified. Referring to the VOF method in the CFD simulation of the two-phase flow, this study proposes a numerical algorithm based on the finite volume method for boundary movements, which computes the numerical solution of the rock wall boundary movement using a fixed grid.

Our analysis of the characteristics of fluid transport in the mining salt cavern solution, reveals that the rock salt dissolution process manifests as the exchange of matter in the boundary layer. The basic process is molecular diffusion. Under the action of diffusion, the salt molecules dissolved from the wall's surface enter the solution through the boundary layer. The rate of molecular diffusion is also related to the concentration of the boundary layer.

The relationship between dissolution rate and concentration of boundary is

$$flux\big|_{\Gamma_1} = k\left(C_s - C\right) \tag{7}$$

During the process of solution mining, the dissolution rates of rock salt are divided into rate for the upper solution, side solution and bottom solution. Considering insoluble deposition at the bottom, we assume the bottom solution rate to be zero.

Table 2 Anisotropic dissolution rates in the cavity (Xue, 1994)

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

According to the above experimental results, the dissolution rate formula for different directions was obtained by fitting:

1) Formula for the rate of upper solution: $flux\big|_{\Gamma_1} = -0.1496C + 41.88$

2) Formula for the rate of side solution: $flux\big|_{\Gamma_1} = -0.0751C + 21.632$

C_s is the saturation concentration of brine, Γ_1 represents the surrounding sidewall (the upper and side surfaces only) of the cavern,

2.4. Definite conditions

The above equations can only be solved with the proper initial and boundary conditions. According to the engineering, the definite conditions can be defined as follows.

(1) *Initial conditions*

Before the salt dissolution, the aqueous solution that makes contact with the rock salt boundary is stationary, so the initial conditions can be expressed as

$$V\big|_{t=0} = 0, C\big|_{t=0} = C_0$$

(2) *Boundary conditions*

For Γ_1, there is a no-slip boundary condition,

$$V\big|_{\Gamma} = 0,$$

the bottom surface of the cavern is impermeable,

$$\left.\frac{\partial C}{\partial n}\right|_{\Gamma_2} = 0,$$

And the solution mining system is considered to have a constant formation temperature,

$$T\big|_{\Gamma=0} = T_0.$$

where C_0 represents the molar concentration of the aqueous solution in the initial state. Γ_1 represents the surrounding wall of the cavern, and Γ_2 represents the bottom surface of the cavern.

2.5 Numerical algorithms

In this calculation, we used the SIMPLE Algorithm for flow and mass transfer and the Boundary Movement Algorithm based on VOF.

2.5.1 The SIMPLE Algorithm

The SIMPLE algorithm is a numerical method primarily used to solve incompressible flow fields. Its core advantage is to use the process of "guess-correction" to calculate the pressure field on the basis of the staggered grid, so as to solve the momentum equation (N-S equations). The calculation process is shown in Fig. 4.

2.5.2 Boundary Movement Algorithm

The basic principle of the VOF method is to determine the solid-liquid interface and track the change of the fluid by studying the mesh volume ratio function F of the fluid in the grid unit. The VOF method defines this function for the entire flow field. In each grid, the function is defined as the ratio of the volume of a fluid (the target fluid) to the volume of the grid.

Assuming that the calculation area is recorded as Ω, the area where the fluid is recorded as Ω^A, the area where solid is recorded as Ω^B, then $\alpha(\vec{x},t)$ is defined as a function,

$$\alpha(\vec{x},t)=\begin{cases}1 & \vec{x}\in\Omega^A \\ 0 & \vec{x}\in\Omega^B\end{cases} \tag{8}$$

where, $\alpha(\vec{x},t)$ satisfies the characteristics of the Lagrangian fluid volume,

$$\frac{\partial\alpha}{\partial t}+u\frac{\partial\alpha}{\partial x}+v\frac{\partial\alpha}{\partial y}+w\frac{\partial\alpha}{\partial z}=0 \tag{9}$$

$$F_{ij}=\frac{1}{\Delta V_{ij}}\int_{I_{ij}}\alpha(\vec{x},t)dV \tag{10}$$

where ΔV_{ij} is the volume of a single grid. F_{ij} is defined as the integral of $\alpha(\vec{x},t)$ for each grid, I_{ij}.

The above formula is a VOF function, and it also satisfies:

$$\frac{\partial F}{\partial t}+u\frac{\partial F}{\partial x}+v\frac{\partial F}{\partial y}+w\frac{\partial F}{\partial z}=0 \tag{11}$$

It can be seen from the above that the volume function for each fluid is essentially:

$$F=\frac{Fluid\ volume\ in\ the\ grid}{Grid\ volume}$$

Obviously, when $F=1$, the grid is filled with fluid A, which we call *fluid grid*. When $F=0$, it is solid grid. When $0<F<1$, it is a grid with a fluid interface called an *interface grid*.

According to the distribution of the *F* function over the whole calculation domain, the solid-liquid interface (i.e., the cavity contour) can be obtained by constructing the isosurface of the *F* function. Then, when solving the physical equation, special fine processing can be performed near the interface to improve resolution and accuracy. Since each grid only needs to store one F value, it can greatly reduce the amount of storage.

The Boundary Movement Algorithm consists of two steps: first, calculating the boundary movement of the top and side surfaces caused by the dissolving the rock salt, and secondly, calculating the bottom surface boundary movement caused by the insoluble substance deposit at this stage.

(1) *Calculation process of solid wall grid dissolution*

This process defines the amount of dissolution for current solid wall to be dV per day; a single mesh volume is V. If $dV \le V$, the mesh boundary moves. If $dV > V$, the current mesh dissolution is complete and hence dissolves the next layer in all directions. The calculation process is shown in Fig. 5.

In the dissolution process of the solid wall, the changes of various mesh types and VOF functions can be divided into several stages as shown in Fig. 6.

(2) *Calculation process of the insoluble substance deposit*

This process defines the total volume of insoluble substance of the fallen solid wall as Vs, while the total volume of fluid in the current layer of the solid wall grid is V_f. When $V_s \le V_f$, all solid wall grids in this layer move synchronously. When $V_s > V_f$, it indicates that the grid of the current layer is filled, and that the next layer will also be filled until all insoluble substances have settled. The calculation flowchart of the insoluble substance deposit is shown in Fig. 7.

2.6. Program development

Based on the continuity equation, momentum equation, convection-diffusion equation, Fick's first law of diffusion equation, the auxiliary equation, and the definite solution conditions, the final governing partial differential equations of the solution mining model are obtained.

As the numerical model was established, the numerical solution was performed on a computer. For this purpose, the numerical simulation application code "TWH solution mining cavern", "TWHSMC" for short, of the TWH cavern is developed to solve the numerical solution of the model. Using the finite volume method, TWHSMC was written in the VC++ language. The flowchart of the program is shown in Fig. 8 and Fig. 9, and the independent operation interface is shown in Fig. 10. There are five function modules in TWHSMC: a) formation information import, b) technical parameter input, c) flow/concentration field calculation, d) cavern boundary calculation, and e) insoluble sediment calculation.

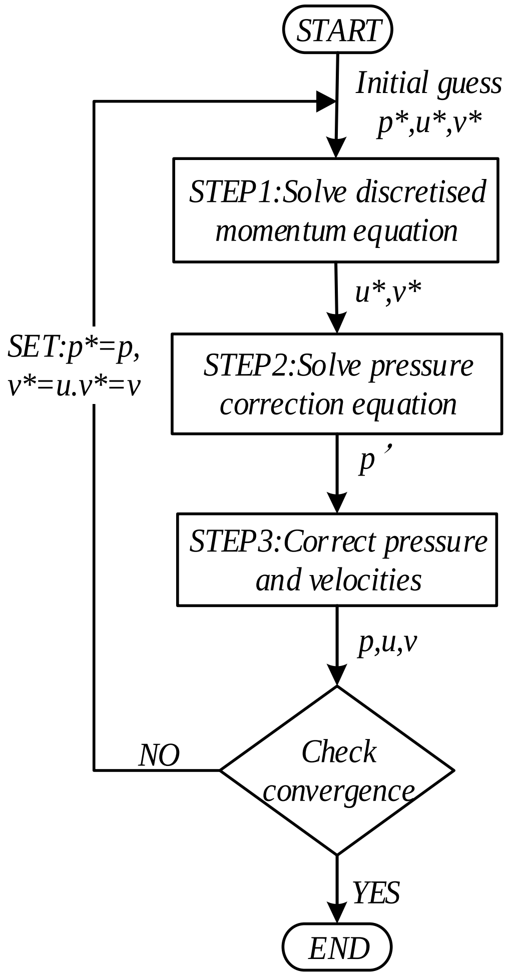


Fig. 4. Flow chart of the SIMPLE algorithm

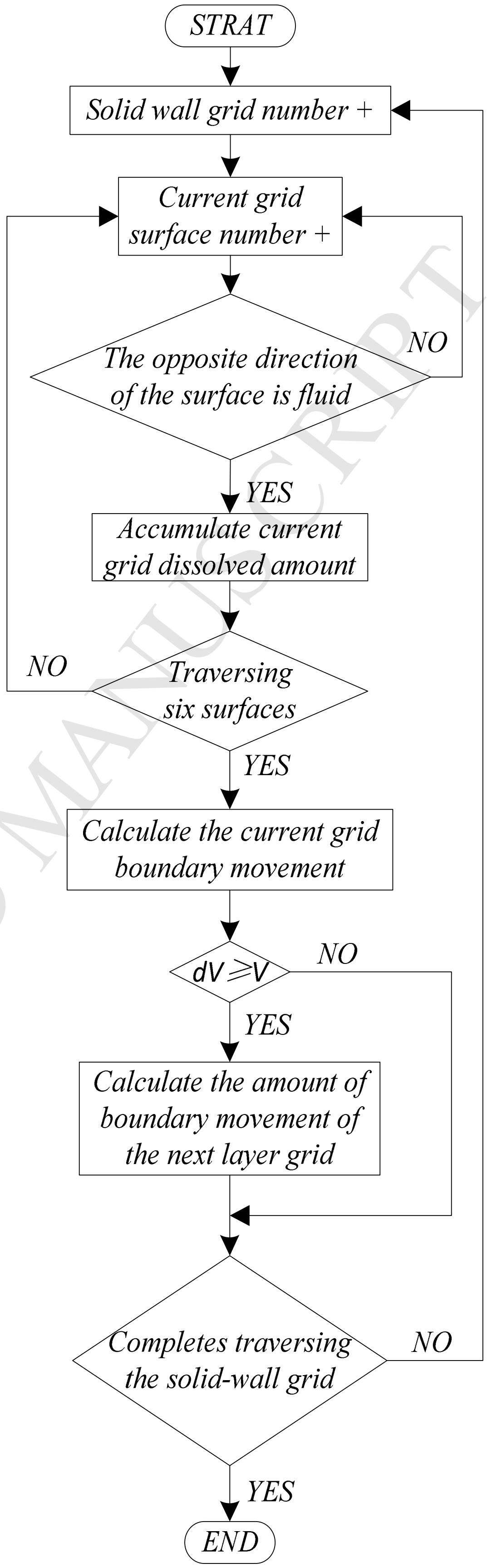


Fig. 5. Calculation flowchart for solid wall mesh dissolution

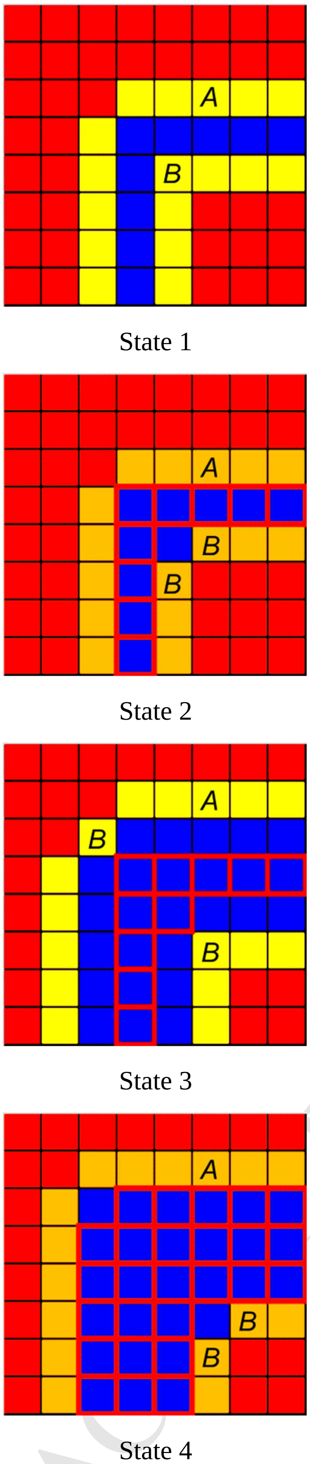


Fig. 6. Changes of various mesh types

Notice: the dark red grid represents the solid area. The dark yellow grid represents the solid wall with a large VOF value. The pale yellow grid represents the solid wall with a small VOF value. The blue area represents the fluid. The dark red wireframe represents the fluid area in the previous step.

Fig. 7. Calculation flow chart of insoluble substance deposit

Fig. 8. Flowchart of pre-processing

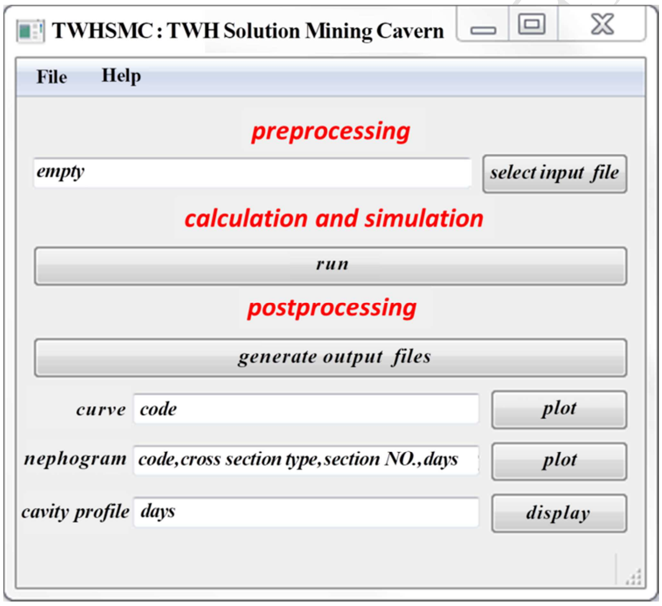


Fig. 10. Program graphical user interface

Fig. 9. Flowchart of the simulation of cavern leaching by TWHSMC

3. Case study and results

In this sectionwe s, imulate the leaching process of a complete salt cavern, using reasonable geological and technological parameters, and then compare the simulation results with the cavern shape of the physical experiment to verify the model.

3.1. Computational case

We assume an idealized TWH cavern model, in which the values of the geometrical and physical properties of the reservoir are referenced from the values employed in previous numerical studies on typical rock salt UGS projects(Ban et al., 2006; Zhicheng et al., 2004), as shown in Fig. 11 and Table 3.

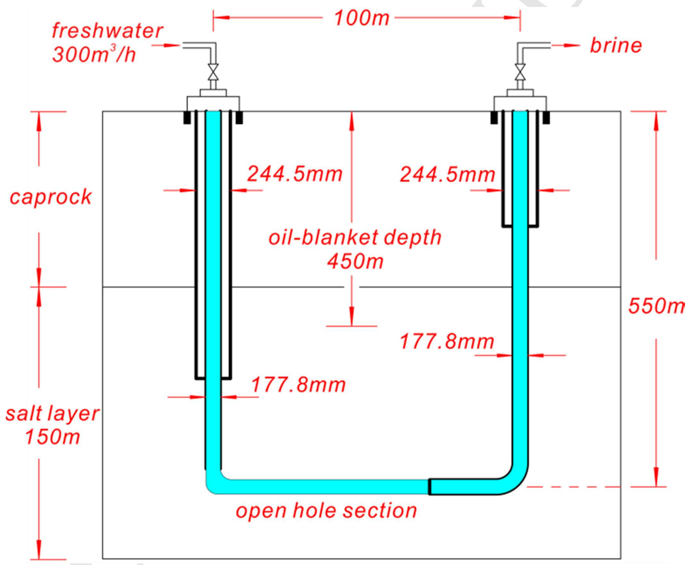


Fig. 11. Schematic diagram of the calculation case

Table 3 Basic parameters of numerical experiments

Formation parameters		Geometry parameters			Working condition		
Thickness	150m	Interwell distance		100m	Oil-blanket depth		450m
Density	2163 kg/m^3	Initial well depth		550m	System temperature		45□
Insolubles expansion coefficient	1.2	Casing diameters	Outer	244.5mm	Water injection	Method	One-way
Insolubles percentage	15%		Inner	177.8 mm		Flow rate	300m^3/h

3.2. Velocity distribution

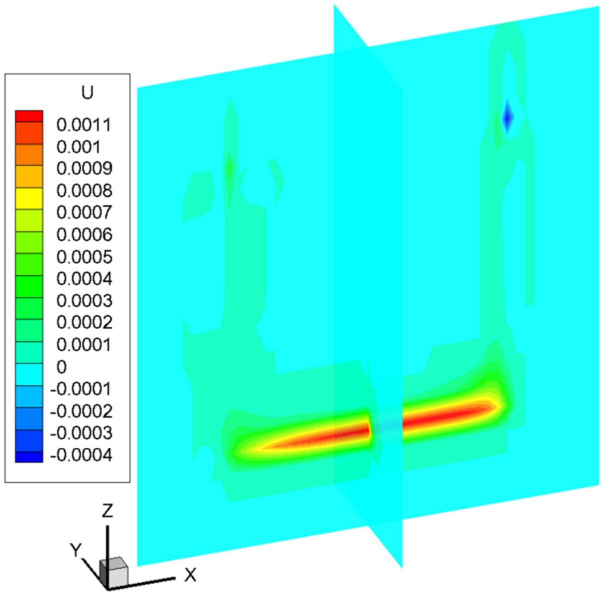


Fig. 12. t= day 100, X-direction velocity distribution

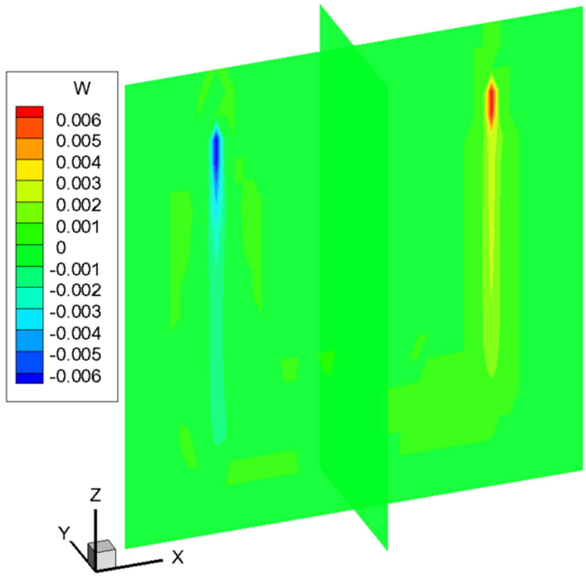


Fig. 13. t= day 100, Z-direction velocity distribution

As shown in Fig. 12, the horizontal well section has a strong flow from injection well to withdrawal well, driven by the pressure differential between them.

3.3. Concentration distribution

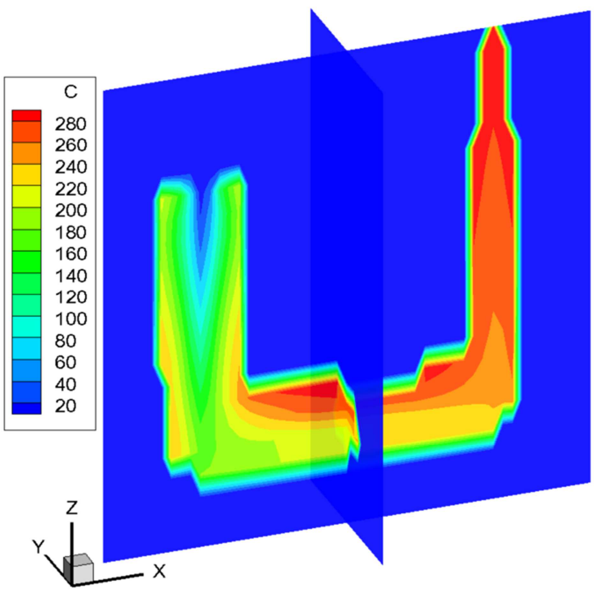


Fig. 14. t= day 100, concentration distribution

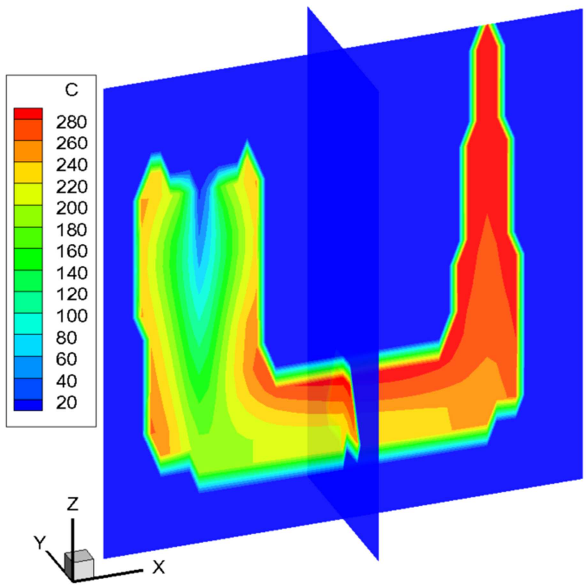


Fig. 15. t=day 200, concentration distribution

According to the concentration distribution (Fig. 14 and Fig. 15), near the injection well, the rock salt that dissolves is mainly near the dissolution starting point. The concentration distribution of brine is affected by gravity, so the deeper brine have higher concentrations. Thus, the brine that squeezes into the horizontal well section has a higher concentration, reducing the dissolution. During the flow in the horizontal channel, the brine concentration continues to increase, and it tends to be saturated when reaching the wellhead of the withdrawal well.

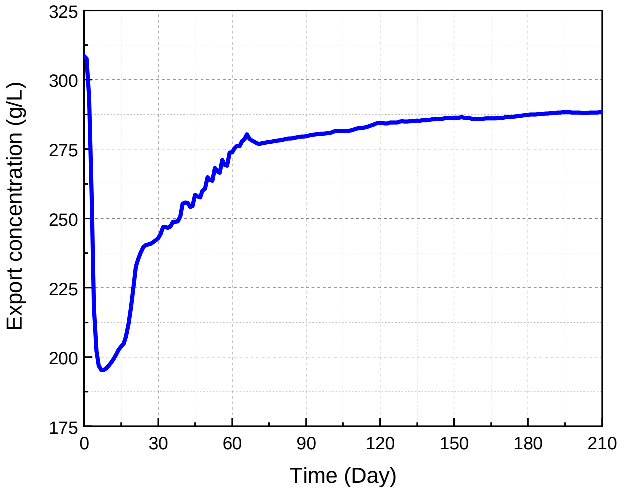


Fig. 16. Concentration-time curve of the numerical simulation

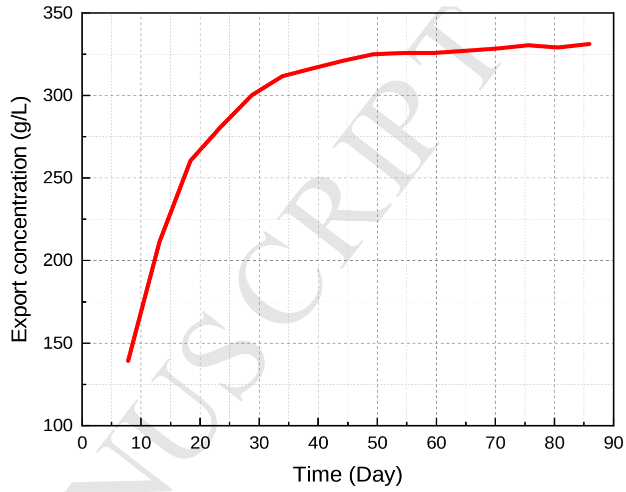


Fig. 17. Concentration-time curve of the experimental simulation(Liu et al., 2017)

Comparing the numerical simulation results(Fig. 16) with the experimental result(Fig. 17) (Liu et al., 2017), under similar conditions, we see that the numerical simulation for the concentration-time curve of the withdrawal well is consistent with the experimental one, hence supporting the validity of the code.

Due to the brine in the carven is saturated in the initial state, the brine of export has a higher concentration. With the injection of fresh water, the concentration in the chamber gradually decreases, and the outlet concentration dropped to about 200 g/L. And then export concentration rises rapidly and gradually stabilizes. This is because the initial dissolution area of the TWH cavern is relatively large. When the concentration reaches a certain level, the concentration growth rate slows down and the curve tends toward the horizontal, indicating that the water injection flow rate and the dissolution rate are near equilibrium. That is, high concentrations protect the deeper rock salt from over-dissolving.

3.4. Numerical process of cavern expansion

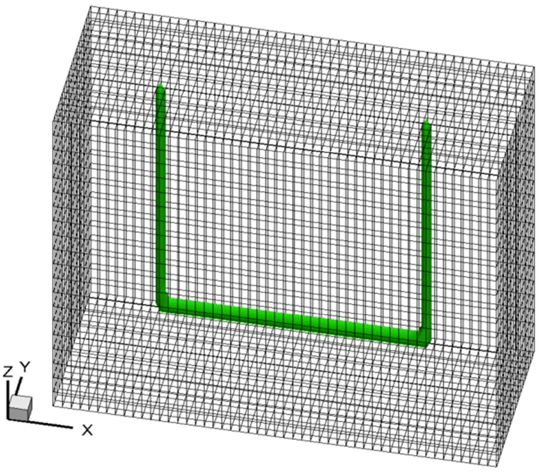


Fig. 18. Initial shape of cavern

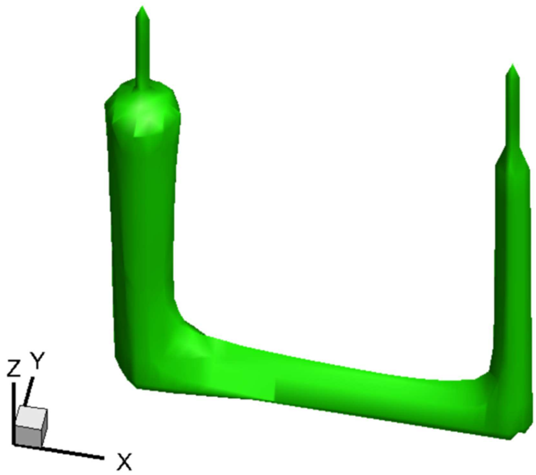


Fig. 19. Cavern shape, t= day 50

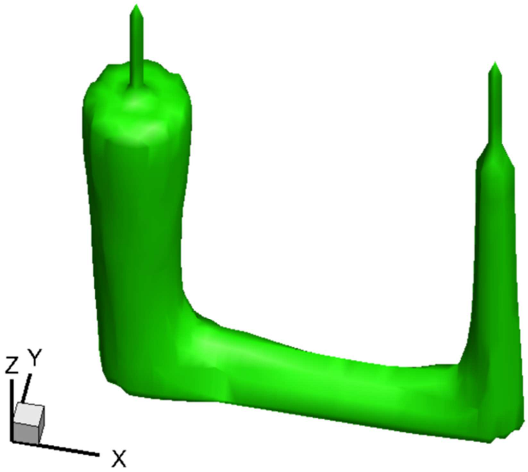


Fig. 20. Cavern shape, t=day 100

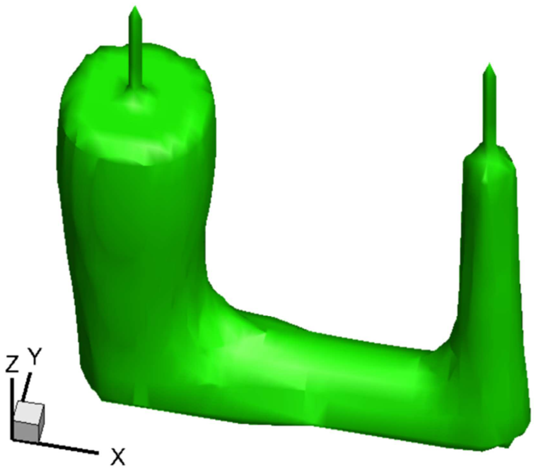


Fig. 21. Cavern shape, t=day 200

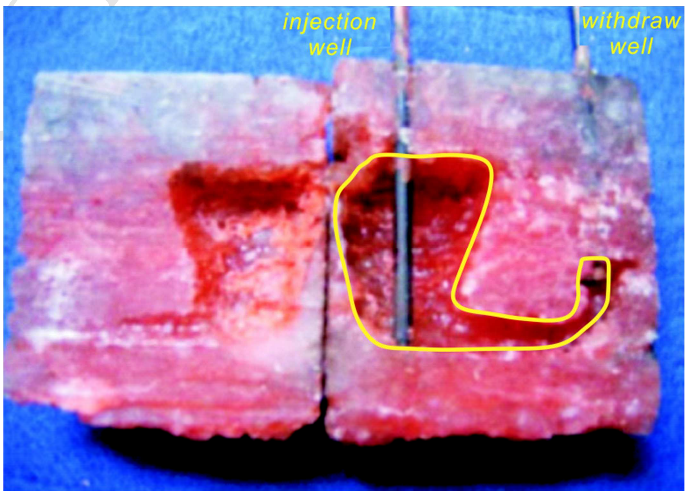


Fig. 22. TWH cavern shape of experimental simulation under one-way water injection(Zheng et al., 2018)

The Fig. 22 shows the TWH cavern cross-sectional shape for the experimental simulation under one-way water injection(Zheng et al., 2018). The numerical cavern shapes agree with the experimental simulation, indicating that the numerical simulation method is effective.

The results of the numerical simulation and experimental simulation, show that the TWH cavern shape under one-way water injection is very asymmetric. Near the water injection well, the dissolving cavity is large, and it mainly dissolves upwards in the early stage, and only dissolves the surrounding sides in the later stage. The injection well cavity forms a similarly inverted truncated cone shape, which is wide at the top and narrow at the bottom. Near the brine withdrawal well, the cavity construction rate is slow, so the cavity is small; and the cross-sectional area of the horizontal section gradually becomes smaller.

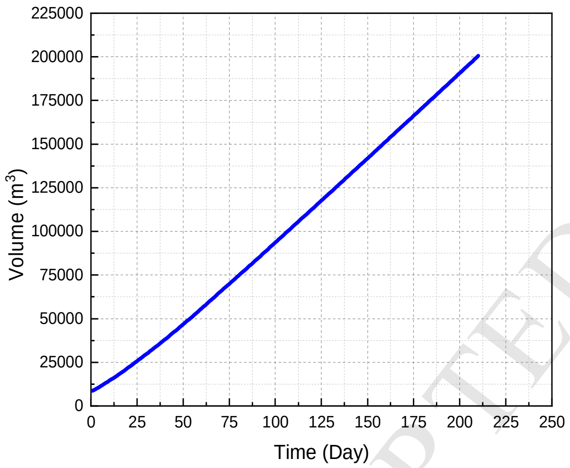


Fig. 23. Volume-time curve of TWH cavern construction

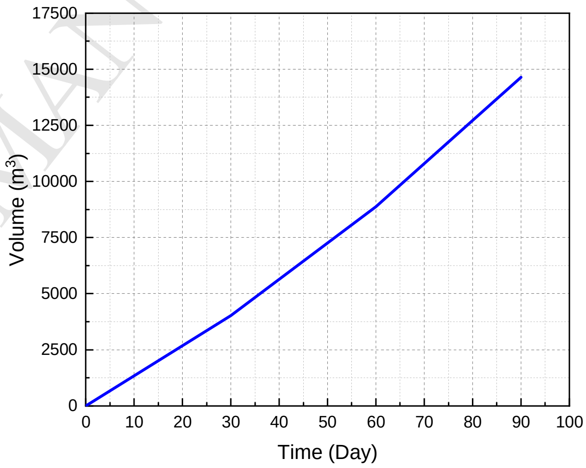


Fig. 24. Volume-time curves of SWV-cavern construction(Zhicheng et al., 2004)

According to numerical simulation for the SWV cavern(Zhicheng et al., 2004), one-way water injection was used to construct a cavern, and 90days were required to achieve a volume of 14636 m^3. Compared with the numerical simulation for the TWH cavern in this study, the SWV case only needed 22 days to achieve the same volume, thus the cavern constructing rate is increased by a factor of 4.09.

4. Conclusion

The main results and conclusions obtained in the study are as follows:

(1) Comparison between TWH and SWV cavern construction, shows that the concentration of brine rises more rapidly during for TWH. In addition, the volume of the salt cavern that can be built is larger. Thus, the TWH cavern method has great potential to be used in UGS storage construction.

(2) The TWH cavern shape under one-way water injection is very asymmetric, as shown in the model. It may lead to excessive dissolution near the injection well, and the span of the solution cavity may exceed the limit, which could present a geohazard such as ground subsidence. Therefore, in the process of TWH cavern construction, the concentration and flow rate of the brine should be monitored in real time, and the injection and withdrawal wells should be alternated according to the working conditions, so that the dissolution cavern can develop as evenly as possible.

(3) The best prediction process for solution mining cavern construction is an effective combination of numerical calculations and experimentation. Therefore, the integrated analysis of numerical and experimental simulation should be carried out in order to understand the mechanism of solution mining cavern construction in layered rock salt. It is important to further improve the reliability of the numerical simulation results as this is the most important direction of development for solution mining cavern construction simulation technology in the future.

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References

Aghahosseini, A. and Breyer, C., 2018. Assessment of geological resource potential for compressed air energy storage in global electricity supply. Energy Conversion and Management, 169: 161-173.

Arfaee, M.I.R. and Sola, B.S., 2014. Investigating the effect of fracture–matrix interaction in underground gas storage process at condensate naturally fractured reservoirs. Journal of Natural Gas Science and Engineering, 19: 161-174.

Ban, F., 2017. Status and development trend of solution mining technologies used for salt-cavern gas storage. Oil & Gas Storage & Transportation, 36(7): 754-758.

Ban, F.S., Geng, J., Gao, S.S. and Shan, W.W., 2006. Studying on basic theory and influence factor of gas storage in salt caverns building with water solution. Natural Gas Geoscience, 17(2): 261-266.

Bowen, D. J., & Priestly, E. B. (1967). U.S. Patent No. 3,347,595. Washington, DC: U.S. Patent and Trademark Office.

Budny, C., Madlener, R. and Hilgers, C., 2015. Economic feasibility of pipe storage and underground reservoir storage options for power-to-gas load balancing. Energy Conversion and Management, 102: 258-266.

De Laguérie, P. and Cambon, J.-L., 2010. Development of new liquid storage caverns at GEOSEL MANOSQUE, Proc. SMRI Fall Meeting, Leipzig, Germany, pp. 161-174.

Evans, D.J. and Chadwick, R.A., 2009. Underground gas storage: An introduction and UK perspective. In: D.J. Evans and R.A. Chadwick (Editors), Underground Gas Storage: Worldwide Experiences and Future Development in the Uk and Europe. Geological Society Special Publication. Geological Soc Publishing House, Bath, pp. 1-11.

Fluent, A., 2012. 14.5, theory guide; ansys. Inc., Canonsburg, PA.

Jiang, D.-Y., Yi, L., Chen, J., Ren, S. and Li, Y.-P., 2016a. Comparison of cavern formation in massive salt blocks with single-well and two-well systems. Journal of the Chinese Institute of Engineers, 39(8): 954-961.

Jiang, D.-Y. et al., 2016b. Laboratory similarity test relevant to salt cavern construction in interlayer-containing moulded saliferous aggregates specimen. Current Science (00113891), 111(1).

Kunstman, A. and Urbanczyk, K., 2000. Computer models of the salt cavern leaching process–evolution over the last 35 years. Salt 2000, 8-th World Salt Symposium.

Kunstman, A. and Urbanczyk, K., 2009. Application of winubro software to modelling of carven development in trona deposit, Solution Mining Research Institute Technical Conference, Krakow, Poland.

Lawal, K.A., Ovuru, M.I., Eyitayo, S.I., Matemilola, S. and Adeniyi, A.T., 2017. Underground storage as a solution for stranded associated gas in oil fields. Journal of Petroleum Science and Engineering, 150: 366-375.

Le Duigou, A., Bader, A.G., Lanoix, J.C. and Nadau, L., 2017. Relevance and costs of large scale underground hydrogen storage in France. International Journal of Hydrogen Energy, 42(36): 22987-23003.

Liu, J., Jiang, D., Jie, C. and Liu, X., 2017. Similar experimental construction and long-term stability analysis of horizontal salt caverns. Journal of Chongqing University.

Liu, W. et al., 2016. Tightness and suitability evaluation of abandoned salt caverns served as hydrocarbon energies storage under adverse geological conditions (AGC). Appl. Energy, 178: 703-720.

Liu, W. et al., 2018. Comprehensive feasibility study of two-well-horizontal caverns for natural gas storage in thinly-bedded salt rocks in China. Energy, 143: 1006-1019.

Michalski, J. et al., 2017. Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. International

Journal of Hydrogen Energy, 42(19): 13427-13443.

Ozarslan, A., 2012. Large-scale hydrogen energy storage in salt caverns. International Journal of Hydrogen Energy, 37(19): 14265-14277.

Parkes, D., Evans, D.J., Williamson, P. and Williams, J.D.O., 2018. Estimating available salt volume for potential CAES development: A case study using the Northwich Halite of the Cheshire Basin. J. Energy Storage, 18: 50-61.

Russo, A. (1995). U.S. Patent No. 5,431,482. Washington, DC: U.S. Patent and Trademark Office.

Russo., A.J., 1983. User's manual for the salt solution mining code, SANSMIC.

Shi, X.L. et al., 2017. Development Prospect of Salt Cavern Gas Storage and New Research Progress of Salt Cavern Leaching in China, 51st U.S. Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association, San Francisco, California, USA, pp. 10.

Slizowski, J., Lankof, L., Urbanczyk, K. and Serbin, K., 2017a. Potential capacity of gas storage caverns in rock salt bedded deposits in Poland. Journal of Natural Gas Science and Engineering, 43: 167-178.

Slizowski, J., Urbanczyk, K., Laciak, M., Lankof, L. and Serbin, K., 2017b. Effectiveness of natural gas and hydrogen storage in salt caverns. Przem. Chem., 96(5): 994-998.

Wang, S.X., Zhang, X.L., Yang, L.W., Zhou, Y. and Wang, J.J., 2016. Experimental study of compressed air energy storage system with thermal energy storage. Energy, 103: 182-191.

Wang, T.T. et al., 2013. A new shape design method of salt cavern used as underground gas storage. Appl. Energy, 104: 50-61.

Wang, T.T., Yang, C.H., Wang, H.M., Ding, S.L. and Daemen, J.J.K., 2018. Debrining prediction of a salt cavern used for compressed air energy storage. Energy, 147: 464-476.

WILKE, F., OBERMOLLER, M. and GREENHOVEN, H., 2011. Solution Mining with Two Boreholes for Gas Storage in Zuidwending, the Netherlands, Solution Mining Research Institute Spring Conference, pp. 2-5.

Xue, Z.Y., 1994. Manual for salt industry. China Light Industry Press, Beijing,China.

Yang, C.H. et al., 2015. Feasibility analysis of using abandoned salt caverns for large-scale underground energy storage in China. Appl. Energy, 137: 467-481.

Zhang, N. et al., 2017. Stability and availability evaluation of underground strategic petroleum reserve (SPR) caverns in bedded rock salt of Jintan, China. Energy, 134: 504-514.

Zheng, Y. et al., 2018. Small-spacing twin well natural solution and communication technology for solution mining of salt cavern underground gas storages. Natural Gas Industry, 38(3): 96-102.

Zhicheng, Z., Weiyao, Z., Wenwen, S. and Yujin, W., 2004. Mathematical model of chamber building with water solution for gas storages in salt beds. Natural Gas Industry, 24: 126-129.

Highlights

For this article, we have summarized three highlights.

1) A 3D mathematical model based on Navier-Stokes equation of TWH salt cavern leaching construction for UGS was proposed for the first time.

2) The numerical calculation method of flow and mass transfer and the boundary movement was established.

3) A VC++ computer program for the TWH salt cavern was developed and was in good agreement with the experimental results.