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Views & Comments

Deep Underground Energy Storage: Aiming for Carbon Neutrality and Its Challenges

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1. Definition of deep underground energy storage

Deep underground energy storage (DUES) is an important strategic practice for ensuring China's energy supply, its national defense, and the realization of China's strategic goals of achieving a carbon peak and carbon neutrality (CPCN). In 2021, China's oil and natural gas consumption reached 712 million tonnes and 372.6 billion cubic meters, respectively, while its external dependence reached about 72% and 45%. China's reserves only met about 30% of the requirements for a safe supply and peak shaving. Thus, large-scale reserves are urgently needed to ensure the security of China's energy and national defense. China's installed solar and wind power capacity reached 3.28×10^8 and 3.10×10^7 kW, respectively, in 2021. One of the best ways to overcome shortages due to discontinuous supply and regional distribution is to convert solar and wind power into compressed-air potential energy and hydrogen energy and store these in deep underground. This is also an effective method to improve the use efficiency of clean energy and an important approach to achieve China's strategic goal of CPCN. The large-scale geological storage of carbon dioxide (CO_2) is another important approach to achieve CPCN.

As an important strategic substance, helium is widely used in aerospace, wafer fabrication, and precision medicine. China's helium imports account for more than 98% of the nation's consumption. According to the experience of the United States and Russia [1], China should have at least ten years' consumption of helium stored to ensure a safe supply. Geological storage is one of the best choices for the large-scale helium reserves.

DUES involves storing petroleum, natural gas, hydrogen, compressed air, CO_2, and helium in deep underground spaces to ensure a safe supply, for peak shaving, and to reduce greenhouse gas emissions. Rock salt formations are the preferred geologic formation for energy storage, and their use is an important development direction for large-scale energy storage in China [2]. DUES requires an energy medium, a host rock formation, and a salt cavern.

(1) **Energy medium.** During DUES, the energy medium undergoes high temperature and high pressure, which cause the phase, state, and motion of the energy medium to change significantly; in addition, the energy medium will have physical and chemical interactions with the geological formation. As a result, it is extremely challenging to predict the physical properties of the energy medium. The migration of an energy medium into a geological formation typically has multiscale and cross-scale effects, such as interfacial tension, wettability, slippage, diffusion and Brownian motion, Darcy flow, and Forchheimer high-speed flow. The laws governing the migration of different energy media are intricate and various.

(2) **Host rock formation.** The stratigraphic longitudinal anisotropy of rock salt formations in China is significant. Main faults appear around the salt basin edges, while secondary faults are well developed in the central parts. Along these faults, different levels of dislocation have occurred. These factors cause the geological structure of rock salt formations to be complex. During DUES, the *in situ* stresses of the geologic body usually reach tens of megapascal, while the temperatures reach tens or even hundreds of degrees Celsius and the pressure of the energy medium ranges from a few megapascal to tens of megapascal. These factors increase the difficulty of evaluating the performance of the geologic formation used for DUES.

(3) **Salt cavern.** The volume of a single salt cavern used for DUES can range from tens of thousands to millions of cubic meters. Such caverns generally have a long design lifetime (over 30 years) and an irregular shape. The salt cavern is subjected to the coupled effects of *in situ* stress, high-frequency injection and production, high temperature, seepage, and chemical corrosion. Thus, it is very challenging to predict the damage to the rock mass around the cavern [3]. DUES usually consists of dozens or hundreds of caverns [2], with a total volume of up to tens of millions of cubic meters. The interactions between these caverns become significant. The local geological conditions of the different individual caverns usually differ, causing the cavern operation parameters to vary. All these factors combine to pose great challenges in the construction and functional support of salt cavern groups. As described above, the characteristics of the energy medium, host rock formation, and salt cavern present a series of theoretical and technical challenges in DUES.

2. Key scientific issues and technical bottlenecks in deep underground energy storage in China

DUES is the cutting-edge topic in discussions of large-scale energy storage in academia and engineering. Compared with the salt dome deposits used for energy storage, China's rock salt

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formations have a typical bedded structure with a small thickness, numerous non-salt interlayers, and high impurity [3], which increases the difficulty of DUES. Moreover, the research and projects carried out in China in this area have mainly focused on underground gas storage. The currently established theoretical system for underground gas storage cannot provide the necessary support for the breakthrough of DUES in China. Thus, the available technology for DUES lags behind the national requirements for the rapid development of large-scale energy storage. A series of scientific problems and technical bottlenecks hamper the implementation of DUES in China.

2.1. Key scientific issues

2.1.1. Multiscale progressive failure of host rock formation during energy storage

When using salt caverns for DUES, the host rock formation will be affected by many factors such as chemical erosion, temperature, and stress, which may lead to multiscale failure such as micro-fissure connectivity at the nanometer scale, surrounding rock cracking at the meter scale, or fault activation at the kilometer scale. In bedded rock salt geology, the thin interbedded structure promotes interbedded fractures. The failures of the rock mass surrounding the caverns change gradually with time. Obtaining an accurate description of the multiscale progressive failure of the host rock formation under multifield and multiphase coupled conditions is the basic prerequisite for energy medium selection, cavern design, and safe operation. There are many types of energy media, including oil, natural gas, compressed air, hydrogen, CO_2, helium, and electrolytes. The types of rock surrounding the caverns include rock salt, mudstone, and anhydrite. Under the high-temperature and high-pressure conditions during energy storage, the energy medium may have chemical reactions with the host rock formation, causing the physical and mechanical properties of the host rock formation to deteriorate. The physical and mechanical properties of rock salt are sensitive to changes in temperature and stress, and when failure occurs in a salt rock mass, it tends to be extensive. Therefore, it is extremely challenging to determine how to accurately describe the multiscale progressive failure of the host rock formation during DUES.

2.1.2. Multiscale seepage of energy media

Different types of energy media differ greatly in terms of molecular size and viscosity coefficient. Under high internal pressure, migration and leakage of the energy media to the host rock formation may lead to micro-cracks, the connection of existing pores, and strength reduction; they may even induce the activation of geological faults, causing disasters. In bedded rock salt, the interlayers with higher permeability will become the preferred channel for leakage. Based on an analysis of the available information on underground gas storage accidents [4], about 70% of such accidents have been caused by leakage. However, due to the complex circumstances of each accident, identifying the failure evolution of leakage and the conditions that may lead to impending disaster remains difficult.

Methane molecules have a diameter of 0.38 nm, while hydrogen molecules have a diameter of 0.26 nm; thus, hydrogen molecules can leak through geological formations with lower permeability and smaller porosity. Injection and production during DUES will cause the mechanical properties to deteriorate while increasing the permeability of the host rock, which increases the risk of leakage. Thus far, no theoretical model has been clearly proposed of the leakage and cracking of a geologic body due to high pressure and long-term leakage migration of the energy medium, considering multifield and multiphase coupling. The critical gradient, leakage path, leakage amount, and leakage range of energy media in geologic bodies remain unclear.

2.2. Key technical bottlenecks

Rock salt formations in China have a typical bedded structure characterized by a thin salt layer, high impurity, and numerous interlayers. The problems of effectively controlling the development of the cavern shape, predicting the shape of the accumulation of insoluble particles, describing the brine concentration, or optimizing the salt dissolution rate in bedded rock salt formations have not yet been solved. These are the key scientific problems and technical bottlenecks that limit the construction of salt caverns for DUES in China. DUES caverns in China usually have a large volume, great height, and poor shape. Such caverns are subjected to high pressure and phase changes of the energy media. These factors cause a gradual decrease in the performance and safety of the caverns, making it extremely challenging to predict performance and safety. For example, a significant collapse is taking place at the top of a salt cavern in the Jintan underground gas storage in China. The collapsed body has a length of about 20 m, a thickness ranging from 2 to 4 m, and a volume of about 3300 m^3, directly threatening the safety of the gas storage [5]. Large-scale energy storage requires the construction of cavern clusters, but the theory of how to prevent and regulate the consequences of the failure of a single cavern in a cavern cluster is still lacking.

3. Research ideas and directions

Due to the special geological characteristics of bedded rock salt in China, the existing basic scientific theories and related technologies cannot be directly used to solve the key scientific and technological challenges discussed above. Moreover, the use of DUES to improve the use efficiency of clean energy is a new research direction that lacks mature theories and technologies. Therefore, China must promote the development path of new DUES technology through basic scientific innovation and realize core theoretical innovations and technological breakthroughs in this field. Ultimately, an entire industrial chain for DUES must be achieved in order to ensure national energy security. This will allow China's scientific and technological innovations in the field of DUES to reach a world-leading level.

To overcome the challenges discussed above, two key scientific problems must be resolved through four research directions. The scientific problems include: ① determining the mechanism of the multiscale immigration of the energy medium; and ② evaluating the performance of the DUES host rock formation. The four research directions include: ① the multiscale migration of the energy medium; ② the performance evaluation of the host rock formation, considering multiple field coupling; ③ the intelligent construction of DUES; and ④ the smart operation of DUES. The relationships between the two scientific problems and the four research directions are illustrated in Fig. 1.

3.1. Multiscale migration of energy media

By simulating multiple fields (i.e., temperature, stress, and chemical corrosion), coupled conditions, and the evolution of physical and chemical characteristics, the multiscale migration of energy media should be systematically studied as the basis of DUES. Detailed research is needed on the following topics:

(1) Determining the physical parameters of oil, natural gas, hydrogen, compressed air, CO_2, helium, and electrolyte; determining the continuity, state, motion equations, and boundary

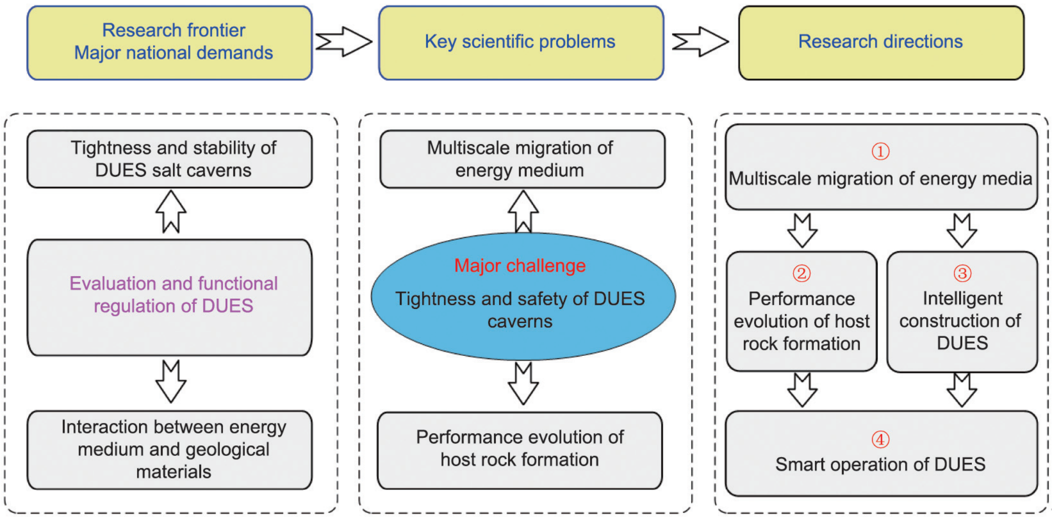

Fig. 1. Research ideas and directions in support of DUES.

conditions of energy media under high temperatures and pressures; and understanding the evolution of the physical parameters of storage media during DUES;

(2) Understanding the physical and chemical reactions between geological materials and energy media under multifield coupled conditions; gaining knowledge of changes in the mechanical properties and the permeability of geological material while considering the effects of physical and chemical reactions; and establishing a matching principle and evaluation method for the energy media and host rock formation;

(3) Establishing a seepage and leakage model of the energy media in the host rock formation and the interface under multifield coupled conditions; investigating the multiscale migration mechanism of energy media along the interface seepage; quantitatively determining the leakage critical-pressure gradient, leakage path, leakage rate, and seepage range of different energy media; and developing simulation technology for multiscale seepage in the host rock formation.

3.2. Performance evaluation of the host rock formation considering multifield coupling

To depict the performance of the host rock formation, multiscale progressive failure tests should be carried out on samples of geologic materials while considering the coupling of temperature, stress, and chemical corrosion. Related mathematical models should be proposed. Based on the proposed models, numerical simulation software for characterizing and predicting the performance of the host rock formation during DUES should be developed. Specific areas of research include:

(1) Developing a theoretical model of the host rock formation that considers size effects and the coupling of temperature, hydraulics, mechanics, and chemistry (THMC); and examining the mechanism and main controlling factors of the functional evaluation of the host rock formation during the service period;

(2) Researching and developing a THMC-coupled experimental system; performing tightness experiments on the host rock formation while considering size effects and THMC coupling; determining the leakage and multifield coupling mechanism of the host rock formation; and quantitatively evaluating the leakage in the host rock formation;

(3) Developing algorithms and software for the numerical simulation of the host rock formation based on the proposed model; and performing three-dimensional (3D) simulations and describing the function evolution of the host rock formation.

3.3. Intelligent construction of DUES

In order to construct more caverns—and large caverns in particular—in China's bedded salt formations, it is necessary to solve a series of theoretical and technical problems. Topics for further study include:

(1) Developing mathematical models of salt dissolution, brine flow, mass transfer, and the fall and accumulation of insoluble impurities;

(2) Developing cavern leaching software and an experiment platform for simulating cavern leaching in bedded rock salt formation; and establishing an intelligent decision-making system for adaptive cavern leaching optimization for different formations;

(3) Developing mathematical models for new cavern leaching methods (e.g., using two small space wells, multi-step horizontal wells, and non-symmetric wells); identifying the main factors affecting cavern leaching efficiency by using these new methods; and developing cavern leaching technology for different formations.

3.4. Smart operation of DUES

To maintain the safety of salt caverns used for DUES over their full life cycle, it is necessary to investigate the functional evolution of the cavern group and develop appropriate monitoring methods. Detailed research is required in the following areas:

(1) Developing a cavern volume shrinkage prediction model, a cavern function evolution system and index threshold, and an intelligent decision-making system for countering cavern shrinkage;

(2) Establishing a long-term subsidence prediction model; setting up a long-term automatic subsidence monitoring network using leveling and interferometric synthetic aperture radar (InSAR) measurements to detect subsidence disasters caused by cavern shrinkage; and determining the subsidence safety threshold;

(3) Setting up a safety evaluation and early warning system for energy storage caverns using micro-seismic monitoring and gas

micro-leakage detection, where the micro-seismic monitoring system monitors the vibration signals formed by microfractures of the cavern or slippage of the structural plane in real time, while the gas micro-leakage monitoring system monitors trace gas near the wellhead in real time.

Based on the research described above, hardware and software systems can be developed for safety monitoring, evaluation, early warning, and decision-making regarding energy storage cavern groups. These systems will be used to collect big data from monitoring, analyze the safety status of the caverns, and display the evaluation results. In case of an emergency, the systems can automatically send an early warning and intelligently start the safety control instruments. Ultimately, an intelligent operational system for DUES cavern groups will be constructed.

4. Summary and conclusions

(1) DUES is defined as the use of deep underground spaces for large-scale petroleum, natural gas, hydrogen, compressed air, CO_2, and helium storage. It is an effective way to improve the use efficiency of clean energy while achieving CPCN; it is also a major strategic demand to ensure energy security in China.

(2) Deep rock salt formations are some of the best places for energy reserves and have been widely used. They are also the ideal host rock formation for energy reserves in China. There are abundant rock salt resources in China in good geographic locations, which can meet the nation's requirements for large-scale energy storage.

(3) The construction of compressed-air power stations and hydrogen storage using deep underground salt caverns will be the key development in large-scale energy storage in China during the period of the 14th Five-Year Plan. The Jintan and Huai'an salt mines in Jiangsu Province, the Yingcheng salt mine in Hubei Province, and the Pingdingshan salt mine in Henan Province possess good geological and geographical advantages.

(4) Rock salt formations in China mainly consist of lacustrine sedimentary bedded rock salts, which have thin salt layers, numerous non-salt interlayers, and a high impurity content. Therefore, the multiscale progressive failure of a host rock formation, multiscale seepage of the energy medium, efficient construction of caverns, and smart operation are the key theoretical and technical problems that must be solved.

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References

[1] Хан СА, Игошин АИ, Казарян ВА, Скрябина АС, Сохранский ВБ. Underground helium storage. Ma XF, Liu JY, editors. Tang L, He G, Ding G, Zheng Y, translators. Beijing: Petroleum Industry Press; 2020. Chinese.
[2] Yang CH, Zhou HW, Li YP. Failure mechanism and protection of salt caverns for large-scale underground energy storage. Beijing: Science Press; 2014. Chinese.
[3] Yang CH, Li YP, Chen F. Bedded salt rock mechanics and engineering. Beijing: Science Press; 2009. Chinese.
[4] Yang C, Jing W, Daemen JJK, Zhang G, Du C. Analysis of major risks associated with hydrocarbon storage caverns in bedded salt rock. Reliab Eng Syst Saf 2013;113:94–111.
[5] Wang T, Yang C, Chen J, Daemen JJK. Geomechanical investigation of roof failure of China's first gas storage salt cavern. Eng Geol 2018;243:59–69.