Research and Application of Monitoring Technologies for Salt Cavern Gas Storage in Compressed Air Energy Storage Smart Stations

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Abstract

With the continuous development of new energy and intelligent technologies, the demand for monitoring salt cavern gas storage in compressed air energy storage (CAES) intelligent stations is increasing daily; however, current systematic research in this area remains limited. Drawing extensively on mature experience from fields such as thermal power and oil and gas extraction, this paper takes the factors influencing the stability of salt cavern gas storage as a starting point. Focusing on three aspects—salt cavern temperature and pressure, gas injection and production parameters, and salt rock creep and damage—it systematically summarizes the necessity, working principles, and technical research progress of various monitoring contents. The paper emphasizes the analysis of the applicability of several existing mainstream and emerging technologies in the context of salt cavern monitoring and provides targeted engineering application schemes. By reviewing existing research and feasible solutions, this study provides theoretical guidance for the development of multi-dimensional and three-dimensional monitoring networks for salt cavern gas storage monitoring.

Full Text

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Abstract

With the continuous development of new energy and intelligent technologies, the demand for monitoring salt cavern gas storage facilities within compressed air energy storage (CAES) smart stations has increased significantly. However, systematic research in this specific field remains relatively limited. Drawing upon mature experience from industries such as thermal power generation and oil and gas extraction, this paper uses the factors influencing the stability of salt cavern gas storage as a starting point to provide a comprehensive overview.

The study systematically summarizes the necessity, working principles, and technical research progress of various monitoring components across three key dimensions: salt cavern temperature and pressure, gas injection and production parameters, and salt rock creep and damage. Furthermore, the paper provides a detailed analysis of the applicability of several mainstream and emerging technologies within the context of salt cavern monitoring and proposes targeted engineering application solutions. By reviewing existing research and feasible schemes, this paper provides theoretical guidance for the development of multidimensional, integrated monitoring networks for salt cavern gas storage facilities.

Keywords: Compressed air energy storage; intelligent field station; salt cavern storage; monitoring technology

1. Introduction

As the global energy structure undergoes a transition toward a new energy system centered on renewables, the large-scale integration and stable dispatch of energy have become critical research directions. As a representative of large-scale, long-duration physical energy storage technology, Compressed Air Energy Storage (CAES) is considered a key method for reducing curtailment rates and improving grid stability due to its clean, efficient, and safe characteristics. CAES power plants can be categorized by their storage reservoirs, including air storage tanks, lined rock caverns, abandoned mines, and aquifers. Compared to surface tanks, underground reservoirs–represented by salt caverns–generally offer lower average investment per kilowatt and larger storage capacities [**?**, **?**]. Currently, most commercial CAES plants utilize salt caverns.

Furthermore, the “smart station” architecture has become an important development direction under the trend of informatization in China’ s energy system. A smart station is characterized by high automation and holistic intelligence, aiming to achieve intelligent equipment monitoring, smart operation and maintenance, and real-time energy dispatch. While this aligns with the traditional energy industry, current research remains limited to photovoltaics and wind power [**?**, **?**], lacking targeted discussions on salt cavern gas storage reservoirs. This paper focuses on CAES power plants based on salt cavern storage and explores monitoring requirements within the smart station framework.

2. Salt Rock Creep and Stability Research

Salt caverns originate from the solution mining of underground salt deposits. Due to low permeability and high plasticity, salt rock is an excellent medium for underground energy storage [**?**, **?**]. However, engineering practice demonstrates that these cavities face failure risks under long-term cyclic operating conditions related to salt rock creep and geological structures.

Salt rock creep stems from complex internal deformation mechanisms. Extensive research has been conducted on the influence of temperature, stress, and composition on creep behavior [?, ?]. Numerical analyses based on nonlinear creep models have elucidated the significant impact of fatigue effects on stability. Studies by [?, ?] confirmed the negative effects of the interaction between creep and fatigue damage. Furthermore, research on salt rock containing impurities indicates that increased confining pressure can suppress these effects, though it may transition the failure mode toward plastic expansion.

A fractional derivative creep-damage constitutive model was established to reveal strain and volumetric shrinkage behavior. By investigating discrepancies between Norton-Power model results and actual values in triaxial tests, researchers have highlighted the limitations of experimental conditions in predicting shrinkage in ultra-deep formations. It has been noted that creep deformation is inversely proportional to the loading stress rate, while the deformation rate is directly related to the stress state. Lower constant gas pressures and lower pressure cycling frequencies exacerbate displacement, plastic zone expansion, and volume shrinkage.

Triaxial tests at various temperatures clarified that increasing temperature promotes both the creep rate and total deformation. A thermo-mechanical coupled model confirmed that temperature fluctuations during injection and production cycles significantly impact cavern shrinkage. During rapid gas production and low-pressure idle periods, salt caverns face collapse risks due to accumulated thermal damage and cavern roof geometry. Studies on cavity shape indicate that geometry significantly alters long-term volumetric shrinkage rates. Additionally, even with appropriate operating pressures, creep leads to unavoidable surface subsidence. Moisture absorption also exacerbates shrinkage by accelerating crack evolution. While impurities can delay the steady-state creep rate, for established caverns, parameters like surrounding rock composition are fixed. Consequently, stability monitoring should focus on temperature, pressure, injection/production parameters, and creep damage.

3. Underground Temperature and Pressure Monitoring

Monitoring temperature and pressure is critical for station operation and maintenance. However, current practices primarily rely on wellhead data [?, ?], which presents challenges: Chinese salt caverns are often at depths of 1200m, and as gas pressure increases, significant discrepancies arise between the cavern top pressure and wellhead pressure. This impacts the accuracy of intelligent station algorithms.

Wellbore integrity must also be considered. Failure scenarios are often dominated by leakage under string deformation or metal damage, which correlate with temperature and pressure [?]. Distributed Fiber Optic Sensing (DFOS) offers a solution for long-distance, continuous, online monitoring. This technology uses optical fiber as both the sensor and transmission medium, utilizing backscattered light to resolve the temperature field [FIGURE:N]. Distributed Temperature Sensing (DTS) based on Raman scattering and Distributed Acoustic Sensing (DAS) based on Rayleigh scattering provide high-resolution data consistent with theoretical expectations.

Fibers are classified into single-mode and multi-mode. Single-mode fibers have lower loss and higher precision, suitable for long-haul DAS applications. Multi-mode fibers offer higher channel capacity for DTS. Recent innovations include integrated cables that bond single-mode fibers for strain sensing (DSS) to loose-tube fibers for temperature sensing, reducing costs while maintaining sensitivity [FIGURE:N].

3.1 Equipment Installation and Application Installation methods include permanent, semi-permanent, and recoverable: - **Permanent:** Fixed to the outside of the casing and bonded with cement. This offers high data quality and assists in evaluating cementing quality but is susceptible to damage during downhole operations. - **Semi-permanent:** Placed in the annular space between the casing and injection pipe. This allows for equipment retrieval via conduits and protects the fiber in annular fluid, though it cannot monitor downhole pressure directly. - **Recoverable:** Placed inside the injection-production pipe. This allows for easy replacement but requires specialized conduits to prevent wear and corrosion from high-velocity gas flow.

4. Gas Injection and Production Parameters

Injection and production cycles influence salt cavern stability. While cycle frequency is determined by grid demand, the loading stress rate depends on gas flow velocity and volume. Monitoring moisture and particulate matter is necessary to mitigate scaling and corrosion risks.

4.1 Moisture and Particulate Monitoring A brine pool inevitably remains at the bottom of the cavern [FIGURE:1]. During gas injection, relative humidity decreases as temperature and pressure rise, promoting brine evaporation. During production, the temperature drop causes water vapor to reach supersaturation, triggering condensation. This cyclic phase change impacts the long-term available volume and energy storage capacity.

High-velocity gas flows can entrain insoluble debris or salt fragments (approximately $10 - 100\mu$m), threatening structural integrity. In humid environments, hygroscopic mineral particles like $NaCl$ exist as aerosols that adsorb onto pipeline walls, leading to salt and oxygen corrosion [FIGURE:1].

4.2 Flow Rate and Velocity Monitoring Flow parameters provide quantitative guidance for power regulation. For large units, gas velocity is a critical criterion for assessing pipeline wear. Erosion wear occurs when solid particles impact the material surface. Research suggests erosion rates relate to gas velocity and particle size, implying a safety threshold for flow velocity. Critical erosion coefficients must be maintained within specific ranges [FIGURE:N].

Technologies for monitoring these parameters include: - **Moisture:** Tunable Diode Laser Absorption Spectroscopy (TDLAS), which offers fast response but must account for salt particle interference. - **Particles:** Charge induction (suitable for high concentrations) and light scattering (Mie theory, high accuracy in low concentrations) [FIGURE:N]. - **Flow:** Ultrasonic and differential pressure methods (e.g., Venturi flowmeters), though the latter poses risks of clogging in solid-containing fluids.

5. Salt Rock Creep and Damage Monitoring

Monitoring surrounding rock creep is paramount for long-term safety. Direct monitoring often relies on independent wells for close-range deployment of technologies like acoustic emission (AE) and microseismic (MS) monitoring.

5.1 Direct Monitoring Technologies AE technology captures elastic waves from stress redistribution. While sensitive in laboratory settings, its field application is limited by energy attenuation in salt formations with interlayers. Acoustic Reflection Imaging (ARI) uses high-frequency waves to image formation interfaces [FIGURE:N]. However, its radial detection distance ($10 - 15$m) and resolution ($0.1 - 0.2$m) are often insufficient to capture slow creep rates.

Microseismic (MS) monitoring captures lower-frequency waves, offering a larger monitoring distance. Multi-well geophone monitoring [FIGURE:N] combines the advantages of surface and downhole monitoring, providing high precision across the entire cavern area, though construction costs are high.

5.2 Indirect Monitoring and Soft Sensing Surface subsidence is the primary indirect indicator of cavern creep. Differential Synthetic Aperture Radar Interferometry (DInSAR) and Multi-Temporal InSAR (MTInSAR) achieve millimeter-level displacement maps [FIGURE:N]. MTInSAR effectively suppresses atmospheric effects, making it suitable for long-term monitoring. Global Navigation Satellite System (GNSS) complements InSAR by providing real-time, high-precision coordinate positioning.

“Soft sensing” technology can be introduced to monitor cavern shrinkage. By constructing mathematical models based on measurable indicators (flow rates, pressure, duration) and utilizing machine learning, the long-term shrinkage rate can be predicted without internal hardware.

6. Conclusion

Salt cavern gas storage facilities require comprehensive, intelligent online monitoring. Stability monitoring should focus on three areas: cavern tempera-

Figure 3

Figure 1: Figure 3

Figure 4

Figure 2: Figure 4

ture/pressure, injection/production parameters, and salt rock creep/damage.

1. **Temperature and Pressure:** Should utilize distributed fiber optic sensing (DFOS) for continuous underground monitoring, with installation methods chosen based on geological conditions.
2. **Gas Parameters:** Monitoring must include moisture and particulate concentrations to prevent pipeline corrosion and erosion.
3. **Creep and Damage:** A combination of direct underground acoustic networks and indirect surface monitoring (DInSAR/GNSS) is recommended.

As monitoring technologies and algorithms evolve, salt cavern storage will transition toward a multi-dimensional, integrated network from space to the subsurface, optimizing operation and maintenance for the intelligent energy industry.

Figures

Source: ChinaXiv —Machine translation. Verify with original.

Figure 6

Figure 3: Figure 6

Figure 9

Figure 4: Figure 9

Figure 11

Figure 5: Figure 11