Design and flow Simulation of compressed Air Energy Storage system in Aquifer

Can Liu
Department of Power Engineering, North China Electric Power University, Baoding 071000, Hebei, China
2658738922@qq.com

Abstract. Compressed air energy storage is the most promising energy storage technology at present, and aquifer compressed air energy storage can achieve large-scale storage of compressed air by breaking the dependence of traditional compressed air energy storage on geological conditions such as large rock caves. Based on Kushnir’s study and some hypotheses, the mathematical model of compressed air energy storage in aquifer is established in this paper. Then, taking 3 MW energy storage scale as an example, the energy storage model of underground aquifer with buried depth of 800m in horizontal stratum is established by using numerical simulation method. The initial gas bag formation after gas injection and the parameters of pressure and gas saturation during the system cycle were analyzed. Experimental results show that the pressure and gas saturation change little after a complete cycle, and the effective gas phase volume of the available energy storage and energy release cycle decreases slowly with the cycle going on. The aquifer is widely distributed and well sealed, so it is feasible to store compressed air energy as a gas storage bank.

Key words: compressed air energy storage; aquifer; flow simulation

1. introduction
Up to now, only pumping energy storage and compressed air energy storage are two kinds of energy storage technology which can be used in 100 MW class and above scale in the world. Pumped energy storage has high energy storage and conversion efficiency, but the application of this technology has great limitations due to the high demand for topography and water source. Large-scale compressed air energy storage systems often require special geological conditions to build large-scale gas storage reservoirs, such as rock caves, salt caves, abandoned mines, and so on, which greatly limits the application of compressed air energy storage.

The groundwater aquifer is widely used in the geological storage of carbon dioxide and the medium of underground storage of natural gas, and it is proved that the aquifer can be effectively stored in the gas, and the water-bearing layer is widely distributed, and the underground water-bearing layer is used as the “gas reservoir”. The invention can greatly reduce the geological condition limitation of the compressed air energy storage, and further can get rid of the dependence of the conventional compressed air energy storage on the large-scale rock cave. In this paper, the underground aquifer is chosen as the storage of compressed air energy, and the compressed air energy storage system is designed mainly for
the underground part. The underground system mainly includes the formation of the initial air bag and the energy storage and release cycle. The pressure and gas phase saturation in the energy storage and energy release cycle of the system are analyzed by numerical simulation to verify the feasibility of aquifer as gas storage for compressed air.

2. Design of aquifer energy storage system

The use of aquifers as compressed air reservoirs has not yet been applied in practice, but the technology of using porous reservoirs (such as underground aquifers) to store natural gas has been implemented since 1915, drawing lessons from the idea of natural gas storage. It is feasible to store compressed air in underground aquifers to achieve large-scale energy storage.

![Figure 1. Schematic of compressed air energy storage system in aquifer](image)

The underground energy storage system of compressed air aquifer mainly consists of two stages: the formation of initial airbag and the subsequent energy storage and release cycle. It is necessary to inject a large amount of buffer gas to form the initial air bag before starting the cycle to provide rapid pressure support for the pumping process and to prevent the extraction of liquid water from affecting the power generation of the system. In this paper, the horizontal aquifer as the gas storage system design. After the formation of the initial airbag, the energy storage and release cycle of the system is carried out. In compressed air aquifer energy storage, the system cycle can be designed as a daily cycle or a weekly cycle.

3. Establishment and analysis of the model

3.1. Mathematical description of aquifer gas storage

Based on Darcy's law and with reference to the results of Kushnir, an air flow model in a compressed air storage device (CAES) aquifer is established under certain gas assumptions.

![Figure 2. Air flow model in a compressed air storage device aquifer](image)
aquifer, and as the air circulates, the air interface moves downward during the gas injection phase and upward during the discharge phase. The gas-liquid two-phase flow phenomenon only has a limited effect on the flow at the vapor-water interface, so it is assumed that the air-water interface is sharp, that is, the bubble domain is assumed to contain no movable water (i.e., only non-reducible saturated water). Based on this assumption, under the constraint of the generalized gas state equation, the continuity equation and the momentum equation of the air zone (ignoring the gravity effect) are as follows:

\[
\frac{\partial (f \rho)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho u_r)}{\partial r} + \frac{\partial (\rho u_z)}{\partial z} = 0
\]

\[
u_r = -\frac{k_r \rho}{\mu} \frac{\partial p}{\partial r}, \quad \nu_r = -\frac{k_z \rho}{\mu} \frac{\partial p}{\partial z}
\]

\[
\rho = \frac{p}{ZRT}
\]

Where \( V_r \) and \( V_z \) represent the radial and vertical surface velocities of the gas, respectively, \( f \) represents porosity, and \( k_r \) and \( k_z \) represent media permeability in the radial (horizontal) and vertical directions, respectively. The remaining symbols are consistent with the usual symbols. The model is established on the premise that the reservoir can be fully expressed as a uniform pore space with constant effective porosity and permeability.

Due to the air cooling in the compression stage and the large thermal inertia of the porous medium, the air flow is essentially isothermal. Set the initial gas storage pressure \( P_0 \) to be uniform, which is equivalent to the local hydrostatic head (the influence of the gas storage static pressure head is negligible). The periodic injection and suction of air creates pressure fluctuations in the stored air. In the case where the pressure fluctuation is less than \( P_0 \), considering the assumption of the isothermal flow, the fluid viscosity and the compression coefficient are regarded as constants, which are equal to \( = (T, P_0), Z = Z (T, P_0) \), respectively.

\[
t = 0, p = P_0 \quad z = 0, 0 < r < \infty, \quad \frac{\partial p}{\partial z} = 0
\]

\[
0 \leq z \leq h, r \to 0, \int_0^h 2 \pi r \rho u_r \, dz = m_c F(t)
\]

\[
h \leq z \leq H, \quad r \to 0, \frac{\partial p}{\partial r} = 0
\]

\[
0 \leq z \leq H, \quad r \to \infty, p \to P_0
\]

Where \( h \) is the permeation length and \( m_c F(t) \) represents the mass flow of gas in the aquifer during system operation. \( m_c \) is the mass flow rate through the compressor, and \( F(T) \) is a dimensionless periodic function of the cycle time \( T_p \). Figure 2 shows the variation of the CAES unit \( F(T) \) operated by the compressor and turbine with a constant mass flow of air. The specified time interval is: charging time is \( t_1 \), storage time is \( t_2 - t_1 \), power generation time is \( t_3 - t_2 \), and \( cd \) is the ratio of discharge to charging mass flow (E).

![Figure 3. Air flow process of compressed air storage device](image)
In order to complete the model establishment, the boundary conditions of the gas-water interface must be determined. As shown in Figure 1, the interface coordinates are specified by \( \eta(r, t) \). The boundary condition of the motion boundary is:

\[
\frac{D(\eta - z)}{Dt} = \frac{\partial \eta}{\partial t} + \frac{v_r \partial \eta}{\partial r} - \frac{v_z}{f} = 0 \quad \text{on} \quad z = \eta.
\]

Ignore the capillary water pressure, the pressure on both sides of the interface is the same under equilibrium. As will be seen later, the short-term transition period beginning at each stage is not included, and the rate of pressure change near the well is medium. Therefore, the interface moves slowly. A reasonable assumption is that the water layer under the airflow is quasi-static and the position of the interface is declining. The pressure position of the interface can be described as

\[
p = p_0 - \rho \omega g (H - z) \quad \text{on} \quad z = \eta.
\]

\( P_0 \) and \( t_p \) are selected as the pressure and time scales respectively, and \( H \) is used as the length scale of the vertical direction. By introducing the correction pressure, the above equation is simplified, and the following equation is obtained:

\[
\frac{\partial \Phi^*}{\partial t^*} = p^* \tau_z \left( \frac{\partial^2 \Phi^*}{\partial r^*^2} + \frac{1}{r^*} \frac{\partial \Phi^*}{\partial r^*} + \frac{\partial^2 \Phi^*}{\partial z^*^2} \right)
\]

\( t^* = 0, \quad \Phi^* = 0 \)

\( z^* = 0, 0 < r^* < \infty, \frac{\partial \Phi^*}{\partial t^*} = 0 \)

\( 0 \leq z^* \leq h^*, r^* \to 0, h^* r^* \frac{\partial \Phi^*}{\partial r^*} = -m_c^* F(t^*) \)

\( h^* < z^* \leq 1, \quad r^* = 0, \frac{\partial \Phi^*}{\partial r^*} = 0 \)

\( 0 \leq z^* \leq 1, r^* \to \infty, \Phi^* \to 0 \)

\[
\frac{\partial \Phi^*}{\partial r^*} - \frac{\tau_z}{2 \rho^*} \left[ \left( \frac{\partial \Phi^*}{\partial r^*} \right)^2 + \left( \frac{\partial \Phi^*}{\partial z^*} \right)^2 \right] + g^* \tau_z \frac{\partial \Phi^*}{\partial z^*} = 0
\]

3.2. Flow simulation

Establish an idealized basic model and select a study area with a plane radius of 2 km in the aquifer and divide it. The injected gas layer is located in the middle of the model, with a thickness of 50 m.

3.2.1. Gas phase saturation distribution.

Figure 4 shows the distribution of gas phase saturation distribution in the formation corresponding to a complete cycle. Taking the lower gas phase saturation \( S = 0.2 \) edge position as an example, the lower
edge of the gas phase saturation at the beginning of the cycle in Fig. 4a is located at 923.2 m. After the gas injection starts, the gas phase increases near the wellbore, and the halo is under. The edge reaches a 928.0 m as shown in Figure 4b. At the end of the pumping process, the lower edge of the halo rises to a level of 922.0 m, as shown in Figure 4c. At the end of the cycle, the lower edge of the halo returns to a position of about 923.2 m. This indicates that after a complete cycle, the gas phase saturation in the formation changes little. Combined with the pressure change analysis results, as the cycle continues, the effective gas phase volume available for the energy storage release cycle in the formation slowly decreases.

3.2.2. Pressure distribution. Figure 5 shows the pressure change with time at the injection point (r = 0.5 m) and the position of two different monitoring points during the initial balloon formation. It can be clearly seen that near the injection point, the pressure increases sharply after the instantaneous injection, and then the pressure tends to be stable as the gas injection is gradually stabilized. The pressure at the monitoring point 1 (r=23.0 m) is relatively flat. At the remote monitoring point 2 (r=142.7 m), the pressure gradually increases with the gas injection, and the growth rate slows down.

3.2.3. Design of aquifer compressed air energy storage cycle system. Compare the bottom hole pressure changes in the daily cycle and the weekly cycle scenario, as shown in Figure 6. In the weekly cycle mode, the energy storage phase occurs on the weekend, so the pressure accumulation at the beginning of the cycle is greater than the daily cycle mode. The highest pressure and the lowest pressure in the initial phase of the release energy are higher than the daily cycle mode, with the release process decreasing day by day and the highest at the end stage. The pressure and minimum pressure are both less than the daily cycle.

4. Conclusion
In this paper, the development and development of compressed air energy storage in aquifer are summarized. Based on the Kushnir research and some hypotheses, the mathematical model of compressed air energy storage in aquifer is established. The design of compressed air energy storage system based on underground aquifer is carried out. The formation of initial air bag in the underground system and the change of parameters during the energy storage and release cycle of the system are mainly studied. The pressure, gas phase saturation and system cycle times in the process of energy storage and energy release are analyzed by numerical simulation method. The experimental results show that the aquifer compressed air system is feasible.
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