Economic Research and Exploration of Comprehensive Utilization of Energy Based on Advanced System Theory and Technology

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Abstract. Electricity is the prerequisite and important guarantee for the progress and development of human society. It has an important position and role in the national energy strategy. Increasing the share of renewable energy generation in electricity production has a broad and far-reaching impact on the sustainable development of China's economy and society. Influences. However, due to the intermittent and instability of renewable energy itself, in order to avoid large-scale renewable energy generation from impacting the power grid, the scale of renewable energy generation and grid-connected power are limited to a certain extent. Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) technology uses a heat storage device (TES) to store compressed heat, eliminating the dependence on fossil fuels and achieving "zero emissions." At present, AA-CAES technology is considered as an energy storage technology with great market development potential. The paper calculates the performance of the system given the input of the air compressor and the output power of the turbine; analyses the parameters such as the storage pressure ratio, convective heat transfer coefficient, and energy release interval time for energy storage density, cycle efficiency and other systems The influence of performance parameters; reveals the temperature and pressure changes of the gas storage chamber with time during a single cycle.

1. Introduction
Compressed air energy storage is to use the excess electricity in the valley of the power grid or new energy to generate electricity to drive the compressor to compress the air, convert the electricity into high-pressure internal energy, and then use the high-pressure air storage chamber to store the high-pressure air. When the system electricity peaks, the high-pressure air is released and directly enters the air turbine for expansion and work or mixed with natural gas and enters the gas turbine to perform work, which in turn drives the generator to generate electricity. In 1978, CAES technology was put into commercial operation for the first time in Hunter, Germany. The compressed power of the power station is 60MW and the turbine output is 290MW. The compressed air is stored in two underground gas storage chambers, and the total gas storage volume is about 3.1 × 105m³ [1]. The successful operation of the power station proves that CAES is a relatively mature large-scale energy storage technology. CAES has similar advantages to PHS technology, such as large capacity, fast response speed, and good economy, but its efficiency is slightly lower than PHS. In addition, the traditional CAES system has not completely...
shaken off its dependence on fossil fuels, which will cause some CO2 emissions. The most significant advantage of CAES technology compared to PHS technology is that the construction of CAES power stations requires relatively mild geographical conditions. Although most compressed air energy storage power stations require large-capacity gas storage spaces, the gas storage space can be realized by natural or artificial means such as natural caves, abandoned mines, and underground pipelines. The PHS power station requires two reservoirs with a significant terrain difference. The dam needs to be built and abundant water resources are needed. This will undoubtedly have an adverse impact on the ecology of the reservoir area and the lives of residents, and may cause certain ecological and social problems. Considering that the scale of distributed energy is relatively small, and new energy power generation is mostly in plains and hills, CAES technology can better couple with distributed energy power generation and help achieve smooth and stable output of new energy power generation. In addition, CAES has the advantages of higher energy storage density and lower initial investment than PHS. It can be seen that CAES technology is obviously more suitable for China’s vast plains and inland areas such as northwest and northeast China, which has a wider application space than PHS technology.

Compressed air energy storage technology has the advantages of high cycle efficiency, low investment and operating costs, good environmental adaptability, and large energy storage density. It is an energy storage technology with great market development potential. In the future energy storage market, CAES technology will certainly occupy a very important position.

2. AA-CAES system overview and thermodynamic model

2.1. System Overview

Due to the different types of heat exchangers and heat exchange methods, the AA-CAES system can be roughly divided into two types: regenerative and regenerative. The structure diagram is shown in Figure 1.

![Figure 1. AA-CAES system structure diagram.](image)

The difference between the regenerative and regenerative AA-CAES systems is mainly due to the different types of TES: the former uses liquid heat storage, the heat storage temperature is relatively low, and the heat exchange between the two fluids is carried out through fixed boundaries at various locations. The temperature in the heat exchanger is only related to the position during the process; the latter uses solid heat such as sand, rock, soil, metal, refractory bricks, etc., and the heat storage temperature can reach above 1000 °C, and the heat transfer during the operation of the latter system is dynamic and depends on location and time. Due to compressor outlet material restrictions, the maximum temperature of the compressor outlet air relative to solid materials is lower than the maximum heat storage temperature. In the absence of external heat sources, liquid heat storage materials that have relatively large specific heat and occupy a small area are mostly used. Therefore, the regenerative AA-CAES
system is taken as an example to briefly introduce the system operation process and model. In the energy storage phase, the AA-CAES system uses renewable energy that cannot be connected to the grid to generate electricity or the excess electrical energy in the power grid to drive the motor, which in turn drives the compressor to compress the air; the air flows through the compressors of each level and the cooling between and after the stages Heat exchange device, finally high-pressure air enters the gas storage chamber for storage; liquid heat storage medium (water, oil, etc.) flows out from the low-temperature heat storage tank, flows into the heat exchangers at all levels, and absorbs the heat of the air at the compressor outlet, and then converges at high temperature Used in thermal storage tanks when energy is released. During the energy release phase, high-pressure air flows out of the gas storage chamber. Before entering the turbine expanders of all levels to perform work, the heater before entering the stage absorbs the heat from the high-temperature heat storage medium of the thermal tank to heat up. Because of the AA-CAES system No air pollutants are generated, so the exhaust gas can be directly discharged; the heat-storage medium after heat exchange enters the cold tank for storage, and is used for the next cycle.

Table 1. Physical parameters and costs of some heat storage media

| Classification of heat storage medium | Storage temperature/ ℃ | Thermal conductivity / W·(m·K)⁻¹ | Specific heat capacity / kJ·(kg·K)⁻¹ | cost/$·kg⁻¹ |
|-------------------------------------|------------------------|-----------------------------------|-------------------------------------|------------|
| Liquid material                     |                        |                                   |                                     |            |
| mineral oil                         | 300                    | 0.12                              | 2.6                                 | 0.3        |
| Synthetic oil                       | 350                    | 0.11                              | 2.3                                 | 3          |
| Silicone oil                        | 420                    | 0.1                               | 2.1                                 | 5          |
| Nitrite                             | 250/450                | 0.57                              | 1.5                                 | 1          |
| Nitrate                             | 265/565                | 0.52                              | 1.6                                 | 0.5        |
| Carbonate                           | 450/850                | 2                                 | 1.8                                 | 2.4        |
| Solid material                      |                        |                                   |                                     |            |
| Concrete                            | 400                    | 1.5                               | 0.85                                | 0.05       |
| Sodium chloride                     | 500                    | 7                                 | 0.85                                | 0.15       |
| cast iron                           | 400                    | 37                                | 0.56                                | 1          |
| Cast steel                          | 700                    | 40                                | 0.6                                 | 5          |
| Refractory brick (silicon)          | 700                    | 1.5                               | 1                                   | 1          |
| Refractory brick (magnesium)        | 1200                   | 5                                 | 1.15                                | 2          |
| Phase change material               |                        |                                   |                                     |            |
| Sodium nitrate                      | 308                    | 0.5                               | 200                                 | 0.2        |
| Potassium nitrate                   | 333                    | 0.5                               | 267                                 | 0.3        |
| Potassium hydroxide                 | 380                    | 0.5                               | 150                                 | 1          |
| Sodium chloride                     | 802                    | 5                                 | 520                                 | 0.15       |
| Sodium carbonate                    | 854                    | 2                                 | 276                                 | 0.2        |

2.2. System thermodynamic model
Due to compressor outlet material restrictions, the compressor outlet air temperature is lower than the maximum heat storage temperature of solid materials. In the absence of external heat sources, the use of solid heat storage materials will lead to an increase in floor space and increased system investment costs. Therefore, a regenerative AA-CAES system is used as an example to build a system model. A complete cycle of the regenerative AA-CAES system can be roughly divided into two phases of energy storage and energy release. The above stages involve all the equipment and structures required for system operation. Therefore, the above stages are used as the starting point to introduce the thermodynamic models of each system in the system. In addition, in view of the important role of the gas storage chamber in the system operation process and the significant impact of different gas storage models on the cycle parameters and system performance, the thermal model of the gas storage chamber is introduced separately. In the system modelling process, the system compression stage is set to Nc,
and the expansion stage is Ne. Air is treated as an ideal gas, and its properties meet the ideal gas state equation, and the specific heat capacity is a fixed value [2]. In addition, the pipelines are ignored. 4. The heat loss of heat storage devices and heat exchangers. Ignore the along-path resistance loss and local resistance loss caused by air flowing through pipes and valves. The pressure loss caused by the working fluid flowing through the heat exchanger is calculated by empirical formula.

2.2.1. Energy Storage Phase. During the energy storage process, the air is compressed by the $N_c$ compressor and then cooled by the gas-liquid heat exchanger. The cooled high-pressure air enters the gas storage chamber for storage; the heat storage medium flows out from the low-temperature heat storage tank and is divided into various levels of heat exchange. The device absorbs the heat of high-temperature air and merges it into a high-temperature heat storage tank. Due to the irreversibility of the actual compression process, it is treated as a variable process. Let the variability index of the compression process be $\eta_c$, then the compressor outlet temperature is:

$$T_{c,\text{out}} = T_{c,\text{in}} \beta^{m_c}.$$

(1)

In the formula, $m_c = (n - 1)/n_c$; $T_{c,\text{in}}$ represents the air temperature of the compressor inlet, K; $\beta$ represents the air compression ratio. The variable efficiency of the air compressor and the variable index have the following relationship [3]:

$$\eta_c = \frac{m_u}{m_c}.$$

(2)

In the formula, $m_u = (k - 1)/k$ and $k$ represent adiabatic indices.

The efficiency and pressure ratio of the compressor are affected by factors such as gas flow rate and impeller speed. The performance of the compressor is generally expressed by a performance curve to apply to different inlet temperatures and pressures. The actual efficiency of the compressor should be obtained by checking the general curve according to the parameters such as the inlet temperature, pressure, and pressure ratio. When the compressor operating conditions deviate from the design operating conditions, the compressor efficiency will change: the larger the deviation, the lower the actual compressor efficiency. However, in simulation calculations, only the effect of pressure ratio on efficiency is usually considered, and the empirical formula is used to calculate the compressor efficiency under variable operating conditions [4]. In order to simplify the calculation, this article only considers the effect of pressure ratio changes on the compressor efficiency. When the pressure ratio deviates from the compressor rated pressure ratio, the compressor efficiency can be approximated by the following formula:

$$\eta_c = \eta_{c,r} - a_c (\beta - \beta_{c,r}).$$

(3)

In the formula, $\eta_{c,r}$ represents the efficiency at the rated pressure ratio of the compressor; $a_c$ represents the reduction coefficient of the compressor efficiency; $\beta$ represents the actual pressure ratio of the compressor; $\beta_{c,r}$ represents the rated pressure ratio of the compressor.

During the energy storage phase, the pressure in the gas storage chamber is continuously changing. Under the condition that the input power of the energy storage system is constant, the air flow of the air compressor must decrease as the compression ratio increases. However, the current practical air compressors do not have such characteristics. For example, the compression ratio of a centrifugal air compressor does not change much with the flow rate of the working fluid, while the flow rate of the working fluid of an axial flow air compressor is almost within its entire compression ratio constant. For
this reason, the compressor speed can be adjusted by a variable frequency drive or the inlet angle of the air can be changed through the inlet guide vanes to achieve the purpose of adjusting the pressure ratio and air flow [5].

2.2.2. Thermal model of gas storage device. The gas storage device is an important device of the AA-CAES system. The selection of this equipment model has a great impact on the parameters such as the system's heat storage and the working fluid temperature at the inlet of the expander. Impact. The gas storage devices are mostly underground gas storage chambers or artificial gas storage cylinders. For large-scale AA-CAES systems, natural or artificially excavated salt caves, natural gas fields, underground aquifers, and abandoned mines are used as gas storage chambers. The above gas storage chambers all have a certain pressure adaptation range, and the cost is relatively low, which can meet the gas storage requirements under different design pressure ratios.

In the early research of the AA-CAES system, the impact of the gas storage device was usually not considered or simplified to a more ideal constant temperature and constant pressure model; as the research went deeper, more constant temperature or constant capacity adiabatic models were used to explore the system Performance changes during actual operation. However, the above models do not consider the temperature change of the working medium during the gas filling and deflation process, nor do they consider the heat exchange between the inner wall of the gas storage chamber and the working medium; in addition, most of the above models are only suitable to investigate the change of system performance with the number of cycles. However, it cannot directly reveal the changes of working medium temperature and pressure ratio with time in the gas storage chamber during a single stable cycle of the system. Therefore, based on models such as adiabatic, constant temperature, and constant capacity, this paper introduces time variables and proposes a more practical constant wall temperature gas storage model in order to more accurately calculate the performance parameters of the AA-CAES system. The gas storage space is taken as the control volume CV. For the system operation process, the first law of thermodynamics can be obtained:

$$\delta Q = dU_{CV} + h_{out} \delta m_{out} - h_{in} \delta m_{in} + \delta W$$

(4)

In the formula, $\delta Q$ represents the heat exchange volume between the interior of the gas storage chamber and the environment; $dU_{CV}$ represents the energy change in the gas storage chamber; $h$ represents the air enthalpy value of the air entering and leaving the gas storage chamber; $\delta m$ represents the air quality of the air entering and leaving the gas storage chamber; The amount of work the interior exchanges with the environment.

3. Thermal performance analysis of AA-CAES system

For the regenerative AA-CAES system, MATLAB was used to program and solve the above model, and then the thermal performance of the system was analysed. Considering that the related literature has analysed the AA-CAES system with different combinations of compression and expansion stages from the perspective of technical feasibility, economy, and system complexity, the results show that when the efficiency is similar, the comprehensive performance of the two-stage symmetrical layout system is better. It has good commercial application prospects and is expected to achieve commercial application in the short term [6]. Therefore, this paper first uses the two-stage compression and two-stage expansion AA-CAES system as the object to calculate and analyse the performance of the thermal system. In the calculation, the energy storage and energy release subsystems adopt equal compression and equal expansion, respectively. Under other conditions, the maximum efficiency of the system can be approximated [7]. In order to simplify the calculation, the components of the system are simplified as follows: 1. The working process of the air compressor and the expander are both actual compression / expansion processes, that is, adiabatic and lossy processes, and the efficiency remains the same; 2. 2. The convective heat transfer coefficient in the gas storage chamber is kept constant, and the thermal
conductivity of the wall surface of the gas storage chamber is infinite. At the beginning of the cycle, the temperature in the gas storage chamber is the ambient temperature and the pressure is the minimum pressure of the gas storage; Ignore the external heat loss of the cold and hot heat storage tanks, and the heat capacity of the heat storage medium is equal to the heat capacity of the working medium in a single cycle, that is, \((cm)_{res} = (cm)_{air}\).

The AA-CAES system only has the input and output of power during the operation, and it ignores the heat dissipation of the heat storage tanks and pipes, and exchanges heat with the external environment. Therefore, the main parameter to measure the performance of the system should be the ratio of output to input power, that is, the cycle efficiency of the system; In addition, the output power corresponding to the unit of gas storage space-energy storage density is also an important indicator of system performance. When the system is circulated for the first time, the temperature of the heat storage tank is set at the ambient temperature, and the temperature of the cold and hot tank at the end of the first cycle is used as the initial temperature of the next cycle. As the number of cycles increases, parameters such as heat storage temperature, input / output power, and cycle efficiency change. The variation of the heat storage temperature of cold tank and hot tank with the number of cycles is shown in Figure 2.

![Figure 2. Change of heat storage temperature with cycle times.](image)

It can be seen from Figure 2 that with the increase of the number of system cycles, the heat storage temperature of the cold and hot tanks is increasing, and the temperature of the hot tank is increasing faster, but when the number of cycles reaches a certain value (about 4 in the figure), the temperature of the two tanks tends to be stable and no longer changes. The reason for the above-mentioned change in the heat storage temperature is the change in the heat release and heat absorption of the working medium during the energy storage and release process. As the number of system cycles increases, the temperature of the cold tank continues to rise, and the air temperature at the compressor outlet remains basically unchanged,. The heat exchange temperature difference between working medium and heat storage medium is reduced. Because the heat exchanger efficiency is maintained constant, the heat storage medium absorbs less heat during the energy storage stage; and because the temperature of the hot tank increases significantly with the number of cycles, the air temperature in the gas storage room The change range is small, and the heat release amount of the heat storage medium in the energy release stage increases. When the heat release amount of the working fluid in the energy storage stage and the heat absorption amount of the heat release medium reach a balance, the temperature of the cold and hot tanks is maintained at a constant temperature. The system power and heat changes during the cycle are shown in Figure 3, which is represented by energy density.
Figure 3. Changes in system energy density with number of cycles.

From Figure 3, it can be seen that the heat change during the system cycle is consistent with the previous analysis, that is, the heat release of the working fluid decreases during the energy storage phase, the heat absorption of the working fluid increases during the energy release phase, and finally the heat absorption and discharge reaches equilibrium. With the increase of the number of cycles, both the compression work and the expansion work of the system decrease, and the compression work decreases by a large margin, and eventually stabilizes. Because the input and output power are constant, the change of compression work and expansion work is closely related to the energy storage and release time. According to the mathematical model, the length of the above time is related to the working medium parameters in the gas storage room.

4. Summary

When the storage pressure ratio is increased by an equal amount, the compression and expansion work also increase, the heat storage capacity increases, the system cycle efficiency also improves, and the efficiency increase is relatively stable. When the storage pressure difference decreases, the equipment operates more efficiently. Both the compression work and the expansion work have decreased significantly, but the cycle efficiency of the system has increased significantly; an increase in the pressure difference in the storage pressure will lead to an increase in the single-stage pressure ratio change, which deviates far from the rated conditions, and the cycle efficiency decreases.

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