Characteristic analysis of compressed air energy storage system based on intermediate cooling

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Abstract—With the shortage of traditional fossil energy and the aggravation of global warming, the demand for transformation from traditional fossil energy to renewable energy becomes more and more urgent. Compressed air energy storage technology is a guaranteed technology to overcome the time limit of renewable energy and achieve sustainable, efficient and large-scale application of renewable resources. In order to solve the traditional compressed air energy storage technology energy output variety is single, there is low grade energy waste defects. This paper presents a compressed air energy storage system based on intermediate cooling. Through the intercooler, the system adjusts the inlet temperature of the expander, improves the output cooling quality, and realizes the coupling operation of refrigeration and energy storage. This paper establishes a thermodynamic model of the system, analyzes the effects of ambient air temperature and inlet temperature of expander on system performance, and compares the energy efficiency ratio of the system with that of compressed air refrigeration system. The simulation results show that the system can adjust the inlet temperature of expander to increase the net power consumption and achieve high quality cooling output.

1. Introduction

With the development of industry in the world, energy crisis and environmental pollution are becoming increasingly serious. In order to solve energy and environmental problems, human beings are gradually accelerating the pace of exploring green energy and technology. Compressed air energy storage technology is one of the effective methods to achieve efficient utilization of renewable energy\cite{1,2}. Compressed air energy storage technology realizes energy storage and release through air compression and release\cite{3-5}. The traditional compressed air energy storage technology needs to consume additional fossil fuels in the energy release stage, and the low-grade energy is seriously wasted\cite{6-8}. Compressed air energy storage system has the potential to combine hot, cold and electric energy needs. If the air temperature is controlled at the inlet of the expander, low temperature air can be obtained at the outlet of the expander to provide users with high quality cold source. Therefore, the compressed air energy storage system can not only increase the types of energy output, but also improve the energy utilization rate\cite{9-12}. At present, most studies on coupling systems are only based on the use of low-grade cold at the outlet of expander, while studies on the coupling of refrigeration and power generation systems based on intermediate cooling to improve the quality of cold at the outlet are limited.

In this paper, a compressed air energy storage system based on intermediate cooling is proposed. The system outputs and stores energy through air expansion and generates low temperature air at the same time to achieve the purpose of combined cooling and power generation. In this paper, the effects of ambient temperature and inlet temperature on system performance are analyzed by calculating the outlet
temperature and output power of air expander and the net power consumption of the system under different conditions, and the energy efficiency ratio of the system and compressed air refrigeration system is compared.

2. System Introduction
The compressed air energy storage system based on intermediate cooling is mainly composed of air compressor, filter dryer, gas storage tank, expander, cooler and cold storage. The operation flow chart and T-s diagram of the system are shown in Fig. 1 (a) and Fig. 1 (b).

In the energy storage stage, the air in the atmospheric environment changes from state point 0 to state point 1 after being compressed by the air compressor, and from state point 1 to state point 2 after being processed by the filter dryer. The treated air enters the air storage tank, and the high temperature and high-pressure air in the air storage tank exchanges heat with the ambient air. The temperature decreases, and the state point 2 changes to state point 3. In the energy release stage, the air in the air storage tank enters the air cooler and exchanges heat with the air at the outlet of the cold storage, changing from state point 3 to state point 4. Then, air enters the expander for work, and state point 4 becomes state point 5. When the temperature is reduced to the set requirements, the air enters the cold storage and changes from state point 5 to state point 6 after heat exchange. After that, the air enters the air cooler to exchange heat with the air at state point 3, and state point 6 becomes state point 7. This reciprocating cycle, to achieve the combined generation of cold and electricity.

3. System Mathematical Model
In order to discuss the performance characteristics of the system, a mathematical model was established and analyzed based on the first and second laws of thermodynamics. The calculation flow chart is shown in Fig. 2(a).

At the same time, in order to simplify the system, the following assumptions are made:

1. the system is in a steady state during operation.
2. The air pressure loss of all system pipelines such as air compressor and expander, filter dryer and gas storage tank are fixed at 5%.
3. Kinetic energy and potential energy are ignored in the process of system operation.
4. Ignore water vapor content in wet air.

The mathematical model of compressed air energy storage system based on intermediate cooling is as follows.

3.1. Air Compressor
The air inlet temperature of the compressor is atmospheric ambient temperature, and the air inlet pressure of the compressor is atmospheric ambient pressure, that is:

\[ T_0 = T_{amb} \]  \hspace{1cm} (1)

\[ p_0 = p_{amb} \]  \hspace{1cm} (2)

Fig. 1 (a) Flow chart of Compressed air energy storage system based on intermediate cooling (b) T-s diagram Compressed air energy storage system based on intermediate cooling
Where, \( p_{\text{amb}} \) is atmospheric pressure, kPa.

\[
p_1 = \frac{\varepsilon}{1 - \varepsilon} p_0
\]

Where, \( \varepsilon \) is the ratio of air outlet pressure to inlet pressure of air compressor.

\[
\eta_{\text{com}} = \frac{h_1 - h_0}{(h_{1,s} - h_0)}
\]

Where, \( \eta \) and \( h \) respectively represent the efficiency and enthalpy of the expander, \( s \) represents the isentropic process.

\[
W_{\text{com}} = m_{\text{air}}(h_1 - h_0)/\eta_g \eta_m
\]

Where, \( W_{\text{com}} \) is the power consumption of the air compressor, \( m_{\text{air}} \) is the mass flow rate of air, \( \eta_g \) and \( \eta_m \) are the efficiency and mechanical efficiency of the motor.

3.2. Filter dryer

\[
p_2 = 0.95p_1 \\
T_2 = T_1
\]

3.3. Storage tanks

As there is a temperature difference with the atmospheric environment, the air in the Storage tanks will exchange heat with the atmospheric environment, so the air storage tank is the pre-cooler of compressed air.

\[
T_3 = T_2 - \Delta T_1
\]

Where, \( \Delta T_1 \) is the temperature drop, \(^\circ\text{C}\), during the storage of compressed air.

Based on the first law of thermodynamics, the following equation can be obtained:

\[
du = m_3 h_2 - m_3 h_3 - Q_{\text{loss}}
\]

Where \( u \) is the specific internal energy of air (kJ/kg), \( h \) is the specific enthalpy of air (kJ/kg); Heat transfer between compressed air and atmospheric environment in \( Q_{\text{loss}} \) tank, kW.

3.4. Air cooler

The energy balance equation in the air cooler is:

\[
h_3 - h_4 = h_7 - h_6
\]

\[
p_4 = p_3 \\
T_4 = T_3 - \Delta T_2
\]

Where, \( \Delta T_2 \) is the temperature drop in the cooling process of compressed air, \(^\circ\text{C}\).

In order to quantify and evaluate the cooling performance of compressed air between the air compressor outlet and the expander inlet, a parameter ATD, is introduced. The formula is as follows:

\[
\text{ATD} = T_5 - T_4
\]

3.5. Expander

The isentropic efficiency of the expander is shown in the following formula:

\[
\eta_{\text{exp}} = \frac{h_4 - h_5}{(h_4 - h_4,s)}
\]

Where \( \eta_{\text{exp}} \) is the efficiency of the expander.

The output power of the expander is shown in the following formula:

\[
W_{\text{exp}} = m_3 (h_4 - h_5) \eta_g \eta_m
\]

Where, \( W_{\text{exp}} \) is the output power of expander.

3.6. System Features

The difference between the power consumption of the air compressor and the output power of the expander is the net power consumption, and the formula is as follows:

\[
W_{\text{net}} = W_{\text{com}} - W_{\text{exp}}
\]

In order to quantify and evaluate the power consumption recovery efficiency of the expander to the
air compressor, a dimensionless parameter $R_{rec}$ was proposed, which was the ratio of the expander output power to the power consumption of the air compressor.

$$R_{rec} = \frac{W_{exp}}{W_{com}}$$  \hspace{1cm} (18)

4. Model Verification

To verify the reliability of the model, the same experiment as the simulated condition was set up. The comparison results of numerical simulation values and experimental values are shown in Fig. 2(b). Under the condition of different air mass flow rate, the maximum error of output power is only 3.96kW, and the maximum relative error is 6.48%. The main reason for the error is the measurement error of temperature, pressure and other parameters. In conclusion, the model is reliable.

5. Results and Discussion

5.1. Effects of atmospheric ambient temperature and ATD on system performance

Air temperature at the outlet of the expander changes with atmospheric ambient temperature and ATD, as shown in Fig. 3(a). Under the condition that ATD remains constant, the outlet temperature of expander increases with the increase of atmospheric ambient temperature. The larger the ATD is, the lower the air outlet temperature of the expander is when the ambient temperature of the atmosphere is kept constant. This is because in the case of a certain compression ratio, when the environment remains unchanged, the increase of ATD means that the inlet temperature of the air expander decreases, which will inevitably cause the air temperature at the outlet of the expander to be lower. Therefore, the system can control the air temperature at the outlet of the expander by adjusting ATD.

As atmospheric ambient temperature and ATD change, the output power of air expander changes as shown in Fig. 3(b). It can be seen from the figure that under the same ATD, the output power of air expander increases gradually with the increase of ambient temperature, which is because the increase of atmospheric ambient temperature increases the inlet temperature of the expander. The specific enthalpy drop of air per unit mass flow rate in expander increases, which is beneficial to increase the output power of expander. With the increase of ATD, the output power of expander decreases under the condition that atmospheric ambient temperature remains unchanged.
As atmospheric ambient temperature and ATD change, the changes of net power consumption and power consumption recovery efficiency are shown in Fig. 4(a) and Fig. 4(b). It can be seen from the figure that, under the condition that atmospheric ambient temperature remains unchanged, with the increase of ATD, net power consumption increases and power consumption recovery decreases. When ATD is kept constant, the relationship between net power consumption and power recovery with ambient temperature is related to ATD. This is because the power consumption of air compressor is related to atmospheric temperature and has nothing to do with ATD. When the atmospheric temperature is constant and ATD increases, the output power of the expander gradually decreases while the power consumption of the compressor is constant, resulting in an increase in net power consumption.

5.2. Comparison of air-cooling performance with ACRC

To sum up, the increase of air temperature at the outlet of expander is at the cost of the increase of net power consumption and the decrease of power consumption recovery. In order to quantify and evaluate the cooling effect of the system, the difference and ratio between the net power consumption $W_{\text{net}}$ of the system and the net power consumption $W_{\text{ACRC}}$ of the ACRC system are taken as evaluation criteria. As ATD and atmospheric ambient temperature change, their differences change as shown in Fig. 5(a). Under the condition that ATD remains unchanged, the difference between ATD and ATD increases gradually with the increase of atmospheric temperature. According to the simulation data, when ATD is less than 12°C, the outlet temperature of the expander is higher than the atmospheric temperature, and the cooling performance is 0. When ATD is greater than 12°C and less than 28°C, the power consumption of the ACRC system is small, resulting in a large $W_{\text{net}}/W_{\text{ACRC}}$ result. Therefore, when ATD is greater

![Figure 3](image_url)  
**Figure 3** (a) Variation of $t_{\text{exp,out}}$ with the ambient temperature and ATD (b) Variation of $W_{\text{exp}}$ with ambient temperature and ATD

![Figure 4](image_url)  
**Figure 4** (a) Variation of $W_{\text{net}}$ with ambient temperature and ATD (b) Variation of $R_{\text{rec}}$ with ambient temperature and ATD
than 28℃, it can be seen from Fig. 5(b) that when ATD is greater than 36℃ and $\frac{W_{\text{net}}}{W_{\text{ACRC}}} < 1$, the refrigeration performance of the system is higher than that of the ACRC system.

6. Conclusion
This paper puts forward a kind of based on intermediate cooling compressed air energy storage cold electricity co-generation system, based on the first and second laws of thermodynamics to build the mathematical model of the simulated calculation, analysis of the atmospheric environment temperature and ATD changes affect the performance of the system, the refrigeration efficiency of the system with ACRC compares the refrigeration efficiency of the system, and the conclusion is as follows:

(1) With the decrease of atmospheric ambient temperature and the increase of ATD, the outlet temperature of the expander gradually decreases. In practice, ATD regulation is easier to achieve than atmospheric temperature regulation. Therefore, the system can control the outlet temperature of the expander by adjusting the atmospheric temperature and ATD, that is, high quality cooling output.

(2) With the increase of ATD, the output power of expander decreases, the net power consumption of the system increases, and the power consumption recovery rate decreases. This indicates that the decrease of the outlet temperature of the expander is at the cost of the increase of the net power consumption of the system.

(3) With the ATD unchanged, the difference between the net power consumption of the system and the power consumption of the ACRC system increases with the increase of atmospheric ambient temperature. When ATD > 36℃, the cooling performance of the system is higher than that of the ACRC system.

In the future, the system can be coupled with the heat storage system to realize the recovery and utilization of heat generated in the compression process. On the premise of high-quality cooling output, net power consumption is reduced, power consumption recovery rate and energy utilization rate are improved.

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