CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081192

Trigeneration Performance Analysis on Adiabatic Compressed Air Energy Storage System Based on Parameters of Discharging Process

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The energy storage technology can be applied for the efficient use of energy, to solve the problem when the source of renewable energy is unstable and the insufficient supply or oversupply caused by peaks and valleys in the power supply network.In view of the energy storage system, the development of adiabatic compressed air energy storage system (ACAES) is rapid. Although the trigenerative ACAES including power output, cooling and heating processes have been studied extensively, the research on discharging process of ACAES is still in lack. In this consideration, this paper studies the influence of key factors in the discharging process on the system performance, and the expansion stage and water mass flow rate of heat exchanger are considered. In the system simulation. the number of expansion stages is set as 2, 3, 4, 5 and 6. And the range of water flow rate is selected from 1 $kg{\cdot}s^{-1}$ to 6 $kg{\cdot}s^{-1}$. On this basis, the following four aspects of performance are analysed: charging and discharging time, power and energy supply, efficiency, and exergy loss. Simulation results indicate that quantities related to the charging process keep constant. With enhancing heat exchange, energy distribution will be changed. And the enhanced heat transfer is suitable for a longer discharging time and less cooling capacity. But the enhancement of heat transfer is limited. As the increasing expansion stages will weaken the output power and cooling supply, the optimal expansion stages should be chosen with the help of efficiency analysis. This paper provides a reference for the practical optimisation of discharging process of ACAES.

1. Introduction

Due to the characteristics of human activities in a certain period of time, there will be a "peak valley" problem in the electricity supply network, which leads to insufficient or oversupply. It is valuable to store the surplus energy in the "valley" period and to release it in the peak period. There are many ways of energy storage, such as pumped hydroelectric storage (PHS), a compressed air storage system (CAES), flywheel storage and so on. Among them, CAES is the best choice for large-scale grid energy storage. Recently, the recovery of compression heat based on CAES is proved that can solve environmental problems and greatly improve the efficiency of the system, so the ACAES is more worthy of study (Zhou et al., 2019). Wind, solar energy has the characteristics of discontinuity and instability, and some researchers proposed that trigenerative system, which includes power output, heating and cooling based on ACAES, can solve these problems.

Generally, the ACAES system has four operation modes, including constant pressure charging, constant pressure discharging, constant-sliding, sliding-constant and sliding-sliding. The sliding-sliding mode has been proved as the best operation one (Han et al., 2018). Another paper devoted to studying sliding and constant pressure charging modes of the ACAES system based on MATLAB. It indicates that the sliding pressure charging mode is better (He et al., 2020).

In research of ACAES technology, many of them are optimisation study. The parametric study results applied on the hot temperature of the thermal energy storage indicate the possibility to find an optimal solution as a trade-off between system performances and other parameters reflecting its cost (Mohamad et al., 2019a). A new method was put forward, corresponding-point methodology (CPM), for analysing and optimising compressed air energy storage (CAES) system. A diagram of thermal exergy and mechanical exergy

Paper Received: 29/04/2020; Revised: 14/06/2020; Accepted: 20/06/2020
Please cite this article as: Du R., He Y., Deng J., 2020, Trigeneration Performance Analysis on Adiabatic Compressed Air Energy Storage System Based on Parameters of Discharging Proce, Chemical Engineering Transactions, 81, 1147-1152 DOI:10.3303/CET2081192

(Eth−Emech diagram), which reflects not only energy loss but also the quantity of stored energy. This method, along with Eth-Emech diagram makes the analysis and optimisation of the CAES system more efficient and explicit (Guo et al., 2018). A novel throttling strategy of adiabatic compressed air energy storage system based on ejector was proposed, for which enhance the system performance. And indicates that the round-trip efficiency improves 2 % than conventional system through energy and exergy analysis (Chen et al., 2018). The energy loss of the A-CAES was analysed, and blade inlet angle was put forward firstly to improve disadvantages of narrow operating conditions and low efficiency. Then, improve energy charging efficiency with wide storage pressure through variable rotating speed method (He et al., 2018).
The thermodynamic model for each component and ACAES system was established (Mohamad et al., 2019b). The thermodynamic analysis model of the variable pressure ratio CAES system was established (He et al., 2019). The thermodynamic model of each component was given for simulating, studied the influence of the water mass flow rate and the compression stages in the charging process on each performance of the ACAES. The trend of round-trip efficiency and exergy efficiency with the change of water mass flow rate and compression stages were showed through energy and exergy analysis of each component (He et al., 2020). However, there is a lack of research and optimisation of discharging process.
One paper indicates that expander has a great influence on power conversion efficiency of the CAES, and elaborated how to select appropriate expander and expander stages according to concrete CAES systems and different operating conditions (He et al., 2018).
In addition to theoretical analysis, scholars also study the actual devices and related experiments. A configuration of trigenerative CAES was introduced to give the preference to the electric energy production (Mohamad et al., 2019a). In another paper, it use an experiment to verify the model, detect the impact of operating parameters on system efficiency and model accuracy. The results show that the cycle efficiency is only 15.6 %, and the error between the model output and the experimental results is less than 13.2 % (Mohamad et al., 2019b).
It has been proved sliding-sliding mode is most efficient. And now there is a lack of research or simulation on the discharging process. This paper establishes the mathematical model of each component to study the simulation of the trigenerative ACAES with MATLAB under the sliding-sliding pressure mode, and explore the influence of the expansion stages and the water mass flow rate in the heat exchanger during discharging process on the system performance. This paper is of great referential value to the system optimisation in the discharging process.

2. System description and mathematical model

The ACAES can be divided into charging, storage and discharging process. The diagram is shown in Figure 1.

2.1 System description

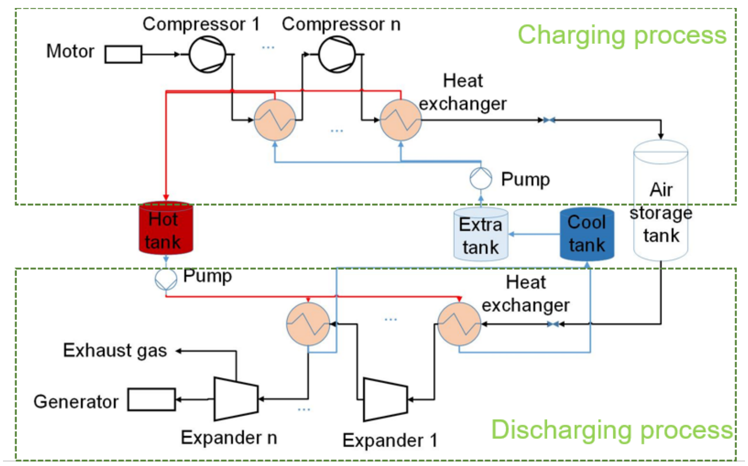


Figure 1: Diagram of ACAES

The charging part includes a multi-stage compressor, heat exchanger and throttling valve. The discharging part includes multi-stage expander, heat exchanger and expansion valve. The air enters the heat exchanger after compression, recovers the compression heat, and enters the air storage tank through sliding pressure mode. Coldwater is pumped into each heat exchanger from the cold water storage tank in parallel and then collected into the hot water storage tank after recovering. And the second process, the compressed air is stored in the storage tank. When power generation is needed, the discharging process starts. After the compressed air is preheated, it enters the expander in sliding pressure mode. The hot water is pumped into each stage of heat exchanger in parallel, and after preheating the expansion air, it then flows into the cold water storage tank. The hot water provides heating, and the cold water provides cooling. After the cooling supply process, the cold water flows into the extra water storage tank, and at the same time, the extra normal temperature water is added into the extra water tank. This paper mainly studies the discharging process. The charging stage is fixed as a four-stage compressor and four heat exchangers. The system parameter settings are shown in Table 1.

Table 1: Concrete parameters of ACAES

Parameter	Unit	Value
The volume of an air storage tank	m^3	5,000
Maximum/minimum pressure of storage tank	MPa	10 / 4.5
Pressure loss in a heat exchanger	MPa	0.02
Heat transfer coefficient of the storage tank	$W \cdot m^{-2} K^{-1}$	50
Pressure of water	MPa	4
Water mass flow rate of the heat exchanger during the charging period	$kg \cdot s^{-1}$	5
Water mass flow rate of the heat exchanger during the discharging period	$kg \cdot s^{-1}$	1,2,3,4,5,6
Rated isentropic efficiency of compressor /expander	---	85 % / 88 %
Rated air mass flow rate of compressor/expander	$kg \cdot s^{-1}$	10

2.2 Mathematical model

The mathematical model of main components are as following:

2.2.1 Compressor

The compression ratio π_c, isentropic efficiency η_c, power input W_c and exergy loss dex_c of off-design performance of centrifugal and axial compressors defined as following (Zhang and Cai, 2002).

$$\frac{\pi_c}{\pi_{c,0}} = c_1 (m'_c)^2 + c_2 m'_c + c_3 \tag{1}$$

Where concrete calculation relationship of c_1, c_2, c_3, m'_c can be seen in this paper (Guo et al., 2019).

$$\eta_c = \frac{h_{c,out,s} - h_{c,in}}{h_{c,out} - h_{c,in}} \tag{2}$$

$$W_c = m_c (h_{c,in} - h_{c,out}) \tag{3}$$

$$dex_c = W_c - m_c [h_c - h_{in} - T_0 (S_c - S_{in})] \tag{4}$$

2.2.2 Expander

The work output W_e is the same as compressor and the exergy loss of expander dex is defined as follows:

$$dex = m(ex_{in} - ex_0) - mW_o \tag{5}$$

2.2.3 Heat exchanger

The heat exchange Q and exergy loss dex in the heat exchanger are calculated by:

$$Q = m_a \left(h_{a,in} - h_{a,out}\right) = m_w (h_{w,out} - h_{w,in}) \tag{6}$$

$$dex = m_w \left(ex_{w,in} - ex_{w,out}\right) + m_a \left(ex_{a,in} - ex_{a,out}\right) \tag{7}$$

In this paper, heat exchangers are suited to the $\varepsilon - \mathrm{NTU}$ method (Yao et al., 2017).

2.2.4 Storage tank

A dynamic model of the storage tank is showing as following:

$$\frac{dM_{st}}{dt} = m_{st,in} - m_{st,out} \quad (8)$$

$$\frac{dM_{st}u_{st}}{dt} = m_{st,in}h_{st,in} - m_{st,out}h_{st,out} - K_{en,st}A_{st}(T_{st} - T_{en}) \quad (9)$$

The temperature and pressure of the storage tank can be known by using the function of density and enthalpy.

2.2.5 Throttling valve

The throttling valve used in this paper is isenthalpic.

3. Results and discussion

The following four aspects are analysed: charging and discharging time, power and energy supply, efficiency and exergy loss.

3.1 Charging and discharging time

From Figure 2 can be seen when water mass flow rate and expansion stages change, the charging time will remain at 7.59 h. Since the expansion stages and water mass flow rate are the quantity of the discharging process, the change of them will not affect the charging process, and the charging time is constant.
The discharging time rises with the increase of water mass flow rate, but it doesn't increase much when the water mass flow rate is 4 kg·s^{-1}, 5 kg·s^{-1} and 6 kg·s^{-1}. When the number of expansion stages is from 2 to 4, the discharging time increases, while when the number of expansion stages is from 4 to 6, the discharging time decreases. There is a state of maximum discharging time, and the number of expansion stages is 4.

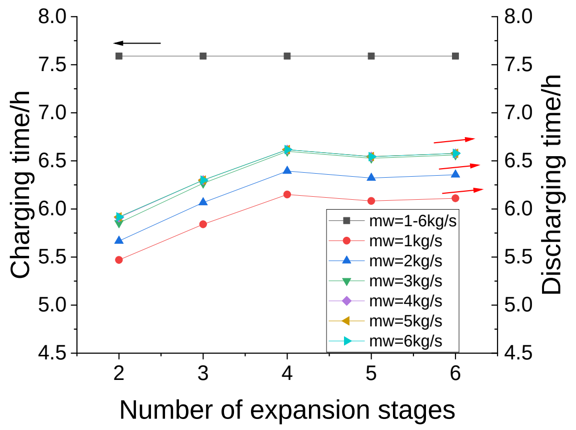
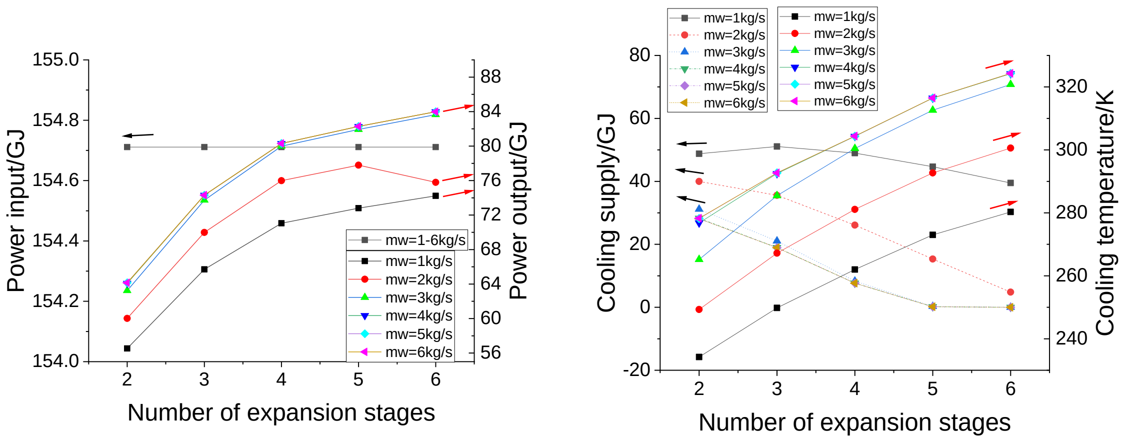


Figure 2: The trend of charging and discharging time

3.2 Power output, heating and cooling supply

Figure 3a shows the total input power is invariant, which is 154.711 GJ. When the water mass flow rate is fixed, the power output increases with the increase of the number of expansion stages; when the number of expansion stages is fixed, the preheating air effect increases with the increase of water flow rate, and the single-stage expansion work increases, so the total power output also increases, but when the water mass flowrate is 4 kg s^{-1}, 5 kg·s^{-1} and 6 kg·s^{-1}, the difference is tiny.
Due to heating is related to charging process, heating supply and temperature is constant.The heating supply is 16.074 GJ, and the available heating temperature is 369.71 K.
Figure 3b shows the total cooling supply decreases with the increase of expansion stages and water mass flow rate. Similarly, it does not change much at 4 kg·s^{-1}, 5 kg·s^{-1} and 6 kg·s^{-1}. The cooling temperature increases with the increase of expansion stages and water mass flow rate. In three processes, only the exhaust gas at the expansion outlet in the discharging process can provide cooling capacity. When the water mass flow rate increases, the heat exchange improves, the inlet and outlet temperature of each stage of the expander will rise,

and the enthalpy of the outlet gas will decrease, so the cooling capacity temperature will rise, and the total cooling capacity supply will decrease.



(a) (b)

Figure 3: (a) The trend of power input and output (b) The trend of cooling supply and temperature

3.3 Efficiency

The round-trip exergy efficiency is the ratio of the sum of the hot water exergy flow and the storage tank exergy flow to the total power input, which does not change in the charging stage. The energy efficiency is the ratio of the sum of the heating and cooling supply to total power input. The energy efficiency increases first and then decreases with the increase of expansion stages, and decreases with the increase of water mass flow rate, ranging from 0.6 to 0.9. It can be seen that when the water mass flow rate is 1 kg·s^{-1}, the maximum efficiency occurs when the expansion stage is 4, when the water mass flow rate grows larger, the maximum efficiency occurs with an expansion stage of 3. When the number of stages is increased, the power input is constant, the output work is increased, the heating supply is constant, and the cooling capacity is reduced, the comprehensive effect makes energy efficiency reduce. When the water mass flow rate increases, power input remains the same, the output work increases, the heating supply remains the same, and the cooling capacity decreases. Similarly, the comprehensive effect makes energy efficiency reduce.

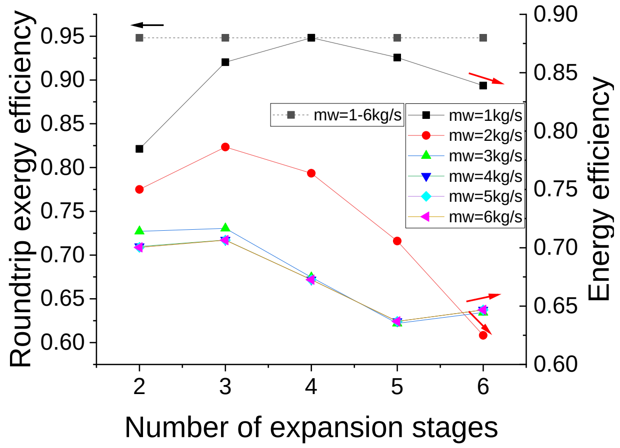


Figure 4: The energy efficiency, round-trip exergy efficiency under different water mass flow rate

3.4 Exergy loss ratio

Under different water mass flow rates, expansion valve has no exergy loss. The exergy loss ratio of the compressor is 11.76 %. The exergy loss of heat exchanger range from 7.61 % to 9.67 %. The exergy loss coefficient of the storage tank is 1.44 % ~ 1.48 %. The exergy loss ratio of turbine is about 15 %. Under different

expansion stages, the exergy loss ratio of the compressor is 11.76 %. The exergy loss ratio of heat exchanger increases from 7.42 % to 7.81 %. The exergy loss ratio of the storage tank is about 1.44 %. With the increase of expander stages, the exergy loss ratio decreases from 21.11 % to 13.56 %.
From above, the turbine is the component which has the largest exergy loss ratio. Because the dependent variables studied in this paper are the water mass flow rate in the heat exchanger and the number of expansion stages, the heat exchanger and turbine are the most sensitive components for the change of exergy loss ratio.

4. Conclusions

(1) Parameters related to the charging process keep constant with different expansion stages and water mass flow rate.
(2) The increase in water mass flow rate enhances the heat exchange, and it will change energy distribution in manners of increasing the proportion of output power and decreasing cooling supply. It also makes the discharging time longer. Thw enhanced heat transfer is suitable for occasions with longer discharging time and less cooling capacity. The enhancement of heat transfer is also limited. The effect of system change is not obvious when the water mass flow rate reaches to a certain value and the water mass flow rate exceeds the certain value should be avoided in the actual operation.
(3) The increase of expansion stages will weaken the output power and cooling supply. It is necessary to use fewer expansion stages when the more output power or cooling capacity supply is demanded. In the case shown in this paper, when the heat exchange effect is poor, the optimal expansion stages are 4, and when the heat exchange effect is strong, the optimal expansion series is 3.
(4) Turbine has the largest exergy loss ratio of all components in the system.

Acknowledgements

This research work is supported by the National Key Research and Development Program of China (Grant No. 2017YFB0903602).

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