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Performance Research on a Compressed Air energy Storage System with Ejector Installed in front of Air Storage Tank

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Adiabatic compressed air energy storage (A-CAES) is a promising massive energy storage to eliminate the fluctuation nature of renewable energy. In a traditional A-CAES system, a throttle valve is installed in front of air storage tank to reduce the unstable effect of pressure change in air storage tank on compression train. This study proposes a novel A-CAES system, where ejector is used to replace the throttle valve to recover pressure energy and reduce throttling loss. The charging process of the proposed A-CAES system included two periods. In the first charging period, the ejector works, and the secondary fluid of the ejector is from the outlet air of the 3rd stage compressor. In the second period, the ejector stops working and the 4-th stage compressor implements varying rotation speed operation to adapt the pressure changing in air storage tank. The mass flow rate of compression train keeps constant controlled by the regulating valve installed inlet of compression train. A dynamic model and an exergy destruction model of the proposed A-CAES system are established. The simulation results show that the ejector can improve exergy efficiency and shorten the range of unstable operation. The average exergy efficiency of proposed system increases with the increase of initial storage pressure and the optimization effect of the varying rotation speed operation on average exergy efficiency is more obvious.

1. Introduction

With the increase of demand for energy and the depletion of fossil fuel, the penetration of renewable energy sources in power system is higher. The intermittent and unpredictable nature make them unstable and uncontrolled energy sources. Compressed air energy storage (CAES) system is one of the energy storage system to overcome these disadvantages. The feasibility of using CAES system to integrate fluctuating renewable power with the electricity grid systems has been proven (Jin et al., 2019).

Some problems of CAES system still need to be solved. Conventional CAES system, such as Huntorf plant and McIntosh plant, used fossil fuel to heat compressed air, which brought environment pollution and limited roundtrip efficiency to 40 – 54 % (Budt et al., 2016). Adiabatic CAES (A-CAES) system was proposed to overcome these shortcomings (Zhang et al., 2020). Li et al. (2019) ultilized phase change materials and sensible materials to store and recycle compression heat, which avoided fuel consumption, and the roundtrip efficiency was improved to 61.15 %. In an A-CAES system with isochoric air storage tank, the pressure of air storage tank effected the steady operations of compressors and turbines if without throttle valve installed at outlet of high pressure compressor and inlet of high pressure turbine. He et al. (2019) used valves to control the connection mode of compressors in series and/or parallel to change the pressure ratio of compression train, where all compressors worked under the rated conditions. Han et al. (2020) researched on three operation modes of compression train in A-CAES system, where the sliding-pressure operating mode without throttle valve connected to the storage tank presented the highest roundtrip efficiency of 51.48 % and constant pressure mode with throttle valve leaded to the minimum roundtrip efficiency of 50.21 % among the three operation modes. The throttling loss from throttle valve in discharging process contributed 3.64 % of total energy loss (Guo et al., 2019).

In order to decrease the throttling loss of throttle valve, ejectors were introduced to the discharging process of CAES system to replace throttle valve and improve the system performances. Chen et al. (2018) investigated

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an A-CAES system equipped with an ejector, where two or more air storage tanks were used and the secondary fluid of the ejectors was from a lower-pressure storage tank. Compared to A-CAES system, the roundtrip efficiency was improved nearly 2 % and the profit increased by more than 21 %.
Many researchers studied multi-stage compressor by adjusting rotation speed to adapt pressure changing of air storage tank, and the A-CAES system compressors varying rotation speed operation on compressors is abbreviated VA-CAES system. Guo et al. (2019) investigated the dynamic process of CAES system, where off-design performance model of the compressor was considered with different speed. He et al. (2018) studied multi-stage centrifugal compressor used in CAES system, where the available range of relative rotation speed for whole compression train was 0.85 ~ 1.05.
Considering the throttling loss of throttle valve and the changing pressure of air storage tank, this paper proposes an A-CAES system with an ejector used in charging process and high pressure compressor with variable rotation speed operation (EVA-CAES). The framework of this paper is as follows: the description of EVA-CAES system is presented in Section 2, Section 3 presents the main thermodynamic calculation model of the system, Section 4 shows the performance analysis of the system, and the conclusions are showed in Section 5.

2. System description

The diagram of charging process in EVA-CAES system is shown in Figure 1. In the charging process, the system is composed of four-stage compressor with four cooling exchangers, four regulating valves, one ejector, one air storage tank, one pump, one cold water tank, and one hot water tank. Previous three-stage compressor work in design condition, and mass flow rate of compression train is controlled by regulating valve installed inlet of first stage compressor. The charging process is divided into two periods.

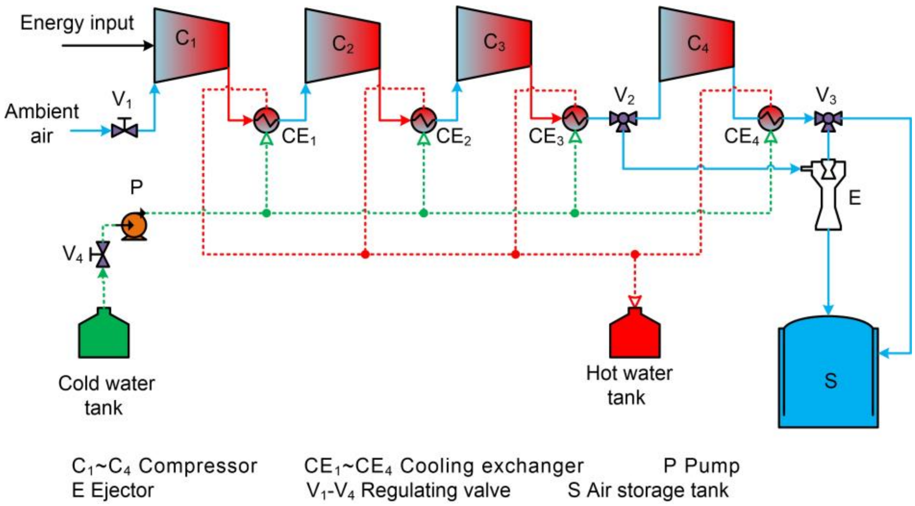

Figure 1: The diagram of charging process in EVA-CAES system

In the first charge period, the mass flow rate of the fourth stage compressor is less than rated value. Ambient air is compressed by first stage compressor, and then is cooled down by the first cooling exchanger. Similarly, air is compressed by the second and third stage compressor, and is cooled down by the second and third cooling exchangers. The outlet air of the third cooling exchanger is divided into two part, where one part is compressed by the fourth stage compressor and cooled down by fourth cooling exchanger, finally goes into the ejector as primary fluid, and another part works as secondary fluid of the ejector. And the mixed fluid of the ejector is ejected into air storage tank. When the pressure of air storage tank is equal to the critical pressure of the ejector, the ejector stops working by adjusting the second and third regulating valves and the first charge period finishes. In the second charge period, the fourth stage compressor is under variable speed operation. When the pressure of air storage tank is equal to the maximum storage pressure of air storage tank, the second charge period finishes.

3. Thermodynamic model

In order to simplify the thermodynamic model properly, the following assumptions are made.
(1) The pressure and heat loss of pipes, cooling exchangers, cold water tank and hot water tank are neglected.
(2) No external heat interacts with ejectors.

(3) Ignore the effect of the kinetic and potential energy.
The calculation model of compressors is used based on loss model in He et al. (2018). The total energy consumption of the i-th stage compressor is,

$$W_{\mathrm{i,tot}} = W_{\mathrm{th}} + \Delta W_{\mathrm{par}} = W_{\mathrm{e}} + W_{\mathrm{int}} + \Delta W_{\mathrm{par}} \tag{1}$$

where W_{e} is the energy consumption of compressor, W_{th} is the energy increase of the air by the compressor. Based on loss mechanism, energy loss includes internal flow loss W_{int} and parasitic loss ΔW_{par}.
The exergy destruction of the i-th stage compressor is,

$$Dex_{\mathrm{i,C}} = m_{\mathrm{i,C}} \cdot (ex_{\mathrm{i,C,out}} - ex_{\mathrm{i,C,in}}) - m_{\mathrm{i,C}} \cdot W_{\mathrm{i,tot}} \tag{2}$$

where $ex_{\mathrm{i,C,in}}$, $ex_{\mathrm{i,C,out}}$ are specific exergy of air at i-th stage compressor inlet and outlet, $m_{\mathrm{i,C}}$ is mass flow rate of i-th stage compressor. Ambient environment takes as reference object.
The exergy efficiency of the i-th compressor is,

$$\eta_{\mathrm{i,ex}} = \frac{W_{\mathrm{i,tot}} + Dex_{i,\mathrm{C}}}{W_{\mathrm{i,tot}}} \tag{3}$$

The exergy destruction of the ejector is,

$$Dex_{\mathrm{E}} = (m_{\mathrm{p}} + m_{\mathrm{s}}) \cdot ex_{\mathrm{E,out}} - (m_{\mathrm{p}} \cdot ex_{\mathrm{p}} + m_{\mathrm{s}} \cdot ex_{\mathrm{s}}) \tag{4}$$

where the first term on right hand side is the outlet exergy of the ejector, and the second term on right hand side is the total exergy of the secondary and primary fluid.
To evaluate the instantaneous exergy efficiency of EVA-CAES system, the exergy efficiency is defined as the ratio of total exergy (the total exergy is the sum of energy consumption of compressors, exergy destruction of compressors and the ejector.) to total energy consumption of compressors, as shown in Eq(5),

$$\eta_{\mathrm{ex}} = \frac{\sum_{i=1}^{4} W_{\mathrm{i,tot}} + \sum_{i=1}^{4} Dex_{\mathrm{i,C}} + Dex_{\mathrm{E}}}{\sum_{i=1}^{4} W_{\mathrm{i,tot}}} \tag{5}$$

where $Dex_{\mathrm{i,C}}$, Dex_{E} are exergy destruction of the i-th stage compressor and the ejector.
In order to evaluate the overall energy utilization in charging process, the average efficiency of EVA-CAES system is,

$$\eta_{aver} = \frac{\int_{t_0}^{t_1} \sum_{i=1}^{4} W_{\mathrm{i,tot}} dt + \int_{t_0}^{t_1} \sum_{i=1}^{4} Dex_{\mathrm{i,C}} dt + \int_{t_0}^{t_1} Dex_{\mathrm{E}} dt + \int_{t_2}^{t_3} \sum_{i=1}^{4} W_{\mathrm{i,tot}} dt + \int_{t_2}^{t_3} \sum_{i=1}^{4} Dex_{\mathrm{i,C}} dt}{\int_{t_0}^{t_1} \sum_{i=1}^{4} W_{\mathrm{i,tot}} dt + \int_{t_2}^{t_3} \sum_{i=1}^{4} W_{\mathrm{i,tot}} dt} \tag{6}$$

where t_0, t_1 are the beginning time and ending time of the first charge period, and t_2, t_3 are the beginning time and ending time of the second charge period.

4. Result and discussion

For an air storage tank with given volume, initial and maximum storage pressure, the EVA-CAES system is proposed using an ejector and variable speed operation to improve system performances. The numerical simulations are carried out by MATLAB2016a (Matlab, 2016) code. The geometry data of compression train is from He et al. (2019), where the 4-th stage of compressors is composed of high pressure sub-stage and low pressure sub-stage (the two sub-stages work in the same axial). Main design parameter of EVA-CAES, VA-CAES (adiabatic CAES with 4-th stage compressor operating in variable speed), A-CAES (adiabatic CAES with throttle valve installed at inlet of air storage tank) systems are shown in Table 1. The thermodynamic simulation about EVA-CAES, VA-CAES and A-CAES system are carried out.
For EVA-CAES system, the variation of the outlet pressure of compressors, ejector and the air pressure of air storage tank with time is shown in Figure 2. In the first charge period, the outlet pressure of ejector and the pressure of air storage tank increase with the increase of time with same tendency. In the second charge period, the outlet pressure of the high pressure sub-stage and low ressure sub-stage increases with time, and the pressure ratio of the two sub-stage adjust by changing rotation speed. Besides, the outlet pressure of previous three-stage compressor are constant in whole charging process.

As shown in Figure 3, in the first charge period, the exergy efficiency of EVA-CAES system is larger than that of A-CAES system, which means the ejector has the potential to avoid throttling loss and improve the exergy efficiency, and the exergy efficiency of EVA-CAES and A-CAES system both increase with time. Besides, the VA-CAES system has the largest exergy efficiency among the three systems. In the second charge period, the exergy efficiency of EVA-CAES and VA-CAES system are the same, and they are both larger than that of A-CAES system except at the end of charging process. And when the pressure of air storage tank is equal to the critical pressure of the ejector, the exergy efficiency of EVA-CAES system has a rapid increase, because of the reduction of exergy reduction from the ejector and the energy consumption of the two sub-stage.

Table 1: Main design parameter of three energy storage systems

Parameters	Unit	Value
Ambient pressure	MPa	0.101
Ambient temperature	K	298.15
The volume of air storage tank	m^3	2,500
The rated mass flow rate of compressors	kg/s	10
The initial storage pressure	MPa	4.5
The maximum storage pressure	MPa	11.3
The wall temperature of air storage tank	K	300

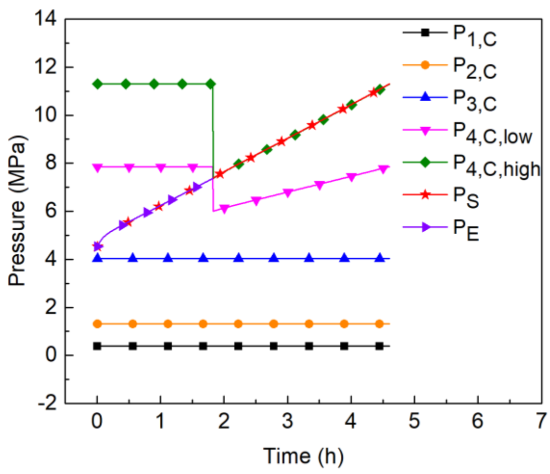

Figure 2: Variation of air pressure of compressors, ejector and air storage tank with time in EVA-CAES system

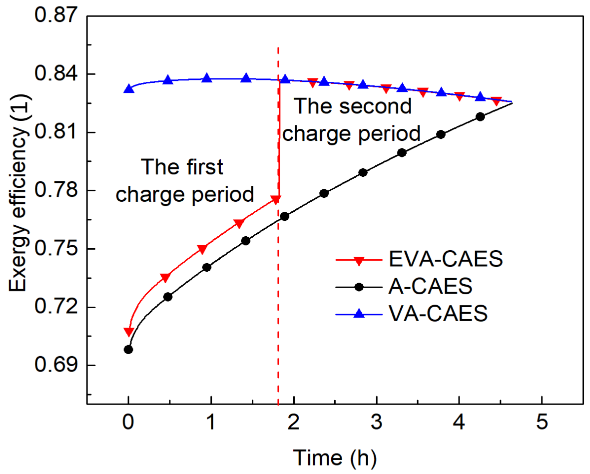

Figure 3: Variation of exergy efficiency with time

As shown in Figure 4, the exergy efficieny of the high pressure sub-stage is sensitive to the relative rotation speed, which means the performance of compression train is easily deteriorated when the relative rotation speed is lower than 0.7. The rotation speed of compressor should be limited in the range of steady operation condition. The range of relative rotation speed in the VA-CAES system is 0.49 ~ 1.0, which means one part of charging process in the VA-CAES system is pretty unstable and the charging process can't realize by only adjusting rotation speed of 4-th stage of compressors for a relatively low initial storage pressure. For EVA-CAES system, the range of relative rotation speed is 0.77 ~ 1.0, where the two sub-stage both work in a relatively stable condition. The ejector in EVA-CAES system shortens the unstable range of rotation speed and avoids the throttling loss. That's to say, it's necessary for A-CAES system to use an ejector and 4-th stage compressor with varying rotation speed operation in a relatively low initial storage pressure condition to improve system performances.

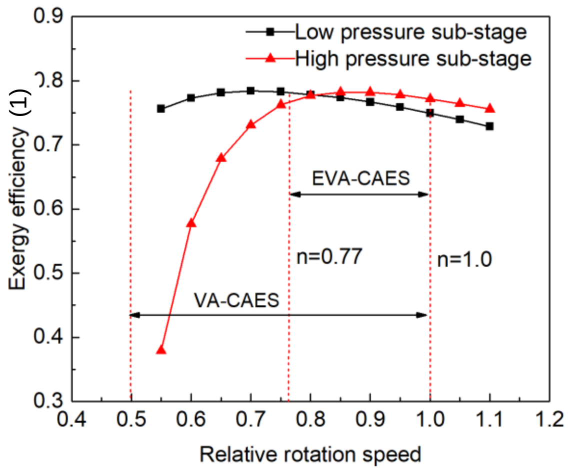

Figure 4: Variation of average exergy efficiency of EVA-CAES system with relative rotation speed

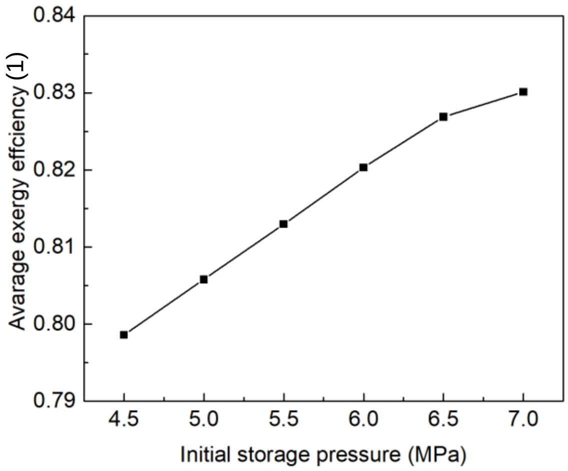

Figure 5: Variation of average exergy efficiency of EVA-CAES system with initial storage pressure

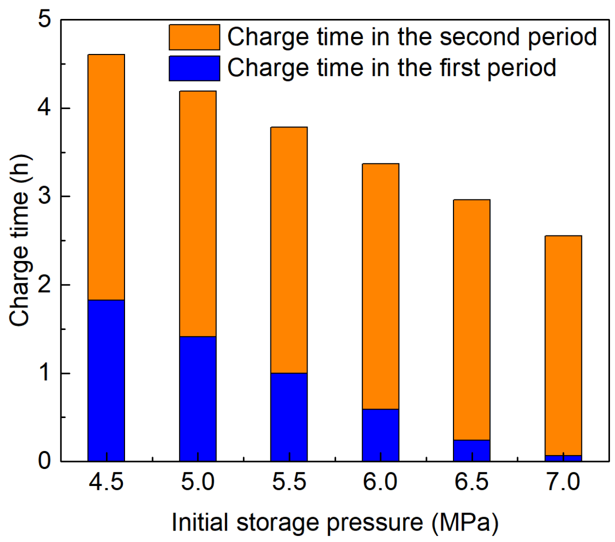

Figure 6: Variation of the charge time with initial storage pressure in EVA-CAES system.

The tendency of average exergy efficiency of EVA-CAES system varying with initial storage pressure is shown in Figure 5. The average exergy efficiency increases with the increase of initial storage pressure, and the increase tendency slows down with the increase of initial storage pressure. As sown in Figure 6, the charge time in the first charge period decreases with the initial storage pressure increasing, and the charge time in the second charge period is nearly the same. Considering the data in Figure 3, Figure 5 and Figure 6, with the increase of initial storage pressure, the optimization effect of the ejector on system performances is less and the varying rotation speed on system performances is more obvious.

5. Conclusions

This paper proposes a new EVA-CAES system with an ejector and fourth stage compressor with varying rotation operation. The simulation about proposed system and A-CAES system are carried out. The performance of compression train is easily deteriorated when the relative rotation speed is lower than 0.7. The proposed system can effectively charge air in a low initial storage pressure condition, where the ejector shortens the range of unstable rotation speed and avoids throttling loss. The average exergy efficiency of proposed system is improved by increasing initial storage pressure of air storage tank. And the proposed system can work well in lower initial storage pressure conditions, compared A-CAES and VA-CAES system. The cost, risks of running and heat loss will take into the future research of the proposed system.

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