Thermodynamic analysis of an isobaric compressed air energy storage (I-CAES) combined with low grade waste heat

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Abstract. Energy storage technology is an efficient way to solve the discontinuous and unpredictable of renewable energy. This paper combined isobaric CAES with low grade waste heat to reduce the pollution of CAES and avoid the exergy destruction in throttling process. The thermodynamic analysis including energy analysis and exergy analysis, was conducted to evaluate the performance of the proposed system. The results show that total round trip efficiency of the proposed I-CAES can be improved nearly 11% and the effective air storage density increases 37.6% compared with the conventional CAES. Meanwhile, a parametric analysis is also conducted to evaluate the effects of several key parameters on the system performance.

1. Introduction

Renewable energy is a cleaner energy compared with the fossil energy, such as mineral oil and coal. However, renewable energy is unpredictable and discontinuous, which do harm to the stability of grid [1]. Energy storage technology is a useful method to smooth the output power of renewable energy power plant [2-4].

The pumped hydro storage (PHES) and the compressed air energy storage (CAES) are the only two large scale energy technology [5]. The PHES is a mature technology with high round-trip efficiency, but it is limited by the geological structure and it may do harm to environment [6-7]. CAES can circumvent geographic restrictions by employing air storage vessels compared with the PHES [8]. But in CAES system, the fossil fuels are essential for discharging process, resulting in the pollutant emission [9-10]. Moreover, conventional CAES needs to throttle the compressed air to a stable pressure during the discharging process. In order to solve the mentioned problems, an adiabatic CAES (A-CAES) and advanced adiabatic CAES (AA-CAES) have been proposed and developed, but A-CAES and AA-CAES need large space and investment on thermal energy storage (TES). In order to solve the heat source of the CAES, Long [11] proposed a CAES system combined with low grade waste heat, which can be regarded as free heat source.

In order to reduce the exergy destruction in throttling process of the CAES. This paper proposed an isobaric compressed air energy storage (I-CAES) system combined with low grade waste heat. We evaluated the efficiency of the proposed I-CAES by thermodynamic analysis. Furthermore, a parametric analysis was conducted to assess the system performance in different working condition.
2. System description

The schematic diagram of the conventional CAES and the proposed I-CAES is shown in Figure 1 and Figure 2. The structure of the two CAES systems are almost the same.

In charging process, the working principle of the two systems are the same. The atmospheric air is compressed by the compression train and then stored in the air storage cavern (ASC). Intercoolers were placed between compressors to cool the high temperature air. After the charging process, compressed air is cooled by aftercooler and stored in ASC.

In discharging process, the working principle of the two systems is different, as shown in Figure 1 and Figure 2. In conventional CAES, compressed air is released from the ASC and throttled to a stable pressure by throttle valve (TV), which caused a non-negligible exergy destruction. Then the compressed air was heated by waster heat in interheater and expand in expansion train to generate power. In the proposed I-CAES, the compressed air is released from ASC at a constant pressure, which is produced by the water. So the proposed I-CAES is more efficiency without suffering the exergy destruction in TV.

3. Thermodynamic analysis

In order to simplify the simulation process, the following assumptions are made:

1. The outlet temperature of intercooler and aftercooler is 5 K higher than ambient temperature.
2. The composition of air in the two systems is consisted of 77% N₂ and 23%O₂.
3. The heat and pressure loss in the pipes can be negligible.
4. All the kinetic and potential effects are ignored.
5. The system in any operation mode reaches steady state.
3.1. CAES and I-CAES model
In the charging process, the proposed I-CAES and conventional CAES are the same. The compression train of the two systems are consisted of three compressors, the outlet pressure of compressors can be written as follows,

\[ P_{\text{out},c} = \pi_c P_{\text{in},c} \]  

(1)

where \( P_{\text{in},c} \) is the inlet pressure of compressors, \( \pi_c \) is the pressure ratio of compressors. The outlet temperature of compressors \( T_{out,c} \) can be defined as follows,

\[ T_{out,c} = T_{in,c} \left[ \frac{\pi_c^{(x-1)/\kappa} - 1}{\eta_c} + 1 \right] \]  

(2)

where \( \eta_c \) is the isentropic efficiency of compressors, \( \kappa \) is the adiabatic coefficient of air.

In the discharging process, the only difference between conventional CAES and proposed I-CAES is that the released compressed air is throttled before expansion in conventional CAES. The expansion train of the two CAES systems is composed of three expanders. The outlet pressure of the expander can be written as follows,

\[ P_{\text{out},e} = \pi_e P_{\text{in},e} \]  

(3)

where \( P_{\text{in},e} \) is the inlet pressure of the expander, \( \pi_e \) is the pressure ratio of the expander. The outlet temperature is,

\[ T_{out,e} = T_{in,e} \left[ 1 - \eta_e \left( 1 - \pi_e^{(1-x)/\kappa} \right) \right] \]  

(4)

where \( T_{in,e} \) is the inlet temperature of the expander, \( \eta_e \) is the isentropic efficiency of the expander.

3.2. System evaluation
Round trip efficiency (RTE) is defined as the ratio between the output power and input power. As the waste heat is considered for free heat source, RTE can be written as follows:

\[ \text{RTE} = \frac{\text{Total electricity output}}{\text{Total power consumption}} = \frac{W_{\text{expand}}}{W_{\text{compress}}} \]  

(5)

where \( W_{\text{expand}} \) is the output electricity, \( W_{\text{compress}} \) is the power consumed by compressors.

The coefficient of exergy destruction is defined as:

\[ \xi_i = \frac{\text{Local exergy destruction}}{\text{Total exergy input}} = \frac{\dot{E}_{x,i}}{\dot{E}_{x,\text{total,input}}} \]  

(6)

Thus, the exergy efficiency of a component and the whole system can be written as:

\[ \eta_{ex,i} = 1 - \xi_i \]  

(7)

The total exergy efficiency (TTE) can be defined as:

\[ \text{TTE} = 1 - \sum \xi_i \]  

(8)

Effective air storage density \( \rho_e \) is defined as the ration between the total air mass \( m_{\text{expansion}} \) in discharging process to the total volume of air storage cavern \( V_{ASC} \):

\[ \rho_e = \frac{m_{\text{expansion}}}{V_{ASC}} \]  

(9)

As the low grade waste heat is considered for free, so only electrical energy is input and output in the whole system, which results in the equalization between RTE and TTE.
4. Result and discussion

In this section, thermodynamic analysis and parametric analysis are conducted to evaluate the system. The parameters setting in the conventional CAES and proposed I-CAES are shown in Table 1. The thermodynamic data obtained from the simulation are listed in Table 2 and Table 3.

Table 1. Parameters setting in I-CAES and conventional CAES system.

| Parameter                  | Unit | Value |
|----------------------------|------|-------|
| Ambient pressure           | kPa  | 101.32|
| Ambient temperature        | K    | 298.15|
| Ratio of specific heats    | /    | 1.4   |
| Waste heat temperature     | K    | 433.15|
| Volume of ASC              | m3   | 1000  |
| Air pressure in ASC        | kPa  | 4176  |
| Isentropic efficiency of compressor | %   | 88    |
| Isentropic efficiency of turbine | %   | 90    |
| Outlet temperature of IC and AC | K | 303.15|
| Outlet temperature of PH and IH | K | 423.15|
| Pressure loss in IC,AC,PH and IH | % | 4    |
| Rated power of compression train | kW | 1000  |
| Rated power of expansion train | kW | 1000  |

Table 2. Thermodynamic data of Conventional CAES.

| Process point | T(K)   | P(kPa)  | h(kJ/kg)  | ex(kJ/kg) | m(kg/s) |
|---------------|--------|---------|-----------|-----------|---------|
| 1             | 298.15 | 101.32  | 298.45    | 0.00      | 1.852   |
| 2             | 473.82 | 437.16  | 476.34    | 163.34    | 1.852   |
| 3             | 303.15 | 419.67  | 302.78    | 121.62    | 1.852   |
| 4             | 481.76 | 1810.71 | 483.72    | 288.18    | 1.852   |
| 5             | 303.15 | 1738.28 | 299.90    | 242.97    | 1.852   |
| 6             | 303.15 | 7200.00 | 480.98    | 363.62    | 3.001   |
| 7             | 298.15 | 7200.00 | 283.21    | 363.62    | 3.001   |
| 8             | 298.15 | 4176.00 | 289.41    | 317.45    | 3.001   |
| 9             | 423.15 | 4008.96 | 421.32    | 335.60    | 3.001   |
| 10            | 312.70 | 1208.94 | 310.83    | 212.31    | 3.001   |
| 11            | 423.15 | 1160.58 | 423.82    | 229.55    | 3.001   |
| 12            | 312.70 | 349.99  | 312.59    | 106.40    | 3.001   |
| 13            | 423.15 | 335.99  | 424.58    | 123.47    | 3.001   |
| 14            | 312.70 | 101.32  | 313.10    | 0.35      | 3.001   |

4.1. Thermodynamic analysis

The comparison of simulation results between conventional CAES and proposed I-CAES are shown in Table 4. It can be seen that with the same inlet pressure of PH, the RTE of proposed I-CAES is 72.89%, which improves nearly 11% than conventional CAES. For a rated compression and expansion power (1000kW), the exergy destruction in TV reached 138.7kW, which results in a efficiency droop compared with I-CAES.
Moreover, compare with conventional CAES, the effective air storage density $\rho_e$ of I-CAES has increased 37.6%. The inlet pressure of ASC in conventional CAES is 3000kPa higher than I-CAES, but the effective air storage density of conventional CAES decreased 37.6% than I-CAES. A lot of power was wasted in the throttling process. Hence, the proposed I-CAES shows more efficient than conventional CAES.

### Table 3. Thermodynamic data of proposed I-CAES.

| Process point | Proposed I-CAES |
|---------------|-----------------|
|               | T(K) | P(kPa) | h(kJ/kg) | $\text{ex}(\text{kJ/kg})$ | $m(\text{kg/s})$ |
| 1             | 298.15 | 101.32 | 298.45 | 0.00 | 2.180 |
| 2             | 447.81 | 364.57 | 449.73 | 138.39 | 2.180 |
| 3             | 303.15 | 349.99 | 302.93 | 106.09 | 2.180 |
| 4             | 455.32 | 1259.31 | 456.77 | 247.13 | 2.180 |
| 5             | 303.15 | 1208.94 | 301.05 | 212.00 | 2.180 |
| 6             | 455.32 | 4350.00 | 454.70 | 353.39 | 2.180 |
| 7             | 303.15 | 4176.00 | 294.77 | 317.50 | 2.180 |
| 8             | 298.15 | 4176.00 | 289.41 | 317.45 | 3.001 |
| 9             | - | - | - | - | - |
| 10            | 423.15 | 4009.00 | 420.09 | 363.15 | 3.001 |
| 11            | 304.55 | 1208.94 | 301.86 | 230.31 | 3.001 |
| 12            | 423.15 | 1160.58 | 423.56 | 247.89 | 3.001 |
| 13            | 304.55 | 349.99 | 304.26 | 115.29 | 3.001 |
| 14            | 423.15 | 335.99 | 424.55 | 132.65 | 3.001 |
| 15            | 304.55 | 101.32 | 304.89 | 0.07 | 3.001 |

### Table 4. Simulation result of conventional CAES and proposed I-CAES.

| Unit | Conventional CAES | Proposed I-CAES |
|------|------------------|-----------------|
| Inlet pressure of ASC | kPa | 7200 | 4176 |
| Inlet pressure of PH | kPa | 4176 | 4176 |
| Charge time | h | 5.365 | 6.273 |
| Discharge time | h | 3.311 | 4.556 |
| $\rho_e$ | kg/m$^3$ | 35.77 | 49.22 |
| Exergy destruction in TV | kW | 138.7 | 0 |
| RTE | % | 61.72 | 72.89 |

4.2. Effect of compression and expansion stage

Figure 3 shows the variation of RTE with the number of compression and expansion stage for I-CAES system. Generally, the RTE should increase with the increase of compression and expansion stage. However, as Figure 3 shown, when compression and expansion stage equals to 7, the RTE can reach a maximum value (82.22%). The reason is the pressure loss in intercooler and aftercooler. The more compression and expansion stage, the more pressure loss in IC and AC, which results in a peak value in Figure 3.
4.3. Effect of ambient temperature  
As Figure 4 shown, with the increase of ambient temperature, the RTE of I-CAES decrease. That is because the increase of ambient temperature results in more exergy destruction in compressor. It can be seen that when ambient temperature equals to 273.15, the optimal compression and expansion stage equals to 8. With the increase of ambient temperature, the optimal compression and expansion stage drop to 7.

5. Conclusions  
In order to reduce the exergy destruction in throttle valve of conventional CAES, an isobaric air storage cavern is utilized to steady the pressure with the help of water. The main concluding remarks can be written as follows:

(1) The RTE of proposed I-CAES is 11% higher than conventional CAES, and the effective air storage density of I-CAES increased 37.6% compared with conventional CAES.
(2) As the pressure loss in heat exchanger exists, the RTE of I-CAES isn’t increase all the time with the increase of compression and expansion stage. The optimal compression and expansion stage is effected by a lot of parameters. In this work, the optimal compression and expansion stage of I-CAES equals to 7.
(3) The RTE of I-CAES decrease with the increase of ambient temperature, and the optimal compression and expansion stage drop to 7 with the increase of ambient of temperature. The reason is the higher ambient temperature results in more exergy destruction in compressor.
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