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Performance study of an advanced adiabatic compressed air energy storage system

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Abstract

Renewable energy sources such as wind and solar, have vast potential to offer cost competitive power supply and reduce dependence on fossil fuels and environmental issues in the electric sector. However, renewable energy systems often have variable and uncertain energy supply which makes electrical energy storage systems highly valuable for renewable energy applications. Compressed air energy storage is one of the most promising technologies that have received wide attention in scientific community. In this paper, a comprehensive thermodynamic model is developed to investigate the thermal performance of an Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system. The effect of key parameters including storage pressure, pre-set pressure along with compressor and turbine efficiencies on the system performance is studied. The results show that the storage pressure has a significant effect on the amount of energy stored in the AA-CAES and power generated by the expander. As the storage pressure increases from 2 MPa to 10 MPa, the amount of energy stored increases from 7.8 MJ/m^3 to 105.6 MJ/m^3 while the output power increases from 4.2 to 63.2 MJ/m^3. The results also show that the overall energy conversion efficiency is dominated by the efficiency of the compressor and turbine. As the efficiencies of both compressor and expander increases from 0.65 to 0.95, the efficiency of the AA-CAES system is improved from 35% to 74%. This study provides a deep understanding of operation characteristics of the AA-CAES system and useful information for system design and optimization.

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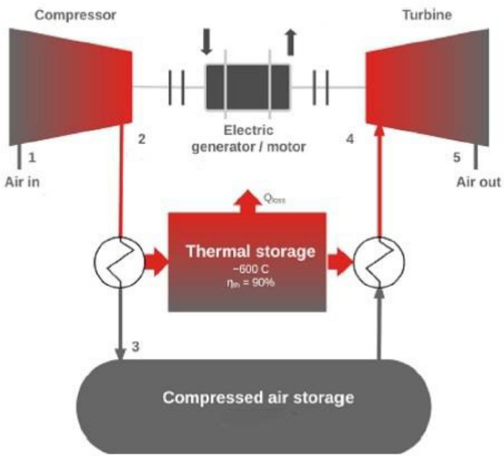
1. Introduction

Due to energy crisis and environment issues such as air pollution and global warming caused by combustion of fossil fuels, the use of alternative sources especially renewable energies has attracted an increasing attention in many countries [1]. However, the main drawback of renewable sources, such as wind energy, solar energy, bio-energy and etc., is their intermittence, randomness and volatility making their development a huge challenge confronted. As a result, in order to effectively utilize these renewable energy sources, it is important to find a way for resolving these drawbacks [2]. There is a variety of possibilities introduced to employ the volatile renewable energy sources [3] among which the energy storage technology is considered as one of the most promising methods. This technology can be divided in two categories of the physical storage, such as flywheel energy storage, compressed air storage and pumped hydro energy storage, and the electrochemical energy storage such as, batteries, fuel cells and electrolytic hydrogen [4].

Amongst all different types of energy storage approaches, the compressed air energy storage (CAES) system offers many competitive features such as large power and energy capacity, high cycle lifespan, and fast response time. These features make CAES systems particularly suitable for energy storage purposes in the electric grid [5]. In a typical CAES, the air is compressed by a compressor using off-peak, cheap electricity or the excess energy of renewable energy sources, such as a wind turbine or solar energy. Before transferring to the storage vessel, the compressed air is cooled to the near ambient temperature to ensure high compression efficiency and maximum storage utilization. This pressurized air is released into a gas turbine to generate electricity when it is on demand in peak hours or for other grid balancing and regulation purposes [6-7]. In recent years, the Advanced Adiabatic compressed air energy storage system (AA-CAES) was proposed to increase the efficiency by improving the cooling procedure of the compressed air. In such systems, a thermal storage made of a fluid or solid is added to store the compression heat for later use during expansion. In other words, by employing a thermal storage, it saves fossil fuels for reheating the air before expansion in the gas turbine. Consequently, AA-CAES systems have shown the potential for higher efficiencies and less greenhouse gasses emissions. A schematic drawing of an AA-CAES system is shown in Fig. 1.

Fig.1. A schematic of an AA-CAES system



There are many studies available in the literature which examined the CAES technology. Kim et al. [8] applied an exergy and energy analysis and investigated the operation characteristics of a constant-pressure CAES system in different compression and expansion processes. In this research, instead of elevation difference of the water column previously proposed in literature [9], a hydraulic pump was designed to provide the CAES with constant air pressure. Grazzini and Milazzo [10-11] developed a thermodynamic analysis for a multistage adiabatic compressed air energy storage system. The storage volume was optimized and a system layout with thermal storage and variable configuration was designed based on the energy recovery efficiency in this research.

In this paper, a comprehensive thermodynamic analysis of the AA-CAES system is performed to broadly investigate its performance and efficiency under different physical processes. The results are obtained for a wide range of parameters including storage pressure and pre-set pressure as well as compressor and turbine efficiencies. These results will explore a deep understanding of operation characteristics of the system. It provides useful information for design and optimization of the system in a specific area according to the geological, financial and market constraints.

2. Thermodynamic Model

In the thermodynamic model for the AA-CAES system, the assumptions are listed below:

- The air circulates in the close loop cycle and is considered as an ideal gas.
- Storage vessel is assumed to be well insulated and no heat loss across the vessel.
- The kinetic and potential energies as well as pressure loss in the connection pipes are negligible.

2.1. Compressor

In an AA-CAES system, the gas turbine is not able to generate the energy when the air pressure falls below a particular value. In order to study the performance of such a system in a complete cycle, it is assumed that the air storage vessel is firstly pressurized up to a pre-set pressure P_1 before the compression process starts. Hence, the total energy required to pressurize the air inside the vessel from pre-set pressure P_1 to maximum pressure P_2 during an isentropic compression process can be obtained by:

$$W_c = \frac{kV_1T_0}{k-1}\left(\left(\frac{P_2}{P_0}\right)^{\frac{k-1}{k}} - 1\right)\left(\frac{P_2}{T_f} - \frac{P_1}{T_0}\right) \quad (1)$$

In relation above, T_f is the final vessel temperature at the end of charging process and is calculated by:

$$T_f = \frac{kT_0}{\left(1 - \frac{P_1}{P_2}\right) + k\frac{P_1}{P_2}} \quad (2)$$

In addition, T_0, P_0, P_2 and V_1 are the atmospheric temperature, atmospheric pressure, compressor discharge pressure and the total volume of the storage vessel, respectively. The pressurized air flows into the vessel to gradually increase its pressure up to the pre-set maximum pressure, named as storage pressure, related to structural safety of the vessel. In this research, the compressor discharge pressure is considered to be equal to the storage pressure.

The energy consumption in an actual compression process is calculated by

$$W_{c,real} = \frac{W_c}{\eta_c} \quad (3)$$

where η_c is the compressor isentropic efficiency.

2.2. Thermal Storage

In order to increase the energy storage density, the compressed air after the compressor is normally cooled to the room temperature. The heat is stored in a thermal storage and is then used to heat up the air before it expands in the gas turbine. By using this energy storage vessel, it can minimize the need of fossil fuels for preheating the air before the expansion process. As a result, the efficiency of the AA-CAES system is enhanced. The temperature at the compressor outlet, total stored energy in the thermal storage and the air temperature at the turbine inlet can be calculated, respectively, by,

$$T_2 = T_0 + \frac{T_{2s} - T_0}{\eta_c}, \qquad T_{2s} = T_0 \left(\frac{P_2}{P_0} \right)^{\frac{k-1}{k}} \tag{4}$$

$$\Delta E_{th} = \frac{kV_1}{k-1} \left(T_2 - T_0 \right) \left(\frac{P_2}{T_f} - \frac{P_1}{T_0} \right) \tag{5}$$

$$T_4 = T_0 + \eta_{th} \left(T_2 - T_0 \right) \tag{6}$$

In relations above, T_{2s} is the air temperature during an isentropic compression. η_{th} is the efficiency of the thermal storage and is defined as the ratio of the output heat energy transferred to the air flow before expansion to the input heat energy from the air flow after compression. In this study, η_{th} is considered to be 0.9.

2.3. Storage Vessel

The total energy transfer to the storage vessel can be obtained using the following equation:

$$\Delta E_{vessel} = \frac{V_1}{k-1} \left(P_2 - P_1 \right) \tag{7}$$

2.4. Expander

During the expansion process, the compressed air pressure gradually decreases from storage pressure P_2 to pre-set pressure P_1. Therefore, the total power energy generated by the ideal expander can be calculated using the following relation,

$$W_e = \frac{kV_1}{k-1} \frac{T_4}{T_0} \left[\left(P_2 - P_1 \right) - \frac{1}{k} \left(P_0 \right)^{\frac{k-1}{k}} \left(P_2^{\frac{1}{k}} - P_1^{\frac{1}{k}} \right) \right] \tag{8}$$

The actual power output in the expander can be calculated by the following:

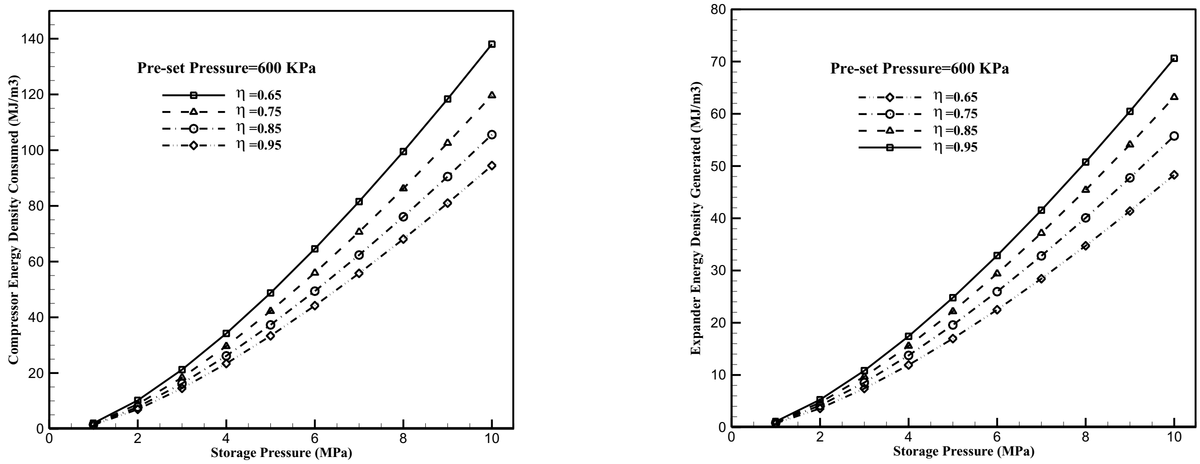
$$W_{e,real} = W_e \times \eta_e \tag{9}$$

Where η_e is the isentropic efficiency of the expander.

3. Results and Discussion

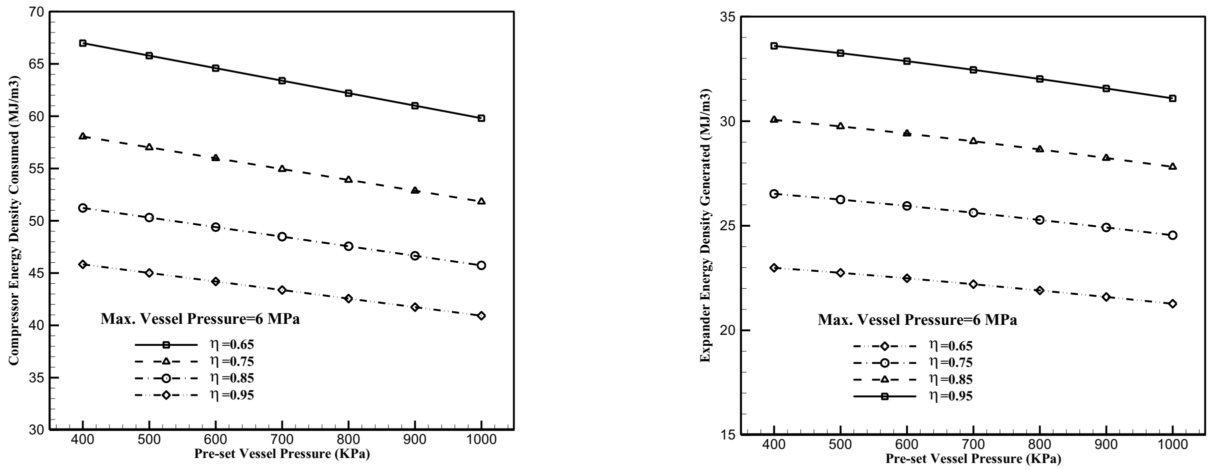
The performance of the AA-CAES system is widely studied by using the thermodynamic model under different working conditions. It provides a deep understanding of the AA-CASE performance in different physical phenomena. It is worth noting that, in this research, the energy density is defined as the total energy divided by total volume of the storage vessel. Based on this definition, figure 2 shows distributions of the energy density consumption of the compressor and energy density generation of the expander at the different storage pressures with various compressor and expander efficiencies. The results show that the storage pressure plays an important role on the amount of energy stored and generated in the AA-CAES system. As the storage pressure increases, both input energy and output energy considerably increase, as well. For instance, by considering a compressor with the efficiency of 0.85, as the storage pressure increases from 2 MPa to 10 MPa, the energy consumption of the compressor increases from 7.8 MJ/m^3 to 105.6 MJ/m^3. While if an expander with the same efficiency is employed, the power generation is significantly improved from 4.2 MJ/m^3 to 63.2 MJ/m^3.

Figure 3 shows variations of the compressor energy density consumption and expander energy density generation with respect to the vessel pre-set pressure. These distributions were obtained for different values of compressor and expander efficiencies when the storage pressure is maintained at 6 MPa. According to this figure, an inverse semi-linear relation is captured between the pre-set pressure and both compressor energy consumption and expander energy generation. It is because by keeping constant the storage pressure, increase of the initial pressure of the vessel results in less air mass to be injected to the vessel. Accordingly, the energy stored and generated is reduced. Another important thing revealed in this figure is the importance of the component efficiency in the amount of energy consumption, or generation, of that component. As it can be seen, for a pre-set pressure of 1000 KPa, for instance, energy consumption of the compressor can be dramatically reduced from 59.8 MJ/m3 to 40.9 MJ/m3 if the compressor efficiency is improved from 0.65 to 0.95. On the other hand, the output power significantly increases from 21.3 MJ/m3to 31.1 MJ/m3 if the expander efficiency is raised from 0.65 to 0.95.



(a) **(b)**

Fig.2. Effect of storage pressure on (a) energy consumption of the compressor (b) energy generation of the expander at different efficiencies



(a) **(b)**

Fig.3. Effect of pre-set pressure on (a) energy consumption of the compressor (b) energy generation of the expander at different efficiencies

The overall efficiency of an AA-CAES system can be defined as the output energy divided by input energy. By using this definition, in Fig. 4, overall efficiency of the AA-CAES is expressed versus different values of the efficiency of thermal machinery (compression/expander). It is worth noting that the pre-set pressure and storage pressure do not directly affect the efficiency of the whole system. However, they may have an influence on the efficiency of components as each component is designed for and idealized in a particular working condition. As the system operates at part-load condition, the component efficiency will be reduced. Expectedly, improving the performance of the compressor and expander has a direct effect on the overall efficiency of the AA-CAES. As depicted in Fig. 4, the system efficiency is improved from 0.35 to 0.74 as the component efficiencies increases from 0.65 to 0.95. However, it should be noted that even in case of using ideal compressor and expander, the efficiency of the whole system would be 0.82. It is because of the energy loss through the thermal storage and hot exhaust gasses.

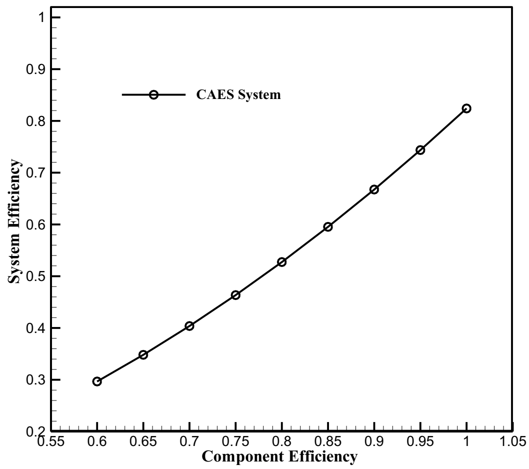


Fig. 4. PHCA and AA-CAES system efficiencies based on the efficiency of their energy-consuming and energy-generation components

4. Conclusion

In this paper, a comprehensive thermodynamic analysis was performed to examine the performance of an Advanced Adiabatic Compressed Energy Storage (AA-CAES) system, which has the potential to gain a higher efficiency among all types of CAES systems. The results obtained from the thermodynamic analysis were presented for a broad range of parameters characterizing the problem including pre-set pressure, storage pressure and; also, efficiency of the compressor and expander. The results showed that the stored and generated energy was reduced in a semi-linear manner as the pre-set storage pressure increased. It was also shown that the storage pressure plays a significant role on the amount of energy stored and generated in the AA-CAES system. As the storage pressure increased, the input energy consumed by the compressor and the output power generated by the expander are dramatically enhanced. Based on these findings, utilization of the AA-CAES seemed to be suitable in large places where a great amount of excess, cheap energy was available. In such places, depending on the availability of the energy, the value of the pre-set pressure and storage pressure could be optimized.

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