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The thermodynamic effect of thermal energy storage on compressed air energy storage system

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ABSTRACT

With the increasing penetration of renewable energy into energy market, it is urgent to solve the problem of fluctuations of renewable energy sources (RES). Energy storage technology is regarded as one method to cope with the unstable nature of RES. One of these technologies is compressed air energy storage (CAES), which is a modification of the basic gas turbine technology. Electric power supplied by CAES can meet peak-load requirement of electric utility systems. Because there is heat waste in the existing CAES systems during compression process, fossil fuels are used to improve the expansion work to generate peak power. In order to avoid the use of fuels and keep high efficiency of system, CAES system with thermal energy storage (TES) is designed to capture and reuse the compressed air heat. This paper uses a thermodynamic model of a CAES system with TES to analyze the effect of TES on system efficiency. Besides, this paper evaluates the influence of temperature and pressure on the utilization of heat in TES. Results show that even when power efficiency reaches maximum, there is still a proportion of thermal energy left in TES for other use. Meanwhile, the utilization of heat in TES can be affected by pressure in the air storage chamber. With appropriate selection of pressure limits, the utilization of compressed air heat can be optimized.

1. Introduction

With the diminution of conventional energy, renewable energy sources (RES) are valued by more and more countries around the world. Although the penetration of RES into energy market is becoming increasingly evident, the development and utilization of RES confront huge challenges considering the intermittent nature and unstable nature of RES. At present, energy storage system is one of the technologies which can solve the problem of fluctuations of RES [1,2].

Compressed air energy storage (CAES) system is a reliable energy storage system based on gas turbine technology. Generally speaking, it incorporates a gas turbine and an underground reservoir, and the compressor and turbine parts of the gas turbine are coupled to a motor/generator. During low-demand periods, power from base load plants or renewable energy is stored into an air storage chamber or an underground reservoir by driving motors to compress air, converting electrical energy into internal energy of compressed air; during peak-load periods, the energy in the compressed air is extracted to produce electricity as compressed air is drawn from the storage chamber, mixed with fuel and then expanded through turbines [3]. Therefore, CAES technology can be used for electricity balancing, and with the development of RES, CAES has been regarded as one of the promising methods for the combination of RES with electricity supply [4].

However, as environmental protection and energy utilization become increasingly important, the requirement of combusting fossil fuels and the contaminating emission make the CAES less attractive [5]. Therefore, optimized CAES systems are proposed with the purpose of better system performance, and one of them, which is called Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), is now being investigated for its properties of large-scale energy storage and high energy recovery.

AA-CAES system is shown in Fig. 1. As thermal energy storage (TES) is substituted for combustion chamber in CAES technology, energy expelled as heat during compression is stored in TES, and the energy can be recovered and reused during expansion. This is the critical technology of AA-CAES system.

As an improved system, the potential applications for this technology have been paid to great attention. Zunft et al. analyzed the feasibility and performance of this technology, and outlined the

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Nomenclature

E	stored energy
N	maximum number of stage
P	power
Q	heat
R_g	gas constant
T	temperature
V	storage volume
W	work
c	specific heat
c_p	constant pressure specific heat
c_v	constant volume specific heat
h	specific enthalpy
k	modified coefficient
m	polytropic exponent
m	mass
n	number of stage
p	pressure
t	time
u	specific internal energy
Greek letters	
β	compression ratio
ε	heat exchanger efficiency
η	energy efficiency
λ	exponent equal to $(m-1)/m$
γ	adiabatic exponent
ω	exponent equal to $(\gamma\text{-}1)/\gamma$
Subscripts	
0	ambient condition
$s1$	chamber state at beginning of charge
$s2$	chamber state at end of charge
$s3$	chamber state at end of discharge
P	work
Q	heat
a	cooling medium
ao	initial temperature of cooling medium
af	temperature of TES
c	compression
h	heated
n	number of stage
s	air storage chamber
t	expansion
CV	control volume
L	low
H	high

key technological problems in this system [6]. The economic feasibility of this system was analyzed by Bullough et al., and they gave a general evaluation to this technology [7]. In his paper, preliminary design and optimization of AA-CAES system was carried out by Adriano Milazzo [8]. Based on the theory of the second law of thermodynamics, system performance was evaluated by William F. Pickard et al., and they discussed advantages and disadvantages of this technology respectively [9].

This paper uses a thermodynamic model of an AA-CAES system to work over the effect of TES technology on the whole system as TES technology is absolutely critical for AA-CAES system. Besides, in order to figure out the impact factors of performance of TES, system parameters are derived from the theory of thermodynamics and the correlation between TES and CAES system is analyzed in the paper.

2. Derivation of thermodynamic parameters

The air storage chamber is assumed adiabatic, and the volume is constant. During a charge process, air in the air storage chamber

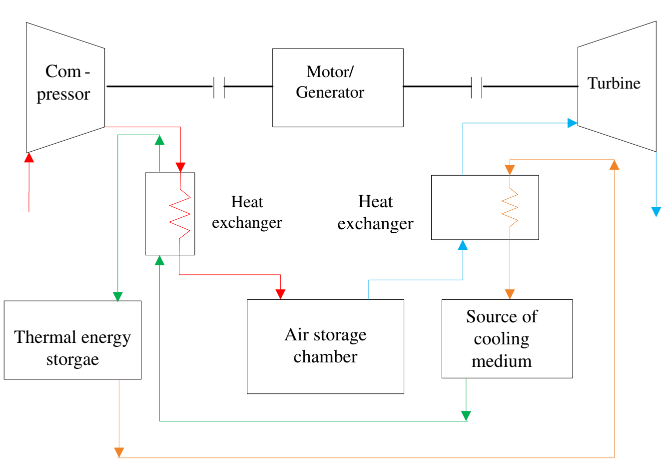

Fig. 1. Scheme of AA-CAES system.

will be pressurized from a pressure p_L to a pressure p_H, and subsequently, during a discharge process, air in the chamber will be depressurized from p_H to p_L. Meanwhile, Air is assumed to be an ideal gas with constant specific heats.

As for the volume of air storage chamber, it may be assumed that during the charge process the input power that system accepted $P = 1.5$ MW, and the charging time $t = 8$ h. Thus the stored energy is $E = Pt = 43{,}200$ MJ. During the charge process, temperature in air storage chamber increases gradually, and T_s is assumed to be the chamber temperature at the end of charging process. Thus the volume of air storage chamber can be given by

$$V = \frac{E}{p_H \frac{T_0}{T_s}\left\{\ln\left(\frac{p_H}{p_0}\right) + \frac{c_p}{R_g}\left[\frac{T_s - T_0}{T_0} - \ln\left(\frac{T_s}{T_0}\right)\right]\right\}} \quad (1)$$

where T_0 and P_0 are temperature and pressure in atmosphere [10].

It is noteworthy that, in Equation (1), the term at denominator is the exergy of the compressed air per unit volume at p_H ant T_s [11,12]. Meanwhile, the stored energy E in Equation (1) is nominal stored energy, which means that compression work is higher and expansion work is lower compared with the energy E.

As non-dimensional work and heat will be introduced, the calculation on the volume of air storage chamber V can be neglected. However, when the air mass in the storage chamber is taken into account, the volume V should be used in equation of state of ideal gas.

For the sake of simplicity, the system process shown in Fig. 1 will be divided into two parts; one is the charge process, and the other is the discharge process. Thermodynamic parameters of AA-CAES system will be derived respectively.

2.1. The charge process

Components of the system involved in the charge process are shown in Fig. 2.

In this process, the temperature of air from environment rises after compressed by a compressor. Heat exchangers placed after the compressor capture compression air heat carried by compressed