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Experimental study of compressed air energy storage system with thermal energy storage

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ABSTRACT

In this paper, the first public experiment on the CAES (compressed air energy storage) system with TES (thermal energy storage) is presented. A pilot plant using water as thermal energy storage working medium was constructed to investigate the performance of the CAES system with TES. An average round trip energy efficiency of 22.6% was achieved. Detailed analysis for a particular test was performed to study the major factors affecting the system. During the charge process, the consumed compressor electric energy was 1375 kWh with the air pressure inside the storage tank increasing from 3.36 MPa to 9.34 MPa. The total amount of heat absorbed was 565 kWh, while the storage water temperature reached 108.6 °C in the TES system. During the discharge process, the maximum generator power of 430 kW was obtained. The output electric energy was 326 kWh with the air pressure inside the storage tank decreasing from 8.65 MPa to 3.05 MPa. Also, the variation of air temperature along with the air pressure inside the storage tank was discussed during both the charge and discharge process. In this research, efforts are being made to validate the theories in the open literature and extend further practical applications of the CAES system with TES.

1. Introduction

To reduce environmental pollution, many researchers now concentrate on the utilization of renewable energy sources such as wind and solar energy. However, instability is a severe obstacle for wind and solar energy, which could cause inconvenience for energy utilization [1]. Energy storage system is the key technology to create flexible energy system with high share of fluctuating renewable energy sources [2,3].

CAES (Compressed air energy storage) system is a potential method for energy storage especially in large scale, with the high reliability and relative low specific investment cost [4,5]. Conventional CAES systems originate from the basic gas turbine technology. During the charge process, the intermittent energy is consumed to produce and store the compressed air in the underground cavern. During the discharge process, the compressed air is vented from the carven and heated before expanding into the gas turbine, and thus the electricity energy is produced. In the heating process, the extra energy source such as natural gas is required [6]. So far two conventional CAES plants have been constructed till now: the Huntorf plant of 290 MW, Germany, constructed in 1978, the McIntosh of 110 MW, USA, built in 1991. The Huntorf plant is applied for leveling the variable power from numerous wind turbines in Germany [7–9]. The evaluation the CAES plants in energy systems with high share of fluctuating renewable energy sources are given [10,11]. Specific CAES plant application which is alone or in combination with another technology are described [12]. The system-economic feasibility of CAES plants is evaluated and the result shows that the conventional CAES technology needs improvement of energy efficiency and system feasibility [13]. The optimization of CAES operation on electricity spot market is also analyzed [14,15]. Optimal strategy and practical strategies are identified and compared by Henrik Lund [16].

However, the greenhouse gas is released in the combustion process of fossil fuels, which is the main disadvantage of conventional CAES technology [12]. This has led to significant efforts being expended on the CAES system optimization. More recently, some more advanced systems came into being, for instance the so called adiabatic CAES using the TES (thermal energy storage). The adiabatic CAES absorbs, stores the high-quality compression heat in TES

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Nomenclature

W	electric energy, kWh
t	time, min
Cp	constant pressure specific heat, kJ/(kg k)
q_m	mass flow rate, kg/min
T	temperature, k
P	pressure, MPa
η	efficiency
k	ratio of specific heat
m	mass, kg
V	volume, m^3
R_g	gas constant, kJ/(kg k)

Subscripts

c	compression
e	expansion
N	number of compression stage
M	number of expansion stage
a	air
st	air storage tank
pump	water pump

Superscripts

in	enter
out	leave

system, and recycles the compression heat to replace the combustion, hence eliminates the need for fossil fuels [17,18].

Extensive studies for CAES system with TES have been conducted in recent years. Adriano Milazzo designed and optimized the CAES/TES systems for renewable energy plants and had a primary estimate of the system energy recovery efficiency [19]. Niklas Hartmann analyzed the efficiency of several adiabatic CAES configurations and pointed out that the key element to improve the efficiency was to develop high-temperature thermal storages (>600 °C) and temperature resistant materials for compressors [20]. The effect of TES system on adiabatic CAES efficiency was evaluated by Yuan Zhang, with the influence of effectiveness and pressure loss in heat-exchanger on energy conversion [21,22]. Mandhapati Raju developed an accurate dynamic simulation model for CAES inside caverns and the Huntorf plant is taken as the case study to validate the model [23]. The thermodynamic effects of different air storage chamber models on adiabatic CAES system were examined by Yuan Zhang [24]. A new constant-pressure CAES system combined with pumped hydro storage was studied by Y.M. Kim [25].

The previous study for the CAES with TES mainly focuses on the simulation and theoretical analysis of the system design or the optimization of the system components. No public experimental data has been collected to test the performance of the CAES system with TES. In this research, a CAES pilot plant with the TES is constructed and the real data has been recorded and processed to validate the theory.

2. Experimental description

2.1. Pilot plant description

To study the energy storage characteristics of CAES system with TES, a CAES pilot plant named "TICC-500" was built up. The project started in 2012 and the site was located in Wuhu, China. The process flow diagram is shown in Fig. 1. The construction diagram and the photograph of the pilot plant were shown in Fig. 2 and Fig. 3. The pilot plant construction was completed in November 2014.

The designed maximum generator output power is 500 kW which has determined the air mass flow rate in charge and discharge process. Under the conditions of the air mass flow rate and the outlet air pressure, the fixed reciprocating air piston compressor has been applied. Since the outlet temperature of piston compressor is always below 150 °C, the pressurized water is used in the TES system as the thermal energy storage working medium. Heat-exchangers are adopted to capture the compression air heat in the charge process and reheat the expanded air in the discharge process. The volume of the air storage tank is 100 m^3 with the storage operation pressure ranging from 2.5 MPa to 9.5 MPa. The stored air is expanded and reheated in three stages through an air turbine. The generator is driven by the air turbine through the decelerator to produce the output electricity energy. All of major components are based on the mature and available facilities within our available financial budget. Also, we did design the major components taking account of construction feasibility and system efficiency.

2.2. Compressor

The reciprocating air piston compressor of pilot plant is a symmetrical model with four-row and five stages. The maximum outlet pressure can reach 11.3 MPa and the rated parameters of the compression in each stage are shown in Table 1. A driven-motor with the rated power of 315 kW is selected. The outlet air temperature of the compression in each stage is designed below 150 °C considering the compressor operation safety.

The rated air mass flow rate of the compressor is 1600 kg/h under the ambient temperature of 25 °C. It should be noted that different ambient temperatures could lead to the variation of the density and mass flow rate of the inlet air, which in turn may affect the compressor power and time of the charge process. For example, the local ambient temperature is probably below 0 °C in the winter, and the practical mass flow rate may be 10 percent larger than the rated.

As the volume of air storage tank is constant and the tank is directly connected to the compressor, the outlet pressure of the compressor (back pressure) is determined by the pressure of the air storage tank ranging from 2.5 MPa to 9.5 MPa. The rated outlet pressure of each stage for the reciprocating compressor is set in the design process. The rated outlet pressure of the 3-stage compression is 2.40 MPa and 4-stage compression is 5.80 MP, which indicates that the charge process can be divided into two periods.

In the first period, the previous three stages are under steady working operations and their outlet pressures remain nearly stable. The outlet pressure of 4-stage are increasing to the rated pressure of 5.80 MPa along with the pressure of the air storage tank. Therefore, the outlet temperature and compressor power of 4-stage also increase to the rated value. The 5-stage compression is idling without load in the first period. When the 4-stage compression reaches the rated operation, the first period will finish.

In the second period, the previous four stages are under the steady working operations. The 5-stage compression is gradually coming into the working operation with its outlet pressure increasing from 5.80 MPa to 9.5 MPa. When the pressure of the air storage tank reaches 9.5 MPa, the charge process will finish.

2.3. Air storage tank

The air storage tank consists of two steel tanks of 50 m^3. The air storage pressure increases in the charge process based on the fact