Applied Thermal Engineering 91 (2015) 812–823

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Performance analysis of a novel energy storage system based on liquid carbon dioxide

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HIGHLIGHTS

- A novel energy storage system based on liquid carbon dioxide is presented.
- The effects of some key parameters on the system performance are studied.
- The operation optimization is conducted by genetic algorithm.
- Comparative analysis of AA-CAES and liquid carbon dioxide system is studied.

ARTICLE INFO

Article history:
Received 26 November 2014
Accepted 25 August 2015
Available online 4 September 2015

Keywords:
Energy storage system
Wind power
Liquid carbon dioxide
Parametric analysis

ABSTRACT

Due to the intermittence and fluctuation of wind resource, the increasing penetration level of wind power will bring huge challenges to maintain the stability of power system. Integrating compressed air energy storage (CAES) system with wind farms can weaken this negative effect. However CAES system needs large caverns or mines to store compressed air, which is restricted in application. In this paper, a novel energy storage system based on liquid carbon dioxide is presented. The mathematical models of compressed liquid-carbon dioxide energy storage system are developed. The parametric analysis is conducted to examine the effect of some key thermodynamic parameters on the system performance. Compared with AA-CAES, the liquid carbon dioxide energy storage system has advantages such as a high energy density, high EVR. Moreover, the round trip efficiency of this system can reach about 56.64%, which is acceptable in consideration of the storage volume. Therefore, this proposed system has a good potential for storing wind power in large scale and offers an attractive solution to the challenges of the increasing penetration level of wind power.

1. Introduction

Increasing energy demand, shortage of fossil fuel resource and rising concern about environment protection have led to worldwide interests in renewable energy sources. In recent years, wind energy as a desirable renewable energy source appears to be the fast growing alternative power generation source. Rapid development of wind energy not only makes extraordinary progress in wind power technology, but also brings challenges to the grid integration of wind power, especially in a high wind power penetration level [1,2]. The reason for this is that wind energy cannot be dispatched and its power production is uncertain due to the intermittency of natural wind. In order to smooth the wind power output, additional controllable power from conventional electricity generation or energy storage system is required. There are many energy storage systems, including pumped hydro storage system (PHS) [3], compressed air energy storage system (CAES) [4], and fuel cell energy storage system.

Pumped hydro energy storage is the oldest and most widely used method of such massive energy storage. A location with a suitable elevation gradient, and a large amount of storage media (water) are required to achieve large scale pumped hydro energy storage [5]. Compared to pumped hydro energy storage, CAES systems will require much less water and do not require a large elevation gradient.

CAES is one of the most promising storage technologies based on gas turbine technology. Due to the fuel dependency of the conventional CAES, several optimized CAES systems are proposed,

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http://dx.doi.org/10.1016/j.applthermaleng.2015.08.081
1359-4311/

Nomenclature

W	power (kW)
Q	heat transfer rate (kW)
m	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
s	entropy (kJ/(kg K))
I	exergy destruction (kW)
P	pressure (MPa)
T	temperature (K)
E	exergy (kW)
t	time (s)
Greek letters	
η	efficiency
Subscript	
0	ambient state
1–17	state point
r245fa	organic fluid (R245fa)
air	air
com	compressor
TES1	heat storage unit
TES2	cool storage unit
con1	condenser 1
con2	condenser 2
tur1	turbine 1
tur2	turbine 2
pu1	pump 1
pu2	pump 2
eva	evaporator
th	thermal
ex	exergy
in	into the system
char	the charge process
dischar	the discharge process
Acronyms	
COP	compressor outlet pressure
TOP	turbine 1 outlet pressure
ORC	organic Rankine cycle
TES	thermal energy storage
RTE	round trip efficiency
EVR	energy generated per unit volume (kWh/m^3)

and one of them, called Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), receives increasing attentions [6–8]. And energy storage hereby is performed by compressed air in caverns. These caverns can either be drilled in salt and rock formations or already existing cavities such as in aquifer strata, which make CAES and AA-CAES be restricted in application.

In order to overcome the restrictions of the CAES relying on the large storage cavern, recently, some studies have been conducted on the novel energy storage technology based on liquid air. Smith (1977) has shown that there is a potential for greatly improving the storage efficiency by recovering cold heat from liquid air to utilize in a liquefaction process when liquid air is fed to a gas turbine. Kooichi Chino and Araki (2000) proposed an energy storage system using liquid air with a simple and realizable cool storage unit [9]. Chen et al. (2007) presented a novel energy storage system [10]. It is found that the liquid air energy storage system has advantages such as a high energy density and no geographical restriction. However, the critical temperature of air is so low that the system needs good insulation measures. And the cryogenic air and its vapor and rapidly freeze human tissue and can cause many common materials to become brittle or even break under stress. So the liquid air system involves potential hazards.

Recently, because of the good properties and characteristics, more and more attentions have been paid to supercritical carbon dioxide cycle [11–13]. Therefore, a novel energy storage system is presented in this paper by combining liquid air energy storage system and supercritical carbon dioxide system. Compared to the liquid air, Carbon dioxide as the working fluid has the advantage of high critical temperature and is susceptible to liquefaction. Moreover, liquid carbon dioxide system has better safety and more flexibility. Meanwhile, little work is investigated on the liquid carbon dioxide energy storage system.

In this paper, a novel energy storage system based on liquid carbon dioxide is proposed. The mathematical models of compressed liquid-carbon dioxide energy storage system are developed and implemented. The parametric analysis is conducted to examine the effect of some key thermodynamic parameters on the system performance. Those analysis results are used to verify the feasibility of this novel system.

The organization of the paper is as follows. Section 2 deals with the detailed presentation of the liquid carbon dioxide energy storage system. In Section 3, the mathematic models of this system are described. Simulations are carried out in Section 4, and conclusions derived from simulation results are presented in Section 5.

2. System overview

In order to reduce the negative effects of the wind power output fluctuations on the power system operation and stability, the wind farm must be equipped with energy storage system. In this paper, the liquid carbon dioxide energy storage system is adopted as the energy storage system, as shown in Figs. 1 and 2. This system consists of twelve components: a compressor, an evaporator, two TES (Heat storage unit and Cool storage unit), two tanks, two condensers, two pumps, and two turbines.

2.1. The charge process

As shown in Fig. 1, the working principle of the charge process is presented as follows:

9–10: The working fluid (carbon dioxide) stored in Tank 2 decreases the pressure to a certain value through the throttle valve, according to the Joule-Thomson effect, and is transported to TES 2 (Cool storage unit).
10–11(1): The cool carbon dioxide decreases the pressure to ambient pressure and is heated while providing cold heat to TES2.
1–2: During off-peak hours, using the surplus wind power, carbon dioxide is pressurized into the state with high temperature and high pressure.
2–3: The compressed carbon dioxide is cooled by the TES 1 (Heat storage unit) to near the liquefaction temperature and the heat produced in the compression process also can be stored.
3–4: Carbon dioxide is cooled by the condenser into the liquid state, and is stored in Tank 1.