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Thermodynamic analysis of a High Temperature Pumped Thermal Electricity Storage (HT-PTES) integrated with a parallel organic Rankine cycle (ORC)

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ABSTRACT

Pumped thermal electricity storage (PTES) using packed bed is an attractive large-scale energy storage technology. The performance of conventional PTES is limited by the existing technology of compressor, such as low isentropic efficiency and cannot bear high temperature. In this work, a high temperature PTES (HT-PTES) based on an additional electric heater is proposed to enhance the energy storage capacity of PTES. Waste heat, which produced due to the irreversibility of heating, compression and expansion process of both PTES and HT-PTES, is recovered by the organic Rankine cycle (ORC) to generate power. Air and argon (Ar) are investigated as working fluid for PTES and air is selected due to its high thermal performance and economy. Five types of PTES combined with ORC system namely, PTES, HT-PTES, PTES + ORC, HT-PTES + ORC and HT-PTES + parallel ORC are investigated based on transient analysis method. The simulation results show that combined with ORC is an effective approach to improve the round trip efficiency (RTE) of both PTES and HT-PTES. In the five types of combined systems, the HT-PTES + parallel ORC is considered as a more promising large-scale energy storage technology which advantages can be illustrated as follows: (1) it with an acceptable RTE of 47.67%, which is 5.68% higher that of HT-CAES and is only 2.46% lower than the maximum RTE of the five types; (2) it shows an appropriate operating pressure, which are 1.05 MPa for HT-PTES subsystem and 12.20 MPa for ORC subsystem (significantly lower than that of 31.2 MPa for ORC in the HT-PTES + ORC); (3) it presents a considerable energy storage density of 218.69 MJ/m^3, which is more than twice that of PTES + ORC (88.14 MJ/m^3).

1. Introduction

Renewable energy sources (RESs) such as sources of wind energy and solar energy are rapidly emerging as solutions to the challenging climate-change problem which caused by utilization of fossil fuels [1]. With the development of RESs, many challenges have presented due to their unpredictable and cannot be easily controlled [2]. Energy storage systems (ESSs) provide a wide array of technological approaches to solve these challenges due to their potential in load balancing in the electricity grid as well as storing the surplus power during peak production periods for later use at peak demand periods [3].

Energy can be stored in various forms, such as mechanical, chemical, electrostatic, magnetic, biological, and thermal [4]. Despite the large number of available storage technologies, only three of them can be considered as large-scale electricity storage technologies currently (> 100 MWh): pumped hydro storage (PHS), compressed air energy storage (CAES) and flow batteries [5].

The PHS has much advantages such as fast response, high round trip efficiency (RTE), low self-discharge rate and long time, hence it is the dominating large-scale ESS technology currently [6]. However, in developed countries, the most suitable sites for PHS are almost being used [7]. Furthermore more, it may have a significant impact on the environment in terms of soil, biodiversity, and water quality [8].

CAES is proposed as an effect energy storage technology due to its high reliability and economic feasibility [9]. However, it suffers from a low RTE and is dependent on fossil fuels results in CO_2 emissions [10]. This problem can be partially solved by an adiabatic CAES (A-CAES). In A-CAES, the heat of compression is absorbed and stored by a thermal energy storage (TES) system in charging process, and it is employed to heat the compressed air in discharging process [11]. As a result, the RTE over 70% can be obtained and fossil fuels are ignored. To meet the different energy requirements in terms of electricity, cooling energy,

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Nomenclature

Symbols

A	area, m^2
c_p	specific heat capacities, kJ/(kg·K)
d	diameter, m
D	diameter, m
Ex	exergy, kJ
G	mass flow rate per unit cross section, kg/(m^3·s)
h	specific enthalpy, kJ/kg
h_v	volumetric heat transfer coefficient, W/(m^3·K)
k	coefficient of thermal conductivity, W/(m·K)
L	length, m
$\dot{m}$	mass flow rate, kg/s
P	pressure, kPa
r	radius, m
t	time, s
T	temperature, K
U	heat transfer coefficient, W/(m^2·K)
V	volume, m^3
$\dot{W}$	work input rate, kW
W	work, kJ
ρ	density, kg/m^3
μ	dynamic viscosity, Pa·s

Subscripts

0	ambient conditions
c	compression process
com	compressor
cold	cold fluid
con	consuming
char	charging process
dischar	discharging process
ES	energy storage
f	fluid
gen	generation
hot	hot fluid
in	inlet
out	outlet
p	particle
s	solid
turb	turbine
w	wall
∞	ambient conditions

Acronyms

CP	compressor
CON	condenser
EH	electric heater
G	generator
HP	high pressure
HE	heat exchanger
HT	high temperature turbine
HHE	high temperature heat exchanger
LP	low pressure
LT	low temperature turbine
LHE	low temperature heat exchanger
M	motor
PH	pre-heater
RTE	round trip efficiency
TB	turbine

Greek letters

π	pressure ratio
η	isentropic efficiency
ε	void fraction
ψ	shape factor

and thermal energy, the tri-generation CAES (T-CAES) is presented [12]. In normal A-CAES, a throttling process should be required to release the air out of vessels, which causes considerable exergy losses. This problem can be partially addressed by the isobaric A-CAES (IA-CAES), and many forms of IA-CAES have been studied, such as based on the pumped water [13], phase change process of volatile fluid [14], and hydrostatic pressure of sea water [15]. For conventional CAES and A-CAES, suitable geographical conditions (underground hard-rock or salt caverns, porous rock formation and depleted natural gas field) are required for air storage, which limit their application. This constrain can be partially addressed by introducing of artificial vessels. Moreover, the air in the artificial vessels is expected to be cleaner, which should increase the operating lifetime of the turbine [16]. However, an additional artificial vessels bring increment of system cost.

Flow batteries are a relatively young technology. Interest in the development of flow batteries for large-scale grid storage is growing, due to their unique features including ease of scalability, high efficiency, flexible operation and long cycle life [17]. However, compared to PHS and CAES, flow batteries provide a limited output power and are still expensive [5].

Pumped thermal electricity storage (PTES) is the last in-developing storage technology suitable for large-scale energy storage applications [18]. The PTES consists a compressor, a turbine, and two man-made thermally isolated tanks: one hot and one cold, and its basic concept is fairly simple. In charging process, a heat pump cycle is adopted, which transforms the renewable energy or off-peak electricity into thermal energy and is stored in hot and cold tanks. In discharging process, a heat engine cycle is employed to convert the stored thermal energy back into electricity. Compared to PHS and CAES, PTES benefits from relatively high energy storage densities, no geographical constraints and a small installation footprint [19].

Thess [20] formulated a simple thermodynamic model based on the Carnot cycle to predicts the efficiency of PTES (defined as Pumped Heat Electricity Storage PHES in literature), which was set as a function of the temperature of the thermal energy storage at maximum output power. Guo et al. [21] proposed a more realistic thermodynamic model for PTES based on the Brayton cycle, at first the finite-rate heat transfer and external heat leakage losses were considered [21], then the internal and external irreversible losses were took into account [22], and more recently a more universal thermodynamic was established which based on the weak dissipative assumption [6].

Brayton cycle is always utilized as thermodynamic cycle for PTES, it uses a single phase gas like air or argon (Ar) as working fluids. Desrues et al. [23] presented a PTES for large-scale electric applications based on Brayton cycle and using argon gas as the working fluid. A RTE of 66.7% can be achieved, while a maximum temperature of 1000 °C should be required, which has further exceeded the working temperature of existing compressor (about 900 K) [24]. The constraint can be partially solved by introducing an additional electric heater. Benato [5] proposed an innovative PTES power system, which also based on Brayton cycle, while air was utilized as working fluid and five types of high storage material properties were investigated. In the PTES an electric heater is employed to enhance the maximum storage temperature, hence this parameter is not affected by the compressor