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Analysis of an integrated packed bed thermal energy storage system for heat recovery in compressed air energy storage technology

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HIGHLIGHTS

- A packed bed TES system is proposed for heat recovery in CAES technology.
- A CFD-based approach has been developed to evaluate the behaviour of the TES unit.
- TES system enhancement and improvement alternatives are also demonstrated.
- TES performance evaluated according to the first and second law of thermodynamics.

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ABSTRACT

Compressed air energy storage (CAES) represents a very attracting option to grid electric energy storage. Although this technology is mature and well established, its overall electricity-to-electricity cycle efficiency is lower with respect to other alternatives such as pumped hydroelectric energy storage. A meager heat management strategy in the CAES technology is among the main reasons of this gap of efficiency. In current CAES plants, during the compression stage, a large amount of thermal energy is produced and wasted. On the other hand, during the electricity generation stage, an extensive heat supply is required, currently provided by burning natural gas. In this work, the coupling of both CAES stages through a thermal energy storage (TES) unit is introduced as an effective solution to achieve a noticeable increase of the overall CAES cycle efficiency. In this frame, the thermal energy produced in the compression stage is stored in a TES unit for its subsequent deployment during the expansion stage, realizing an Adiabatic-CAES plant. The present study addresses the conceptual design of a TES system based on a packed bed of gravel to be integrated in an Adiabatic-CAES plant. With this objective, a complete thermo-fluid dynamics model has been developed, including the implications derived from the TES operating under variable-pressure conditions. The formulation and treatment of the high pressure conditions were found being particularly relevant issues. Finally, the model provided a detailed performance and efficiency analysis of the TES system under charge/discharge cyclic conditions including a realistic operative scenario. Overall, the results show the high potential of integrating this type of TES systems in a CAES plant.

1. Introduction

Currently, the worldwide installed capacity for electrical energy storage (EES) is dominated by pumped hydroelectric energy storage (PHES). In 2015, with 145 GW installed, PHES represented about 97% of the global EES capacity [1]. The power ratings of the existing PHES plants are in the range of 1 MW up to 3 GW with a cycle efficiency of 70–85% [2]. Despite PHES is a well-known, mature and efficient solution it has also some major limitations such as: applicability limited to suitable locations and relatively low energy density, which translates into a considerable environmental impact.

In the field of large-scale EES, a valid alternative to PHES is represented by compressed-air energy storage (CAES). CAES plants operate on a "decoupled" Brayton cycle. During electric energy

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Nomenclature

B	exergy (J)
C_2	inertial resistance factor (m^{-1})
c_p	specific heat at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$)
d_p	particle diameter (m)
L	tank height (m)
Ma	Mach number (v/v_{sound}) (–)
H	enthalpy (J)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)
p	pressure (Pa, bar)
Re_p	particle Reynolds number ($v_\infty \cdot \rho \cdot d_p \cdot \mu^{-1}$) (–)
S_i	source term ($kg \cdot m^{-2} \cdot s^{-2}$)
S	entropy ($J \cdot K^{-1}$)
T	temperature (K)
t	time (s)
v	velocity ($m \cdot s^{-1}$)
v_{sup}	superficial velocity ($m \cdot s^{-1}$)
ε	void fraction (–)
η	efficiency (–)
σ	permeability (m^2)
$\bar{\bar{\tau}}$	stress tensor (Pa)
ρ	density ($kg \cdot m^{-3}$)
μ	viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)

Subscripts

amb	ambient
B	exergy
c	charge
d	discharge
eff	effective
f	fluid
s	solid
1	top
2	bottom
I	first thermodynamics law
II	second thermodynamics law

Abbreviations

A-CAES	adiabatic compressed air energy storage
CAES	compressed air energy storage
CFD	computational fluid dynamics
CSP	concentrated solar power
D-CAES	diabatic compressed air energy storage
EES	electrical energy storage
HTF	heat transfer fluid
LTE	local thermal equilibrium
MAE	mean absolute error
PHES	pumped hydroelectric energy storage
PISO	pressure-implicit with splitting of operators
PRESTO!	pressure staggering option
RMSD	root mean square deviation
TES	thermal energy storage
UDF	user defined function

storage, the air compression operation occurs and electricity is absorbed from the grid to activate a motor-compressor train (see Fig. 1). The thermal energy produced during compression is removed by means of intercoolers and after-coolers and the high-pressure low-temperature air is then stored in a large air reservoir, usually a cavern. When electric energy is requested from the grid, the compressed air is extracted from the reservoir, is flown and heated in a combustion chamber and, at high enthalpy, it is expanded in a gas turbine that drives itself an electric generator. As of today, two industrial-scale CAES plants are successfully in operation: the 321 MW Huntorf plant in Germany, and the

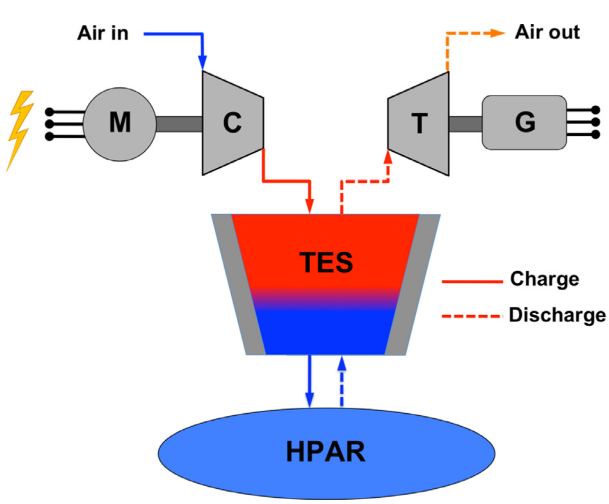

Fig. 1. Scheme of the A-CAES plant with integrated packed bed TES tank. M: electrical motor; C: compressor train; T: turbine; G: electric generator; TES: thermal energy storage; HPAR: high pressure air reservoir.

110 MW McIntosh plant located in Alabama, (U.S.). Commissioned at the end of 1978, the Huntorf plant is the world's first CAES plant, whereas the McIntosh CAES plant, commissioned in 1991, can be considered as a second-generation CAES in which a recuperator is exploited to pre-heat the compressed air before entering the combustion chamber. With this enhancement the electricity-to-electricity cycle efficiencies of McIntosh reached 54% vs. 42% of the Huntorf plant [3].

Since several CAES concepts have been proposed/developed, a general classification can be based upon how thermal energy is managed during air compression/expansion stages [3]. If thermal energy is wasted during compression and provided prior to expansion by burning natural gas in a combustion chamber, the CAES concept is known as diabatic (D-CAES); Huntorf and McIntosh are D-CAES plants. Conversely, if thermal energy produced during compression is stored into a thermal energy storage (TES) system, from which is recovered before expansion, the associated CAES concept is known as adiabatic (A-CAES) [4]. The development of the A-CAES concept was the subject of the research project "ADELE" (2010–2013) [5] with the construction of the world's first 260 MW prototype expected as outcome of the "ADELE-ING" project (2013-present) [6]. Since in the A-CAES concept there is no need of burning fuel for the air heating process before expansion, the expected round-trip efficiency is in the order of 70% [5]. As a consequence, the TES system becomes a key component for a successful commercial implementation of the A-CAES technology.

TES systems can store thermal energy in the form of sensible heat, latent heat [7] or by thermochemical reactions [8]. The large majority of the high-temperature TES systems nowadays in operation in concentrating solar power (CSP) applications [9] or industrial process heat recovery [10], store sensible heat with a two-tank storage configuration [11]. However, and by considering its high-efficiency, affordability and simplicity, the single-tank or