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Modeling and integration of a heat storage tank in a compressed air electricity storage process

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ABSTRACT

In an adiabatic compressed air energy storage process (A-CAES), heat storage tank operation is a key factor that determines the overall energy performance of the process. To highlight energy issues linked to a correct tank design in the specific case of an A-CAES system, a two-dimensional thermal numerical model was developed. Thermal efficiencies of the tank are presented with abacus defined from the four dimensionless numbers defining the thermal behavior of the reservoir. Cycling effects are explored with a realistic case study corresponding to an A-CAES system design to deliver an electrical power of 250 MWel for 4 h, the daily peak demand. Extended beyond the thermal reservoir, A-CAES thermodynamic analysis combined with the dynamic simulation makes it possible to generate a direct quantitative link between reservoir sizing and A-CAES global efficiency.

1. Introduction

The current energy context is marked by the progressive planned integration of renewable energies into electrical energy production networks [1,2]. The intermittent nature of all forms of renewable energy implies that this objective is necessarily associated with the deployment of electricity storage technologies [3,4]. While various storage modes are available today, most of them are not specifically adapted to the case of large-scale storage, capable of providing flexibility to power grids. The most mature technology for utility-scale electricity storage (several hundred MWh) is pumped hydroelectricity [5,6]. However, in developed countries, the most favorable sites for uptake of this technology are already being used [7].

Compressed air energy storage (CAES) opens a new option to diversify technologies for massive electricity storage [8,9]. During off peak hours, an electric motor consumes energy available on the network to compress atmospheric air and fill underground caverns. During peak hours, the stored air pressure is removed from the caverns and then heated by burning natural gas or fuel in a combustion chamber. The hot air is expanded in a turbine to drive a generator and produce electricity. Only two CAES facilities are currently in operation around the world: (i) Huntorf, a 290 MW plant with a 3-h capacity, open in Germany since 1978, with an overall yield of 42%, where air is compressed and stored in two salt domes that measure 150,000 m^3 each; and (ii) McIntosh, a 110 MW plant with a 26-h capacity, open in the United States (Alabama) since 1991, with an overall yield of 49%. The performance differential between the two systems is due to the fact that the McIntosh facility recovers a part of the ultimate output energy of the turbine to preheat the air leaving the underground cavity. This performance differential also underscores the interest of improving management of the heat flows necessarily associated with these storage electricity plants.

With this objective in mind, it has been shown that using a thermal heat sub-storage integrated to the CAES system could significantly improve the overall process yield to achieve an ideal theoretical value of about 70% [10,11]. While no facility currently works according to this principle, the idea is to remove the combustion chamber used in conventional CAES technology and upgrade to 'adiabatic CAES' (A-CAES). The aim is to integrate a thermocline thermal energy storage to allow the storage of the heat produced by air compression for recovery and subsequent transfer to the air at the cavern outlet before it enters the turbine.

Prior to the thermal study the principles of operation of the overall A-CAES process, particularly the thermocline storage, were set out. Indeed, if experimental [12] and theoretical heat storage [13–15] integration is well studied in the literature in solar energy application especially in the case of CSP, this is far from being the case for CAES technology that involves specific working constraints.

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Nomenclature

A	fluid–solid heat exchange surface (m^2)
Bi	Biot number (–)
C_p	specific heat (J/kg K)
Eff	thermal efficiency (–)
h	enthalpy (J/kg)
h_c	convective heat exchange coefficient (W/m^2 K)
L	plate length (m)
l	half plate thickness (m)
le	half width between plates (m)
Lo	plate width (m)
m	mass (kg)
$\dot{m}$	mass flow (kg/s)
Np	plate number (–)
NTU	number of transfer unit (–)
P	pressure (bar)
Pe	fluid Peclet number (–)
Q	energy (J)
R_A	air specific constant (J/kg K)
T	temperature (K)
t	time (s)
u	speed (m/s)
V	volume (m^3)
$\dot{W}$	mechanical power (W)

Greek symbols

α	thermal diffusivity (m^2/s)
β	pressure ratio (–)
η	yield (–)
γ	specific heat ratio (–)
λ	thermal conductivity (W/m k)
ρ	density (kg/m^3)

Subscripts

comb	combustion
comp	compression
ech	exchange
f	fluid
ini	initial
is	isentropic
max	maximum
p	resident
br	breakthrough
pr	process
s	solid
ts	thermal storage
tur	turbine
1...5	of the characteristic points of the process (Fig. 1)

Simulations of in-tank temperature profiles during the heat storage/removal phases allow the local description of the heat transfer between the fluid and the solid which is important for thermal management. Within this objective, several authors used the model originally developed by Schumann and thoroughly presented by Schmidt and Willmott [16]. A generalized method, including axial thermal dispersion and intra-particle conduction, was also presented by, for example, Saez and McCoy [17]. Bindra et al. [18] examined numerically the effects of particle size, void fraction, flow rate, and fluid inlet temperature. In the case of solar application, Yang and Garimella [13], Flueckiger et al. [14] outlined the influence of the boundary conditions and the heat loss on the thermal behavior of a TES thermocline working with quartzite as solid and molten salt as fluid. Very recently, Anderson et al. [19] presented a validated model to predict the fluid and solid temperatures in a packed bed thermal energy storage vessel using compressed gas for thermal energy storage. The model was validated against experimental data obtained from a packed bed of alumina. In our work, the objective is to highlight energy issues linked to a correct tank design in the specific case of an A-CAES system. Also, the approach adopted for the tank thermal modeling consisted in working on the basis of a simple geometry and providing a generalization framework based on the definition of dimensionless numbers. Thermal tank efficiency during one discharge phase is systematically determined as a function of the characteristic dimensionless numbers, providing a reservoir design and scale up chart. Development of a highly detailed thermal model, to demonstrate its accuracy by comparison with an experiment is out of the scope of the paper.

As for any cycling storage process [15] successive cycles are necessary to reach a reproducible mode from one cycle to the other. This is illustrated through a realistic case study corresponding to an A-CAES system design to deliver an electrical power of 250 MWel for 4 h, the daily peak demand.

The last step is devoted to generating a formal link between A-CAES process yield and thermal reservoir efficiency determined as a function of the tank design. This is achieved by process thermodynamics analysis combined with the results of dynamic simulations. The effect of the thermal reservoir design on A-CAES performance is quantified.

2. CAES and A-CAES working mode

Electricity storage consists in a transfer of the excess energy produced by the thermal power plants during off-peak hours to periods of high demand [8,9]. The CAES system (Fig. 1) involves five main modules: a motor-generator; a series of compressors; a gas turbine; one or more compressed air storage caverns; and a combustion chamber. During peak periods, the electric motor consumes energy available on the network to compress atmospheric air and fill underground caverns. In the schematic flowsheet presented in Fig. 1, the maximum temperature of the air leaving the compressors is 900 K at a pressure of 30 bars, making it possible to consider the use of low-cost undergrounds such as former salt caverns. During storage of the compressed air, the energy content of the heated air, which may also partially damage the cavern walls [20], is irremediably lost by convective heat exchange between the fluid and geological cavity. Thereafter, during peak hours, the flow of air stored under pressure is extracted from the cavern at a near-ambient temperature, then heated to 900 K by burning natural gas or fuel in the combustion chamber, and finally expanded in a turbine to drive a generator and produce electricity.

The A-CAES concept consists of storing the thermal energy necessarily produced by air compression for later re-use–recovery for the air expansion and electric power generation phases. The thermal reservoir used for this objective should ideally bypass the need for a combustion chamber to heat the air, thus marking an upgrade on conventional CAES [21]. In practice, it should minimize the energy provided to compressed air before it enters the turbine. This thermal tank containing a solid is positioned at the inlet of the cavern (Fig. 1). The implementation of the thermal tank leads to the definition of points numbered 0–6 that are characteristic of the thermodynamic state of the air during a storage/de-storage cycle.