Journal of Energy Storage 17 (2018) 140–152

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 2: Tests with combined sensible/latent thermal-energy storage

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ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form 6 February 2018
Accepted 6 February 2018
Available online xxx

Keywords:
Advanced adiabatic compressed air energy storage
Thermal-energy storage
Packed bed
Pilot plant
Simulation
Phase-change material

ABSTRACT

Experimental and numerical results from the world's first pilot-scale advanced adiabatic compressed air energy storage plant with combined sensible/latent thermal-energy storage are presented. The combined thermal-energy storage was composed of sensible and latent units with maximum capacities of 11.6 MWh_{th} and 171.5 kWh_{th}, respectively. The latent thermal-energy storage consisted of a steel tank with 296 stainless-steel tubes encapsulating an Al–Cu–Si alloy as phase-change material. The combined thermal-energy storage was investigated using four charging/discharging cycles with durations of about 3 h each and air inflow temperatures of up to 566 °C. The experimental results showed that the latent thermal-energy storage reduced the drop in the air outflow temperature during discharging. Minor leaks of the phase-change material were traced to the welding seams in the encapsulation as well as to holes required to insert resistance temperature detectors. Analysis of the leaked phase-change material revealed degradation and/or phase separation, which were attributed to the initial off-eutectic composition of and impurities in the phase-change material and resulted in a reduced heat of fusion. Simulations predicted the performance of the combined thermal-energy storage with good overall accuracy. Discrepancies were put down to changes in the thermophysical properties.

1. Introduction

Among large-scale energy-storage technologies, advanced adiabatic compressed air energy storage (AA-CAES) has recently attracted much interest because of projected high power outputs (above 100 MW), high efficiencies (about 60–75%), and low capital costs, see Luo et al. [1], Budt et al. [2], and Sciacovelli et al. [3]. Experimental and numerical results from the first pilot-scale AA-CAES plant with high-temperature sensible thermal-energy storage (TES) were reported in Part 1, see Geissbühler et al. [4]. The results demonstrated the technical feasibility of both the AA-CAES technology and the packed-bed TES that used rocks as the storage material and air as the heat-transfer fluid (HTF).

Sensible TES systems using rocks as storage material and air as HTF are of interest because experimental and numerical investigations have found them to be promising in terms of efficiencies and costs. One drawback of such TES systems is that during discharging, the temperature of the outflowing air decreases with time, which is unfavorable for the turbine in an AA-CAES plant. To overcome this drawback, a relatively small amount of phase-change material (PCM) can be placed on top of the packed bed of rocks, resulting in a so-called combined sensible/latent TES.

Combined sensible/latent TES has been investigated numerically and experimentally by several authors. Zanganeh et al. [5] and Geissbühler et al. [6] performed numerical and experimental analyses of a 42 kWh_{th} laboratory-scale combined storage consisting of a packed bed of rocks and an eutectic aluminum–silicon alloy as PCM encapsulated in steel tubes. They demonstrated stabilization of the air outflow temperature around the melting temperature of the PCM. In addition, Geissbühler et al. [6] used simulations to show that 23 MWh_{th} and 1000 MWh_{th} combined storages have higher exergy efficiencies and lower specific material costs compared to sensible storages for a given maximum outflow temperature drop during discharging. Galione et al. [7] compared numerically several industrial-scale combined storage configurations for a 50 MWh_{el} concentrated solar power plant and found that a storage consisting of multiple layers of sensible materials and PCMs diminishes the degradation of the thermocline and has a higher utilization factor. Zhao et al. [8] investigated numerically storage concepts with an output of 250 MWh_{th} and found that a storage consisting of sensible

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https://doi.org/10.1016/j.est.2018.02.003

Nomenclature

Abbreviations

AA-CAES	advanced adiabatic compressed air energy storage
DSC	differential scanning calorimeter/calorimetry
HTF	heat-transfer fluid
LFA	laser flash analysis
PCM	phase-change material
RTD	resistance temperature detector
TES	thermal-energy storage

Greek characters

α	thermal diffusivity (mm^2/s)
ρ	density (kg/m^3)

Latin characters

c_p	specific heat capacity at constant pressure (kJ/kg K)
$\dot{m}$	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
k	thermal conductivity (W/m K)
T	temperature (°C)
t	time (h)
x	axial coordinate (m)

Subscripts

bot	bottom of the storage unit
el	electric
exp	experimental results
lat	latent unit
ref	reference
sens	sensible unit
sim	simulation results
th	thermal
top	top of the storage unit
c	charging
d	discharging
f	fusion
l	liquid
m	melting
pc	pre-charging
s	solid

material and PCMs at the top and bottom of a tank with an optimum configuration is more cost-competitive than other thermocline TES systems for the same design requirements and operating conditions.

In summary, the literature shows that combined sensible/latent TES can be superior to sensible-only TES in terms of both efficiency and cost. While the combined sensible/latent TES has been investigated experimentally at the laboratory scale, to our knowledge it has so far not been tested at the pilot scale. Therefore, the overall goal of this paper is to investigate experimentally and numerically the performance of a combined sensible/latent TES in the pilot-scale AA-CAES plant introduced in Part 1. The specific objectives of this paper are:

1. Demonstrate the feasibility of a combined sensible/latent TES in the pilot-scale AA-CAES plant using several charging/discharging cycles.
2. Validate the quasi-one-dimensional heat-transfer model of Geissbühler et al. [6] using the experimental data collected with the combined TES.
3. Assess the thermal and mechanical stability of the latent TES tank, the encapsulation, and the PCM in response to the temperature and pressure variations during the charging/discharging cycles.

2. Plant description

The pilot-scale AA-CAES plant and its main components are described in detail in Part 1. Because the plant used to produce the results reported in this paper differs from that described in Part 1 only through the TES, this section is restricted to a description of the combined sensible/latent TES.

2.1. Combined sensible/latent TES

As shown in Figs. 1 and 2, the combined sensible/latent TES actually consists of two separate storages: a sensible storage, identical to that described in Part 1, and a latent storage. The main reason why the two storages are separate is that they were designed and constructed at different times. Additional reasons that justify using two separate TES units will be given below. It is important to note that the addition of the latent storage affects the performance of the sensible storage because during charging, the compressed air flows first through the latent storage from top to bottom and then through the sensible storage from top to bottom. Therefore, the melting temperature of the PCM and thermal losses from the pipe connecting the two storages affect the temperature of the air flowing into the sensible storage. As a result, the maximum capacity of the sensible storage is 11.6 MWh_{th} (calculated for an inflow temperature of 529 °C) rather than 12 MWh_{th} given in Part 1 (calculated for an inflow temperature of 550 °C). The maximum capacity of the latent storage is 171.5 kWh_{th} (calculated for an inflow temperature of 566 °C).

During the preparation of the experiments with the combined TES and accounting for the constraints imposed by the previously constructed sensible TES, three options were considered: (1) placing the encapsulated PCM directly on top of the packed bed of rocks, (2) placing the encapsulated PCM inside the air distributor, which is indicated in Fig. 2, and (3) placing the encapsulated PCM in a separate storage. Option (1) was adopted in the laboratory-scale combined storage by Zanganeh et al. [5] and Geissbühler et al. [6]. Due to the limited space available above the packed bed and the resulting poor heat transfer, this option could not be pursued. Similarly, option (2) was discarded because of the limited space available inside the distributor and because it would have required

Fig. 1. Picture of combined sensible/latent TES, with latent storage in foreground and sensible storage in background. The insulated pipes between the heater and the latent storage and between the latent and sensible storages can be seen.