Applied Energy 158 (2015) 243–254

Contents lists available at ScienceDirect

Applied Energy

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

Trigenerative micro compressed air energy storage: Concept and thermodynamic assessment

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HIGHLIGHTS

- The trigenerative-CAES concept is introduced.
- The thermodynamic feasibility of the trigenerative-CAES is assessed.
- The effects of the relevant parameter on the system performances are dissected.
- Technological issues on the trigenerative-CAES are highlighted.

ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 16 July 2015
Accepted 12 August 2015

Keywords:
Compressed air energy storage
Trigeneration
Distributed generation
CHP
Electricity storage

ABSTRACT

Energy storage is a cutting edge front for renewable and sustainable energy research. In fact, a massive exploitation of intermittent renewable sources, such as wind and sun, requires the introduction of effective mechanical energy storage systems.

In this paper we introduce the concept of a trigenerative energy storage based on a compressed air system. The plant in study is a simplified design of the adiabatic compressed air energy storage and accumulates mechanical and thermal (both hot and cold) energy at the same time. We envisage the possibility to realize a relatively small size trigenerative compressed air energy storage to be placed close to the energy demand, according to the distributed generation paradigm. Here, we describe the plant concept and we identify all the relevant parameters influencing its thermodynamic behavior. Their effects are dissected through an accurate thermodynamic model. The most relevant technological issues, such as the guidelines for a proper choice of the compressor, expander and heat exchangers are also addressed. Our results show that T-CAES may have an interesting potential as a distributed system that combines electricity storage with heat and cooling energy production. We also show that the performances are significantly influenced by some operating and design parameters, whose feasibility in real applications must be considered.

1. Introduction

Balancing supply and demand of electricity is nowadays a key issue for many countries, due to the increasing penetration of intermittent renewable energy sources (RES) and of distributed generation (DG) [1,2]. Different approaches are possible to cope with this problem including, updating the power regulation strategy for DG plants, utilizing electrical boilers and heat pumps, modifying the consumer demand of energy, switching to electricity based mobility, fast ramping conventional plant, and updating the electricity distribution infrastructure [1-3]. In this scenario, electricity storage certainly plays a key role especially for a large scale exploitation of intermittent RES, such as wind or solar power [2,4].

Despite only two working applications of compressed air energy storage (CAES) exist [3,5,6] these storage systems claims the greater economical feasibility [1,2], among all the technological alternatives for large scale electricity storage (e.g. pumped hydro and batteries), thanks to their relatively low investment cost per unit capacity [2]. Nevertheless, the assessment of the economic potential of such a technology is still an open research issue [1,2,4,7,8]. In a CAES the mechanical energy is stored by

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http://dx.doi.org/10.1016/j.apenergy.2015.08.026

Nomenclature

$\dot{C}_j$	chilling power exchanged in the j-th re-heater
$\beta_c(t)$	compression stage pressure ratio
β	ratio between maximum reservoir pressure and environmental pressure
δ	pressure loss in the heat exchangers and connecting pipes
$\dot{m}$	air mass flow
$\dot{Q}_i$	thermal power exchanged in the i-th inter-cooler
$\dot{Q}_\mathrm{R}$	thermal power lost through the reservoir walls
$\dot{V}$	volumetric flow rate
η_c	compressor small stage efficiency
η_e	small stage efficiency for the expander
η_p	small stage efficiency general
η_{ad}	adiabatic efficiency
η_{el}	electrical efficiency
η_{ex}	second law efficiency
η_{iso}	isothermal efficiency
γ	ratio between maximum and minimum reservoir pressure
$\mathcal{T}$	storage capacity
Nu_ext	Nusselt number relative to the air outside the reservoir
Nu_int	Nusselt number relative to the air inside the reservoir
Ra	Rayleigh number
Re	Reynolds number
μ	compressor load coefficient
ν	air kinematic viscosity
ϕ	compressor flow coefficient
ρ	air density
Θ	time interval between charge and discharge of the volume
ε	compression transformation exponent
ξ	polytropic exponent
A	heat exchange surface
a	zeroth order coefficient of air constant pressure specific heat
a^*	zeroth order coefficient of air constant volume specific heat
b	first order coefficient of the air specific heat
B_c	exergy relative to a chilling energy flux
B_t	exergy relative to thermal energy
C_i	thermal energy exchanged at the i−th re-heater
c_w	water specific heat
c_{p_a}	constant pressure specific heat for air
c_{v_a}	constant volume specific heat for air
D	reference length scale
d	hydraulic diameter
d_2	peripheral rotor blade diameter
d_s	specific diameter
h_ext	convective coefficient outside the reservoir
h_int	convective coefficient inside the reservoir
h_ri	enthalpy of the air entering the reservoir
H_s	isentropic enthalpy change across the compressor
k_air	thermal conductivity of air
k_iron	thermal conductivity of structural material
k_wool	thermal conductivity of insulation material
M	mass of air contained in the volume
N	rotating velocity
N_IC	number of inter-coolers
N_RH	number of re-heaters
N_c	number of compression stages
N_e	number of expansion stages
N_s	specific speed
p_env	environmental pressure
p_max	maximum reservoir pressure
p_min	minimum reservoir pressure
p_R	pressure of the air in the reservoir
Q_i	thermal energy exchanged at the i−th inter-cooler
R	gas constant relative to air
r_1	internal radius of the reservoir (see Fig. 2)
r_2	external radius of the structural part of reservoir (See Fig. 2)
r_3	external radius of the reservoir (See Fig. 2)
S	flow area
T	air temperature
t	time
T_ri	reservoir inlet temperature
T_ci	compressor inlet temperature
T_co	compressor outlet temperature
T_env	environmental temperature
T_{ico_i}	water temperature at the outlet of the i−th inter-cooler
T_{rho_j}	temperature at the outlet of the j−th re-heater
T_R	air temperature in the reservoir
T_ti	turbine inlet temperature
T_to	turbine outlet temperature
U	global heat exchange coefficient
u_2	peripheral blade speed
V	storage volume
W_c	compression electrical work
W_d	expansion electrical work
A-CAES	adiabatic-CAES
CAES	compressed air energy storage
CHCP	combined heat cooling and power plant
CHE	compact heat exchanger
DG	distributed generation
HE	heat exchanger
IC	inter-cooler
PCHE	printed circuit heat exchanger
PFHE	plate-fin heat exchanger
PHE	plate heat exchanger
RES	renewable energy sources
RH	re-heater
STHX	shell and tube heat exchanger
T-CAES	trigenerative-CAES

compressing air from the environment into a high pressure reservoir, through a compressor driven by an electrical motor. When electricity is required from the CAES the air is expanded through a turbine. In case of Diabatic-CAES, air is heated through the combustion of a fossil fuel before expansion [6]. On the other hand, in Adiabatic-CAES (A-CAES), air heating is performed by recovering the heat in the inter-cooled compression and no additional fuel is required [9–13].

Most of the literature related to CAES is focused on utility-scale applications [1,4,7,14], that are very large plants located close to the energy production. Nevertheless, the development of small scale A-CAES (micro-CAES) to be placed close to the energy demand is of great interest [15–17]. Such a solution allows a more tight coupling between the energy storage systems and the energy demand. Moreover, micro-CAES may act as trigenerative systems, which is to say combined heat, cooling, and power plants (CHCP) by recovering heat after air compression and cooling energy during or after the expansion phase [15,16]. Trigeneration is possible only placing the CAES close to the energy demand, given the technical difficulty to transfer thermal and chilling energy at large distances. Such a plant allows to conjugate the widely recognized advantages of distributed trigeneration (see for instance [18–20]) with those of