Applied Energy 134 (2014) 239–247

Contents lists available at ScienceDirect

Applied Energy

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

Parameters affecting scalable underwater compressed air energy storage

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HIGHLIGHTS

- UWCAES design parameters were studied to determine influence on round-trip efficiency and exergy destruction.
- Air compression and expansion contributed the most to total system exergy destruction for all parametric study cases.
- The system was most sensitive to pipe diameter, followed by expander and compressor efficiencies, and air storage depth.
- Increasing expander and compressor efficiencies showed greatest improvements to UWCAES performance.

ARTICLE INFO

Article history:
Received 14 August 2013
Received in revised form 22 July 2014
Accepted 6 August 2014

Keywords:
UWCAES
Underwater
First order efficiency
Exergy analysis
Sensitivity analysis

ABSTRACT

Underwater compressed air energy storage (UWCAES) is founded on mature concepts, many of them sourced from underground compressed air energy storage technology. A fundamental difference between the two systems is the way in which air is stored. UWCAES utilizes distensible boundary, submerged air accumulators as opposed to rigid walled caverns. This paper presents an analysis of the primary design parameters in a basic UWCAES system. The results from the parametric study and first-order sensitivity analysis show the importance and impact each design parameter has on overall system performance and can serve as a first reference guideline in system design. The analysis revealed significant system sensitivities to pipe diameter, expander and compressor efficiencies, and air storage depth. The air compression and expansion processes contributed most to system exergy destruction for all parametric study cases.

1. Introduction

Electrical energy storage (EES) is an increasingly important element to the modernization of the electrical grid. Traditionally, the aging infrastructure currently in place handled stable electricity production from large, centralized plants. With the advent of wide-scale deployment of renewable energy generation from wind and solar, electricity distribution networks are required to incorporate energy sourced from smaller, naturally intermittent distributed generation, while ensuring power reliability. Various technologies and policies have technological been proposed for integrating renewable energy sources [1], with EES gaining traction as a critical solution for reliable renewable energy integration [2–6]. As well, EES has been recognized for the services and benefits it provides to electricity grid operation [7,8].

EES is a set of technologies that decouples electricity production and demand, by allowing the flexible storage of power for later use [9]. As electricity itself cannot be stockpiled in large quantities, EES systems convert the electrical power into a storable medium that includes chemical, mechanical and electrical potential energies. When electrical power is needed, the stored energy is converted back into electricity and is injected into the electrical grid. One such technology gaining interest is compressed air energy storage (CAES).

CAES is a technology that stores energy through the utilization of air compressors to pressurize and store air in reservoirs. When needed, the compressed air is converted back to electricity by generator-coupled air expanders. In its applications to date, CAES systems have been applied at large utility scales (>100 MW) for bulk energy storage. CAES has often been considered as an alternative to pumped hydro storage (PHS) for large-scale storage [10], primarily due to its low energy costs due attributed to its inexpensive storage media and its large storage capacity [11,12].

This paper examines a novel adaptation of CAES technology known as underwater compressed air energy storage (UWCAES), where submerged, distensible air accumulators are used to facilitate energy storage. The accumulators used in the system offer two important design characteristics – a scalable design and isobaric system charge and discharge profiles. These characteristics

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http://dx.doi.org/10.1016/j.apenergy.2014.08.028
0306-2619/

Nomenclature

Variables

c_p	constant pressure specific heat (kJ/kg K)
c_v	constant volume specific heat (kJ/kg K)
D	pipe diameter (m)
f	Darcy's friction factor
g	gravitational acceleration constant (m/s^2)
K_L	minor loss coefficient
k	specific heat ratio
L	pipe length (m)
m	mass (kg)
N	number of compressor/turbine stages
n	polytropic exponent
P	power (kW)
p	pressure (kPa)
p_L	pressure loss (kPa)
R	universal gas constant (kJ/kg K)
Re	Reynolds number
s	specific entropy (kJ/kg K)
T	temperature (K)
t	time (s)
u	specific internal energy (kJ/kg)
$\overline{V}$	velocity (m/s)
V	volume (m^3)
v	specific volume (m^3/kg)
w	specific work (kJ/kg)
X	exergy (kJ)
X_D	exergy destruction (kJ)
x	specific exergy (kJ/kg)
z	accumulator depth (m)
β_i	stage pressure ratio
ε	pipe roughness (m)
η	efficiency
ρ	density (kg/m^3)

Subscripts

0	at reference condition

address some limitations of conventional CAES systems pertaining to the storage reservoir, that is, the geology-restricted system capacity [3,6] and capacity-linked storage pressure variation [13]. This study presents an energy and exergy analysis of an UWCAES system in order to understand the impact design parameters may have on the system's overall performance. As well, a sensitivity analysis is performed to determine a hierarchy of influential system variables. The findings of this paper can serve as an initial guideline for the design of future UWCAES systems.

2. Underwater compressed air energy storage

The UWCAES system builds on established concepts proven by reliable installations in Huntorf, Germany [14] and McIntosh, Alabama, USA [15], to bring CAES applications to smaller scales while eliminating fossil fuel use. It is similar to that of the adiabatic CAES concept, in which thermal energy storage is used to replace the combustion chamber of a CAES system [16]. The basic process architecture of an UWCAES system is given in Fig. 1. A general UWCAES system consists of five main components: compressor, turbine, motor/generator, thermal recovery unit (TRU) and storage (air and thermal). The air storage is made up of a series of air accumulators, all of which are connected to an air delivery pipe network. Figs. 2 and 3 depicts two possible configurations of an UWCAES system. During the system charge phase where energy is stored, ambient air is compressed and sent to the air accumulators. Heat generated during the compression process is extracted from the air by the TRU – a series of heat exchangers (HEX) – and stored in a suitable thermal storage medium. In the case of discharging, the air is first released from storage, heated up by the TRU and expanded through a turbine. A generator is connected to the turbine to produce an electrical output.

The storage reservoir is a critical element for consideration when designing and siting a CAES system. The application of submerged, distensible air accumulators is the UWCAES system's defining aspect. Traditional CAES has relied on locations with suitable geologic formations, demonstrated in the world's two operating CAES plants – a 290 MW plant in Huntorf, Germany and a 110 MW plant in McIntosh, Alabama, USA – both using large underground, solution-mined salt caverns [12]. Such fixed reservoirs are rigid in nature causing CAES systems to operate under constant volume conditions and experience variable pressures based on its filled capacity. In the UWCAES solution, the air accumulators are anchored to the bedding of lakes or oceans and rely on the hydrostatic pressure exerted by the surrounding water at depths to maintain the stored air pressure. The flow of air entering and leaving the air accumulators exhibit a near-isobaric behavior regardless of the accumulator's filled capacity [17].

It is desirable for CAES systems to operate under constant pressure conditions as it leads to increased efficiency in the pneumatic equipment, specifically the turbine, as well as constant power profiles. The two existing CAES facilities have pursued this aspect by throttling air flow at the turbine inlet to maintain a high pressure [13]. When system efficiency is paramount, this method can lead to unwanted losses. As such, a couple of alternate solutions to achieve isobaric performance in land-based CAES systems have been proposed. In [18], a water-compensated CAES system using a water head supplied by an aboveground water reservoir was analyzed. Its design used a choice of a water column or hydraulic pump to maintain constant air pressure in the storage cavern; the choice depends on the depth of the cavern below surface. It should be noted that a water-compensated CAES system can only be applied to certain storage reservoirs; for example, a salt cavern air reservoir is unsuitable for this configuration. A unique CAES concept was proposed in [19], where constant pressure airflow is achieved by storing compressed air in nano-porous material.

In terms of storage capacity, the UWCAES air reservoir can be scaled by the addition or subtraction of accumulator units. This allows for CAES application at scales normally impractical for geologic CAES. Fig. 4 shows UWCAES with respect to other energy storage technologies. Aside from UWCAES, other investigations for small-scale CAES have been performed, mainly achieved by using pressure vessels. In [20], quasi-isothermal and adiabatic configurations of water-compensated micro-CAES systems using man-made air vessels was analyzed. In [21], a pressure tank-based CAES system was evaluated for integration in hybrid wind–diesel generation systems located in remote regions. Guidelines for pressure vessel sizing for small-scale CAES systems were discussed in [22]. The study examined a stress analysis model for different vessel volumes subjected to various pressures, and provided an approximate equation for determining the pressure associated with the minimum vessel cost. Aside from pressure vessels, the feasibility of steel pipe piles for small-scale CAES was presented in [23].

Few researchers have explored the underwater CAES adaptation thus far. In [24], the concept of an ocean compressed air energy storage was discussed. In this system, a receiver vessel, vented to