Journal of Energy Storage 18 (2018) 349–359

Contents lists available at ScienceDirect

Journal of Energy Storage

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

A comparative study of liquid, solid and hybrid adiabatic compressed air energy storage systems

Haobai Xue, Alexander White*

Department of Engineering, University of Cambridge, United Kingdom

ARTICLE INFO

Keywords:
Energy storage
Adiabatic compressed air storage
Cost and efficiency optimization
Thermodynamic analysis
Exergy loss

ABSTRACT

The increasing penetration of renewable energy sources into the power grid has prompted the development of many energy storage systems, amongst which Adiabatic Compressed Air Energy Storage (A-CAES) is deemed one of the more promising technologies. A-CAES systems can be categorized into solid A-CAES and liquid A-CAES, both of which have received extensive treatment in the literature. In this paper, thermodynamic and economic models are built for each of these systems and their sub-components, and the appropriate materials are selected for the corresponding Thermal Energy Storage (TES). A hybrid TES system is also considered, combining solid TES for low-pressure air with liquid TES for higher pressure. Results for this are compared with the other two systems. Parametric and optimisation studies have been carried out and suggest that the hybrid system has thermodynamic and economic advantages over the other two. The trade off between efficiency and cost and the factors affecting this trade off are also investigated.

1. Introduction

According to UK's target for the EU Renewable Energy Directive, more than 30% of electricity will come from renewable energy sources by 2020 [1]. Much of this energy may be in the form of solar energy or wind (including off-shore wind) which are intermittent, difficult to predict and uncontrollable by nature [2]. These characteristics pose significant challenges for the large-scale integration of renewable generation into the power grid, for which production and consumption of electricity must exactly balance [3]. Load balancing issues are usually addressed by spinning reserve, such as peak-lopping gas turbines or coal fired power plant, but it is now accepted that storage is also likely to play a significant role, together with grid interconnection and demand-side management.

Energy storage systems convert surplus electricity into a storable form when supply exceeds demand, whilst during high demand, the stored energy is reconverted to electricity and then fed back to the power grid [4]. Adiabatic CAES is one of the various energy storage technologies being proposed [5]. During charge, air is compressed near-adiabatically and stored, typically in underground (but potentially also underwater) caverns, whilst the thermal energy (colloquially the "heat of compression") is stored separately. As discussed in [6], thermal storage may be achieved by cooling the air in heat exchangers which allow the energy to be transferred to liquid tanks. Alternatively, heat may be transferred directly to a solid storage material, for example in a packed bed. Research and development in this area has been very active in recent years. Bullough et al. [2] were the first to study and compare solid and liquid TES for A-CAES systems, proposing several suitable TES materials that cover temperatures from 50 to 650 °C. RWE Power Ltd. proposed the ADELE project in Germany which is intended to operate at high temperature (600 °C) and high pressure (100 bar), with a targeted system efficiency of 70% [7]. Barbour et al. [8] presented a thermodynamic analysis of a two-stage solid A-CAES system and suggested that solid A-CAES is superior to its liquid counterpart because this system has no costly thermal fluid requirements and enjoys higher system efficiency and energy density. These studies all propose high temperature TES systems, but there are also numerous concepts that operate in the range of 80–200 °C. Low-temperature A-CAES (LTA-CAES) was advocated by Wolf et al. [9] who highlighted several advantages: fast cycling and wide-ranging part-load capability, and avoidance of various high-temperature challenges. These benefits come at the expense of lower efficiency, which is anticipated to be in the range 52–60%. Grazzini and Milazzo [10] proposed a system in which the TES comprises pressurized water at 120 °C combined with a high-pressure artificial air reservoir. The system efficiency is estimated at 72% which clearly competes with other energy storage technologies.

Many cycle analysis studies for A-CAES systems have been reported in the literature, including those of Luo et al. [6] for a liquid-based TES system, who concluded (not surprisingly) that efficiency is determined mainly by compression and expansion losses and heat exchanger

* Corresponding author.
E-mail address: ajw36@cam.ac.uk (A. White).

https://doi.org/10.1016/j.est.2018.05.016
Received 22 December 2017; Received in revised form 18 April 2018; Accepted 18 May 2018
2352-152X/

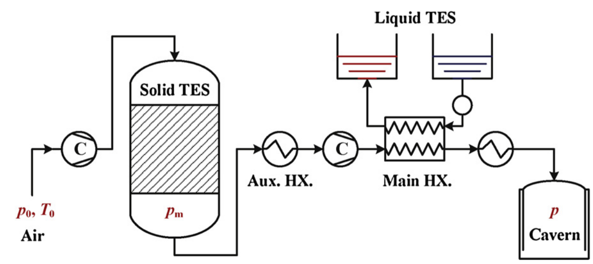

Fig. 1. Schematic diagram of the hybrid A-CAES system.

effectiveness. Buffa et al. [11] proposed a system under the project "ENEL Ingegneria e Innovazione", with seven stages of compression and six stages of expansion. Due to the large number of stages, the TES temperature is low enough that ambient water can be used as the thermal fluid, but the system efficiency is estimated to be only 52%.

Despite these and many other studies of different A-CAES configurations, a comparative study of liquid and solid based systems from both thermodynamic and economic perspectives has so for been lacking. This forms the subject of the present paper, together with the investigation of a hybrid solid-liquid system aimed at achieving high efficiency whilst reducing capital cost. The motivation for hybrid A-CAES lies in the fact that the packed bed is generally more efficient and cheaper than heat exchangers at low pressure, but becomes exorbitantly expensive at high pressures.

2. Systems description

A general A-CAES configuration comprises N stages of compression/expansion (with some form of TES between each stage) and an air-storage cavern or accumulator. The TES need not be the same for all stages: for example, for the system shown in Fig. 1, there is one stage of solid TES and two stages of liquid TES. This system is referred to as the hybrid A-CAES in this paper. If there are n solid TES and $N-n$ liquid TES stages in the hybrid A-CAES, then the pressure ratio for each solid stage is:

$$\beta_i = \left(\frac{p_m}{p_0}\right)^{\frac{1}{n}} \quad (i \le n) \tag{1}$$

and that for each liquid stage is:

$$\beta_i = \left(\frac{p}{p_m}\right)^{\frac{1}{N-n}} \quad (i > n) \tag{2}$$

where p_0, p_m and p refer to pressures in the atmosphere, after the last solid stage and in the cavern respectively (see Fig. 1). For a solid only system $p_m = p$, whereas for a liquid only system $p_m = p_0$. The heat transfer between the compressed air and the liquid media is achieved through the main heat exchangers, for which the heat transfer losses are inversely related to the size and cost of the device. This indirect contact separates the working fluid from the liquid media and thus enables the cost of liquid TES to be independent of the operating air pressure. For solid TES, on the other hand, it is easier to exploit direct-contact heat transfer between the air and solid media. For example, a packed-bed thermal reservoir can fulfil this function, and the heat transfer losses can be decreased by reducing the particle size, without increasing the capital cost simultaneously. However, direct-contact heat transfer requires the operating pressure of the solid TES to be the same as that of the air, thus the capital cost of solid TES (dominated by the pressure vessel) is more or less proportional to the operating pressure. However, solid TES benefits from a wider temperate range and as a result it is usually operated at higher temperature, typically ~600 °C. Liquid storage is generally operated at temperatures up to ~300 °C, depending on the storage fluid and storage pressure. It is assumed here that all like forms of storage (i.e., solid or liquid) have the same maximum allowable temperature and hence the pressure ratio is equally partitioned amongst each like stage (see Eqs. (1) and (2)).

Auxiliary heat exchangers are included in the cycle after each TES, as shown in Fig. 1, to further cool the air to ambient temperature T_0. This prevents the inlet temperature of the next stages becoming too high if the solid TES is small (such that thermal fronts emerge from their exit) or the liquid TES is inefficient. Since the waste heat is not recycled but simply dissipated in the auxiliary heat exchangers, a high water flow rate (hence a low heat capacity ratio C_r) is usually adopted to reduce the heat exchanger size and cost. The effectiveness of any heat exchanger with $C_r = 0$ is given by $\varepsilon = 1 - \exp(-\mathrm{NTU})$ [12], so with the 'number of thermal units' as low as NTU = 2 an effectiveness ε of 0.86 is attained. This type of auxiliary heat exchange is used for each TES and its cost added into the total, as described in Section 4.

In the absence of pressure losses (as in many cycle analyses) the stage pressure ratios during compression (charge) and expansion (discharge) are the same so that $\beta_c = \beta_e = \beta_i$. However, in order to study the impact of pressure losses (for example, those generated by heat exchangers and packed beds) in a simple and general manner, a pressure loss factor f_p is applied to each stage. Thus the actual stage compression ratio becomes $\beta_c = \beta_i/(1-f_p)$, whilst stage expansion ratio is $\beta_e = \beta_i(1-f_p)$. In practice, the pressure loss factors are dominated by viscous effects in heat exchangers and packed beds, as described in Section 3.

After N stages of compression, the compressed air is finally stored in an air reservoir, as shown in Fig. 1. Although artificial caverns have been proposed by many researchers, the size needed for a large-scale CAES installation (400–800 MWh) is in the range of 150,000 to 500,000 m^3. Solution mining or the use of existing natural caverns are therefore the most feasible options. In the present study the nominal energy and power are set as 400 MWh and 100 MW respectively and the cavern volume is calculated from the energy distribution between the cavern and each TES. The cavern is assumed isochoric by nature and therefore the pressure varies within a range p_{min} to p_{max}. The value of p_{max} is constrained by geological conditions (e.g., the depth of the cavern) whilst p_{min} is determined by the extent of discharge and the minimum pressure required to maintain the cavern's integrity. Storage density and round-trip efficiency will in general depend on both p_{max} and the ratio p_{min}/p_{max}.

The TES subsystems all include the following three components: storage material (i.e. liquid or solid), containment vessel (or tank) and an insulation layer. For solid TES, the commonly used packing materials are natural stones, ceramic and metal oxides, which are generally very cheap and have wide temperature range. Materials selection essentially becomes finding the substance with the largest *volumetric* heat capacity because cost tends to be dominated by the pressure vessel. On the basis of work reported in [13], magnetite (Fe_3O_4) has been used as the solid storage medium for the analysis presented here, and the maximum temperature is set at 600 °C. For liquid TES, mineral oil, molten salt and water are the most widely used thermal fluids. Their selection, however, is less straightforward due to the vast differences of cost, heat capacity and operating temperature range. A simple multi-objective optimization has therefore been carried out (see Section 6.3), from which mineral oil has been selected as the best option. The maximum allowable temperature is accordingly set at 340 °C [14,15].

3. Thermodynamic modelling of components

3.1. Solid TES systems

Solid TES is assumed to be provided by packed-bed thermal reservoirs. (Solid storage with indirect heat exchange has not been considered here.) Equations governing the behaviour of such reservoirs have been presented many times in the literature, e.g., [16–18]. The