Energy 106 (2016) 528–534

Contents lists available at ScienceDirect

Energy

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

Exergy analysis of an adiabatic compressed air energy storage system using a cascade of phase change materials

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ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form
8 March 2016
Accepted 9 March 2016
Available online 11 April 2016

Keywords:
Compressed air energy storage
Phase change materials
Exergy analysis
Thermal energy storage
PCM (phase change material)
CAES (compressed air energy storage)

ABSTRACT

Adiabatic compressed air energy storage is an emerging energy storage technology with excellent power and storage capacities. Currently, efficiencies are approximately 70%, in part due to the issue of heat loss during the compression stage. An exergy analysis is presented on a novel adiabatic compressed air energy storage system design utilizing a cascade of PCMs (phase change materials) for waste heat storage and recovery. The melting temperatures and enthalpies of the PCMs were optimized for this system and were shown to be dependent on the number of PCMs, the number of compression stages, and the maximum compression ratio. Efficiencies of storage and recovery using this approach are predicted to be as high as 85%, a 15% increase over current designs which do not incorporate PCMs.

1. Introduction

The global supply of renewable energy is rapidly increasing due to increases in generating facilities such as those from wind and solar sources; however the inherent instability of renewable energy sources has led to the practical restriction that only a maximum of 15–20% of a grid's power can be derived from these sources [1]. This restriction can be eliminated by integrating EES (electrical energy storage) technologies into the grid [2]. EES technologies are highly desired for both their environmental and economic benefits, such as allowing increased utilization of existing power plants and introducing possibilities of energy arbitrage [3]. Recent investigations of 100% renewable energy solutions have also featured EES technologies as part of integrated energy solutions which combine heating/cooling, electrical and transportation systems. Smart grid technologies which can rapidly adapt to fluctuations in electrical demand or supply can greatly benefit from EES systems [4–7]. However, reducing efficiency losses and costs associated with EES systems is an important factor concerning commercial feasibility.

Of the existing EES technologies, pumped hydro storage has the largest installed globally storage capacity at over 129 GW [8,9], which accounts for more than 99% of the total electrical energy storage capacity [10]. However, geographical (limited number of candidate sites) and ecological (concerns with dams causing habitat destruction) considerations will likely limit future development of pumped hydro storage. The only grid energy storage technology with similar performance to pumped hydro storage is CAES (compressed air energy storage) [8]. While pumped hydro storage stores energy using the gravitational potential energy of water, CAES stores energy in the elastic potential energy of compressed air. CAES was originally developed in the early 1960s along with other gas turbine plant technologies [11]. This technology was first implemented in the construction of a 290 MW CAES plant in Huntorf, Germany in 1978 and a second 110 MW plant in McIntosh, Alabama in 1991 [12]. With the demand for energy storage technologies following the rapid increase in deployment of renewable energy sources, starting in the mid-late 1990s [1], there has been renewed interest in CAES, sparked by low greenhouse gas emissions and respectable economic viability compared to alternatives [13]. A significant technical issue with CAES is that when the air is compressed approximately half of the exergy created is in the form of heat, as shown in the theory section of this work: this is energy that is lost if not properly stored and recovered. Improving the efficiency, as reported herein, or the coupling of CAES with an

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http://dx.doi.org/10.1016/j.energy.2016.03.042
0360-5442/

integrated grid will both make this technology more attractive and economically viable [14].

To reduce the efficiencies lost by heat in CAES, different proposals have been advanced in the literature to store heat using sensible heat storage materials. Sensible heat storage materials store heat through temperature changes, with their heat storage density being proportional to their heat capacity. This concept of storing the thermal energy in a heat storage material is known as adiabatic compressed air energy storage. In adiabatic compressed air energy storage designs, sensible heat storage materials are frequently employed as a heat transfer fluid such as an oil that transfers between a hot and cold storage tank. Alternatively, sensible heat storage can be used in a stationary heat storage approach with a material such as concrete or water. Various designs for configuring the compression train have been proposed, including using a series of compression stages to reduce the work of compression [15–19].

An alternative approach to storing heat in a material is through the latent heat of a first order phase transition. Materials chosen for this purpose are known as a PCM (phase change material). Due to phase transitions being approximately isothermal, PCMs have found a growing market in temperature regulation applications, such as maintaining building temperatures [20,21]. However, the literature has not considered PCMs to be a viable thermal energy storage material for compressed air energy storage with claims such as "no single (PCM) system can cover the (large temperature) range" [22]. Employing PCMs would be preferable to sensible heat storage materials for their higher energy density, reducing material requirements, and improving efficiency, as first-order phase transitions are reversible processes.

Here, a novel approach employing a series of PCMs with different phase change temperature in a CAES system is proposed. We present a model of the thermodynamics of an example CAES system using PCMs. Following the compression stage is a series of PCM thermal energy storage stages, as illustrated in Fig. 1 for the case of four PCM stages. The PCM storage stages are assumed to operate isothermally, and the air is heated and cooled through the stages isobarically. During pressurization the air passes through a series of PCMs with decreasing melting temperatures to strip heat from the air, increasing the compressibility. Prior to decompression, the air again passes through the PCMs in the opposite direction, with increasing melting temperatures prior to decompression. This functions to heat the air before it reaches the turbines in stages, further increasing the efficiency of the system. As the air leaves the air storage unit at an ambient temperature, it will only pass through

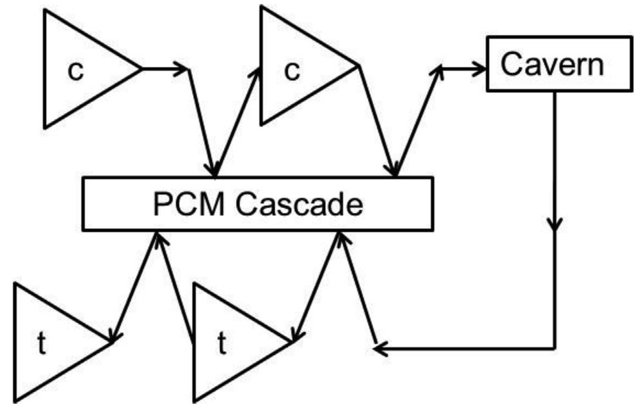

Fig. 2. Multistage cascade CAES scheme for two compression and expansion stages.

a PCM stage if the PCM has remaining latent heat. This can be accomplished by either using a series of valves, or selecting the PCM melting temperatures such that the PCMs complete melting as decompression completes (see Fig. 2).

This approach has the advantage that the series of PCMs can cool/heat the air in stages. This means the temperature difference between the two materials that are exchanging heat is less, leading to a reduction in entropy generation, and thus improving the roundtrip exergy efficiency. Additionally, PCMs have a higher energy density than sensible heat storage approaches, and therefore the requirements for material and storage volume are lower.

2. Theory

The temperature of the air, assumed to be an ideal gas, leaving the compressor and decompressor, T_2, is assumed to compress and decompress according to a reversible adiabatic process, and so is dependent on the input temperature, T_1, as well as the ratio of the input and output pressures, p_1 and p_2, respectively.

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

The value of the polytropic exponent, γ, is fixed to 1.45 for compression and 1.36 for expansion, in agreement with the literature [16]. For simpler notation, the ratio of pressure to ambient pressure, p_0, is taken to be β

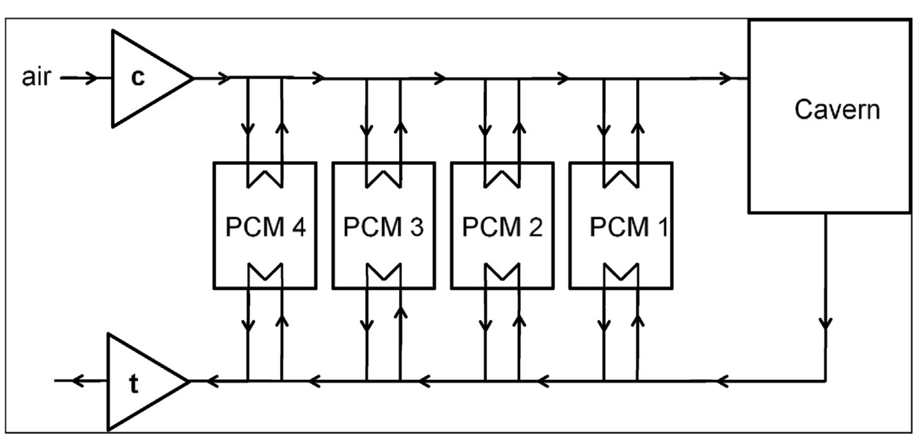

Fig. 1. Cascade compressed air energy storage scheme, for the case of four PCM stages. Air is compressed from atmospheric temperature, where it then cools through a series of PCM stages. During the expansion process, the air reheats by passing through the PCM stages again.