Energy 106 (2016) 260–269

Contents lists available at ScienceDirect

Energy

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

Performance optimization and comparison of pumped thermal and pumped cryogenic electricity storage systems

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form
18 February 2016
Accepted 12 March 2016
Available online 5 April 2016

Keywords:
Pumped thermal electricity storage
Pumped cryogenic electricity storage
Irreversible loss
Performance evaluation
Optimum criterion

ABSTRACT

Two generic models, one of a PTES (pumped thermal electricity storage) system and another of a PCES (pumped cryogenic electricity storage) system, are established in which the finite-rate heat transfer and external heat leakage losses are considered and several important parameters connecting the charging and discharging phases are introduced. Analytic expressions for the round trip efficiency and power output of PTES and PCES systems are derived. The influences of some important parameters on the performance characteristics of the PTES and PCES systems are presented, and the optimally operating region of each system is determined. The performances of PTES and PCES systems are compared. The advantages of the PTES system are highlighted. The effects of external heat leakage losses are discussed in detail. Notably, the results reveal that external heat leakage losses must be considered in the performance investigation of the PTES system.

1. Introduction

Currently, renewable energy technologies play an important role in both solving the environmental challenges caused by the use of traditional fossil fuels and achieving a sustainable energy supply [1–3]. However, the inherently uncontrollable and intermittent nature of renewable energies cannot ensure that electrical demand is met at all times and is thus becoming one of the major constraints of the application of renewable energy sources [4]. As a result, large-scale EES (electricity energy storage) technologies, which are considered as a crucial approach to overcome these inherent disadvantages of renewable energies, have attracted much attention in recent years [5–9].

Among various large-scale EES technologies, the PHS (pumped hydro storage) technology is the most mature and widely used and the CAES (compressed air energy storage) technology, as a hot research topic, has attracted the interest of numerous researchers because of their high round trip efficiency, long lifetime, fast response, and low self-discharge rate [7,10–12]. However, the drawbacks of PHS and CAES systems are obvious, i.e., the high initial capital cost and the strict geographical and geological constraints. To overcome these disadvantages and establish site-independent electricity storage technologies, various forms of TES (thermal energy storage) technologies have been proposed [6,13–17]. As one of the latest TES technologies, PTES (pumped thermal electricity storage) has been introduced very recently and has become a popular research topic [18–25], despite being in the early stages of development, with no demonstration plants built.

In Ref. [26], two concise theoretical models of the PTES and PCES (pumped cryogenic electricity storage) systems consisting of a Carnot cycle and a reverse Carnot cycle were proposed, by which the author investigated the performance of PTES and PCES systems at the maximum power output by introducing some assumptions. In addition, the author in Ref. [26] attempted to derive the highest round trip efficiency of the PTES and PCES systems at the maximum power output and claimed that the expression is as simple as the Carnot efficiency and CA efficiency [27], only depending on the temperatures of two heat reservoirs. However, there are some problems that must be further investigated regarding the PTES and PCES systems investigated in Ref. [26]. One issue is that the general expressions of the round trip efficiency and power output of PTES and PCES systems including some important parameters, e.g., the heat transfer rates in various processes, have not been derived. Consequently, the influences of the heat transfer rates in various processes on

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http://dx.doi.org/10.1016/j.energy.2016.03.053
0360-5442/

the performance characteristics of PTES and PCES systems cannot be discussed, the optimal relationship between the round trip efficiency and the power output cannot be revealed, and the optimally operating regions of PTES and PCES systems cannot be determined. Another issue is that despite being one of the main sources of irreversible losses [28–30], the external heat leakage losses of PTES and PCES systems were not taken into account in Ref. [26]. It is more critical that the correct results related to the performance of PTES and PCES systems were not obtained in Ref. [26]. Thus, it is of great significance to further develop the models of PTES and PCES systems established in Ref. [26] by considering external heat leakage losses and introducing some important parameters, followed by revealing the general performance characteristics of these updated models.

The present paper is organized as follows. In Sect. 2, the thermodynamic models of pumped thermal and pumped cryogenic electricity storage systems with external heat leakage losses are proposed. In Sect. 3, the expressions of the round trip efficiency and power output are derived. In Sect. 4, the general performance characteristics of PTES and PCES systems are analyzed. The optimal relationship between the round trip efficiency and the power output are revealed, and the optimally operating regions of key parameters are determined. In addition, the performances of PTES and PCES systems are compared. In Sect. 5, the performance characteristics of PTES and PCES systems without external heat leakage losses are directly derived. The results obtained are used to address the existing problems in Ref. [26]. Furthermore, the effects of external heat leakage losses on the performances of the PTES system are discussed in detail. The importance of considering the external heat leakage losses in the models of electricity storage systems is revealed. Finally, some important conclusions are summarized.

2. Model descriptions of pumped thermal and pumped cryogenic electricity storage systems

2.1. A pumped thermal electricity storage system

We consider a PTES system consisting of a Carnot heat pump and a Carnot heat engine operating between the environment at temperature T_O and the thermal energy storage reservoir, which is assumed to be large enough [26] and has a constant temperature T_H $(T_H > T_O)$ during a round trip cycle, as shown in Fig. 1 (a) and (b), where T_i, K_i, and t_i $(i = 1, 2, 3, 4)$ are the temperatures of the working substance during four isothermal processes, the corresponding heat transfer coefficients between the working substance and the heat reservoirs, and the corresponding time durations of the working substance contacting with heat reservoirs, respectively, q_i $(i = 1, 2, 3, 4)$ are the heat flows between the working substance and the heat reservoirs in various processes, $Q_i = q_i t_i$ are the heats transferred between the working substance and the heat reservoirs during a Carnot heat engine cycle and a Carnot heat pump cycle, $P_{PE,In}$ and P_{PE} are, respectively, the power input and output of the PTES system, and L_{PE} is the external heat leakage rate of the PTES system. In the charging phase [18–26], electrical energy is used to drive a Carnot heat pump to extract the thermal energy from the environment and pump it into the thermal energy storage reservoir. When electrical energy is required, a Carnot heat engine is used to convert a part of the heat in the thermal energy storage reservoir into electricity.

When heat transfer processes are assumed to obey Newton's law [27,31–34], the net heats released and absorbed by the heat reservoirs during a Carnot heat engine cycle and a Carnot heat pump cycle can be expressed as

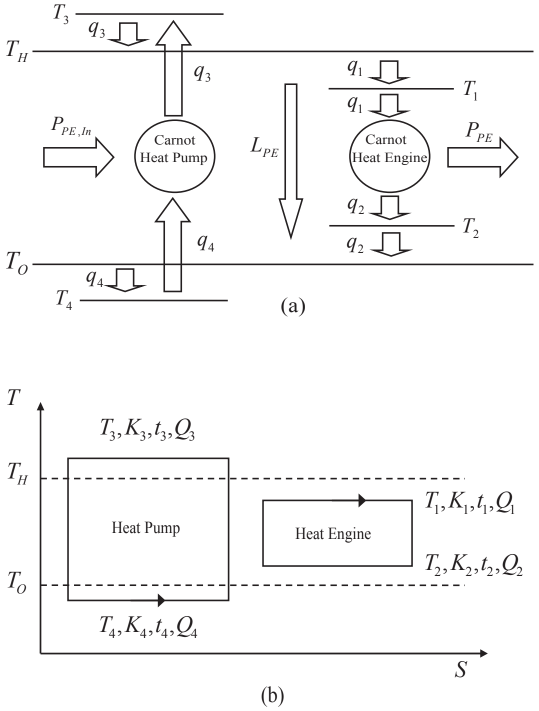

Fig. 1. (a) The schematic diagram and (b) the $T-S$ diagram of a PTES system.

$$\begin{aligned}Q_{E1} &= q_1 t_1 + L_{PE}(t_1 + t_2)\\ &= K_1(T_H - T_1)t_1 + K_{LPE}(T_H - T_O)(t_1 + t_2),\end{aligned} \tag{1}$$

$$\begin{aligned}Q_{E2} &= q_2 t_2 + L_{PE}(t_1 + t_2)\\ &= K_2(T_2 - T_O)t_2 + K_{LPE}(T_H - T_O)(t_1 + t_2),\end{aligned} \tag{2}$$

$$\begin{aligned}Q_{P3} &= q_3 t_3 - L_{PE}(t_3 + t_4)\\ &= K_3(T_3 - T_H)t_3 - K_{LPE}(T_H - T_O)(t_3 + t_4),\end{aligned} \tag{3}$$

and

$$\begin{aligned}Q_{P4} &= q_4 t_4 - L_{PE}(t_3 + t_4)\\ &= K_4(T_O - T_4)t_4 - K_{LPE}(T_H - T_O)(t_3 + t_4),\end{aligned} \tag{4}$$

respectively, where $q_1 = K_1(T_H - T_1)$, $q_2 = K_2(T_2 - T_O)$, $q_3 = K_3(T_3 - T_H)$, $q_4 = K_4(T_O - T_4)$, $L_{PE} = K_{LPE}(T_H - T_O)$, and K_{LPE} is the external heat leakage coefficient between the thermal energy storage reservoir and the environment.

2.2. A pumped cryogenic electricity storage system

Similarly, Fig. 2 (a) and (b) show a PCES system consisting of a Carnot refrigerator and a Carnot heat engine operating between the environment at temperature T_O and a cryogenic energy storage reservoir, which is assumed to be large enough [26] and at a constant temperature T_L $(T_O > T_L)$ during a round trip cycle, where T_i $(i = 5, 6, 7, 8)$, K_i, and t_i are the temperatures of the working substance during four isothermal processes, the corresponding heat transfer coefficients between the working substance and the heat reservoirs, and the corresponding time durations of the working substance contacting with heat reservoirs, respectively, $q_i (i = 5, 6, 7, 8)$ are the heat flows between the working substance and the heat reservoirs in various processes, $Q_i = q_i t_i$ are the heats