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Research paper

Analysis of pumped heat electricity storage process using exponential matrix solutions

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HIGHLIGHTS

- Matrix exponential solutions are obtained for cyclic steady state operations.
- Dimensionless analysis is performed for process design and development.
- Effects of heat transfer resistance and turbomachine efficiency are compared.
- Symmetric operation for PHES processes is favored over asymmetric operation.

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ABSTRACT

Pumped heat electricity storage (PHES) is a recently proposed competitive energy storage solution for large scale electrical energy storage (EES). It is especially valuable for regions where specific geological structures are not available. The performance of PHES depends on two factors: the operations of turbomachines and the thermal storage system. The former is characterized by pressure ratio, polytropic efficiency and gas heat capacity ratio. The latter contains the parameters of heat regenerators that can be summarized into two dimensionless numbers: length Λ and step time π. The overall process operation can be described by temperature difference representing the energy stored per unit heat capacity, the storage bed utilization ratio and the turn-around efficiency. Exponential matrix solutions are obtained for a discretized heat transfer model of a typical pumped heat electricity storage process. Using the cyclic steady state and transient state solutions, we are able to analyze how dimensionless length and step time affect the storage bed utilization ratio as well as the turn-around efficiency. This model provides basic guidance for further development of such processes.

1. Introduction

The need to store excessive amount of electrical energy comes with the fact that the demand has peaks and valleys while the output of a power plant, especially nuclear power plants, is relatively stable. Additionally development of intermittent renewable energy like wind, solar and tides further provides an incentive for the development of such processes. It is also reported [1] that electricity storage has many benefits ranging from renewable energy integration to power quality and reliability. The most commonly used processes for large scale electrical energy storage (EES) are pumped hydroelectric storage (PHS), compressed air energy storage (CAES) and flow batteries [2].

PHS is comprised of two water reservoirs at different elevations and electrical energy is stored as gravity potential energy. CAES compresses air into large caverns up to 10 MPa and uses gas turbines to recover the energy. Flow batteries have two half-cell electrolyte reservoirs, from which electroactive species flow through a power cell to reversibly convert chemical energy into electricity or vice versa. All three of them have a high turn-around efficiency of 60–90% [3], which is defined as the ratio between the amount of electricity retrieved and the amount of electricity stored. Among the nonchemical techniques PHS and CAES require particular geological structures, which might not be available to regions that EES is needed.

Thermal energy storage could provide a nonchemical solution for regions without any geographical features like rivers and caverns. However as is said by Morandin et al. [4] there is little literature available on the transformation of electrical energy into thermal energy for storage, because electrical energy is believed to degrade

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once it is converted to heat. It is mentioned by Chen et al. [3] that the turn-around efficiency for thermal energy storage is usually below 60%. A new thermal electrical energy storage process, referred as pumped heat electricity storage (PHES) in Refs. [5], thermo-electrical energy storage (TEES) in Refs. [4,6,7] or pumped thermal electricity storage (PTES) in Refs. [8–11], has recently been proposed and studied by several independent groups [4–6,8–19]. In this study it will be referred as pumped heat electricity storage (PHES).

1.1. Recent development on PHES processes

PHES is able to achieve high turn-around efficiency by acting as a heat pump during loading and as a thermal engine during delivery. In an ideal case where a reversible Carnot heat pump with efficiency of $\eta_1 = T_1/(T_1 - T_0)$ and a reversible Carnot heat engine with efficiency of $\eta_2 = (T_1 - T_0)/T_1$ are applied, and pressure drop, thermal losses and properties dependence on temperature are neglected, it could have a turn-round efficiency of $\eta_1\ \eta_2 = 100\%$. A simple finite-time thermodynamics study has been done recently by Thess [5] predicting that the turn-around efficiency of PHES would be comparable to that of advanced-adiabatic CAES under certain conditions.

However the concept is not new and dates back to the work published in 1924 by Marguerre [20], which has not been translated into English. The development of such a concept over the last century is well illustrated in the work by Mercangöz et al. [21]. Recently two types of PHES based on the same basic principle appeared in literature: one is based on using transcritical CO_2 as the working fluid with hot water and ice storage (patented by ABB Ltd. [19]), the other one is based on using inert gas as the working fluid with hot and cold solid material storage tanks (patented by Isentropic Ltd. [22] and SAIPEM S.A. [23]). Although both of them are still under development and no demonstration plants have been built, an increasing number of journal papers and patents shows that this is an area gaining lots of interest.

Full scale process modeling and optimization studies exist for both types of PHES. Morandin et al. [4,7] optimized the procedure for the synthesis of the heat exchanger network and the storage tanks for the transcritical CO_2 PHES, and achieved a maximum turn-around efficiency of 60% with the isentropic efficiency of compressors and expanders around 0.85. McTigue et al. [11] studied the second type of PHES and concluded that the success of PHES would hinge upon compressor and expander performance and with polytropic efficiency of 0.99 the turn-around efficiency could be close to 70%. The prototype machines development is reported by Howes [16] that 2 prototypes machines were developed at Isentropic Ltd with reciprocating compressors and expanders and based on that preliminary tests a hypothetical 2-MW storage machine is defined with a turn-around efficiency of 72%.

In this work we will focus on the study of the second type PHES with the same configurations as described by Desrues et al. [15]. Our model is based on the cyclic steady state solution obtained by Carnish and Caram [24] for heat regenerators. Traditional full scale simulation of the cyclic heat regenerator operation requires calculation from the initial state and progressively reaches the cyclic steady state. With the help of the exponential matrix solution we are able to express the cyclic steady state solution of the temperature distribution explicitly thus provide an efficient alternative method to evaluate the process. A disadvantage of such a solution is that it cannot be applied to cases where parameters are dependent on temperature, which prevents it from being used for more detailed engineering simulation. To our best knowledge this method has not been applied to the PHES process, our aim is to provide a different approach to evaluate the second type PHES process and a guideline for further development.

2. Process description

The process includes a high pressure (HP) tank and a low pressure (LP) tank packed with solid refractory material, pairs of compressors and turbines to transfer electrical energy into thermal energy and vice versa, a heater and a cooler to regulate the process gas temperature, and a circulating inert gas flow connecting the components listed above. The operation schedule can be divided into two steps: the loading step and the delivery step. Electrical energy is stored as sensible heat in the solid material inside the tank during the loading step and released during the delivery step. The process flow diagrams are shown in Figs. 1 and 3 while the corresponding T–S diagrams are shown in Figs. 2 and 4.

During the loading step the gas flows clockwise. The compressor works as a heat pump and raise the gas temperature to a desired point to heat up the HP tank while the expander provides a cold stream to cool the LP tank down. Hence the hot thermal wave moves towards the bottom of the HP tank while the cold thermal wave moves towards the top of the LP tank. The step is stopped before either thermal wave breaks through, otherwise it will become a great burden for the heater and the cooler and decrease the overall energy efficiency.

During the delivery step the gas flows counterclockwise. The expander works as a heat engine to release the thermal energy previously stored in the system. The thermal waves move upward in the opposite direction compared to that of the loading step. The LP tank is heated up while the HP tank is cooled down. The low temperature of the gas stream coming out of the bottom of the LP tank actually reduces the work needed at the compressor.

A cooler is added to remove the extra heat generated by the irreversibilities of the turbomachines at room temperature T_{0nom}. A heater is added to maintain the temperature of the gas going into the compressor at T_{2nom} during the loading step thus increase the total energy stored in the HP tank. Depending on the electricity supply and demand the loading step time and the delivery step time may vary.

3. Model description

An exponential matrix solution for the temperature distribution in the storage vessels can be obtained using the method proposed

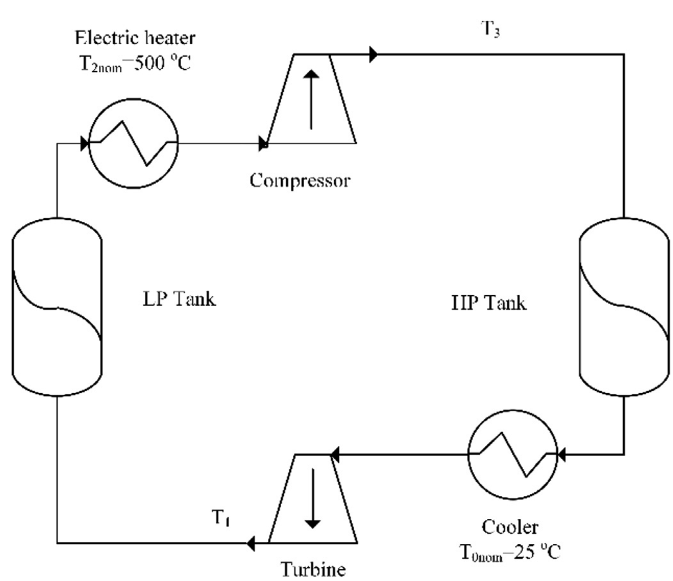

Fig. 1. Process flow diagram during the loading step.