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Exergy analysis of discharging multi-tank thermal energy storage systems with constant heat extraction

J.D. Osorio *, A. Rivera-Alvarez, M. Swain, J.C. Ordonez

Department of Mechanical Engineering, Energy and Sustainability Center, Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310, United States

HIGHLIGHTS

- Dimensionless model for discharging multi-tank TES systems in series was developed.
- Uneven mass distribution provides higher efficiency for short discharging process.
- Variable mass distribution allows maximum efficiency during the entire time span.
- Optimum discharging times were determined for different operating conditions.
- Energy losses and pumping effects were analyzed.

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ABSTRACT

In this work, an exergy analysis of discharging multi-tank thermal energy storage systems with constant heat extraction is studied. Theoretical models are developed to analyze the effect of the induced stratification through storage division into several tanks for different system configurations: multi-tank systems with even mass distribution, and two-tank systems with uneven and variable mass distribution. The instantaneous and the process efficiencies are defined to assess the performance of the system as function of operation parameters. For two- and four-tank systems with mass evenly distributed, efficiency increments around 4% and 7%, respectively, are possible. For two-tank systems, higher efficiencies are accomplished for short times when the mass is unevenly distributed and larger amount of the mass is in the hotter tank. For longer times, the even distributed mass situation provides the highest performance. To achieve superior efficiency of two-tank systems during the entire timespan, a time varying mass distribution $\chi = 0.5(1 + e^{-2t^*})$ is proposed. Finally, the energy losses as well as the pumping effects on the performance of one- and two-tank systems are analyzed. It is found that, both, the pumping effects and the energy losses are generally negligible and the efficiency can be improved dividing the storage system, rather than increasing the mass flow rate.

1. Introduction

Renewable energy resources have attracted the interest of researchers during the last years as an alternative to supply the growing energy needs in the world and to reduce the environmental impact caused by the use of traditional technologies based on fossil-fuels. Most of the studies about technologies based on renewable energy are focused on improving efficiency in order to make them suitable to replace or assist conventional energy conversion devices. Solar energy is one of the most advantageous resources because it is free and abundant. Although some remarkable alternatives such as photovoltaic generation and the use of Rankine power cycles to generate electricity from solar energy have been developed, the intermittent availability of solar energy is still a challenge that needs to be addressed. Thermal energy storage (TES) is an alternative to alleviate the temporal mismatch between supply and demand. Some specific strategies to face energy fluctuations, for instance, include additional TES loops [1]. In TES systems, the thermal energy can be stored in sensible heat form using materials such as water, oils or molten salts. Also, it can be stored in a latent heat form through ice or other phase-change materials. Common application for TES systems are currently found in power generation, refrigeration, and heating and cooling spaces [2–4]. One of the most common mediums to store solar-based sensible energy is water. Its high thermal

* Corresponding author.
E-mail addresses: jdo12@fsu.edu (J.D. Osorio), rivera@caps.fsu.edu (A. Rivera-Alvarez), mas10h@my.fsu.edu (M. Swain), ordonez@caps.fsu.edu (J.C. Ordonez).

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capacity, nontoxicity, availability, among others features, make water suitable for industrial and domestic applications. However, for operation temperatures greater than about 150 °C, other materials such as synthetic oils or molten salts are commonly used [5,6].

Exergy analysis of water and oil tank systems have been performed in previous studies in order to improve the efficiency of their charging, storing and discharging processes [7–10]. Also, energy analysis of various TESs configurations and cold TES systems for air conditioner applications have been studied as a function of fluid properties and operation parameters [9,11]. Efficiency analysis based on energy conservation provides an assessment of the change of energy of a system as a result of the process underwent by the system and its interaction with the surroundings. However, energy analysis does not consider the energy quality and its degradation as a consequence of irreversibilities during the process. Exergy analysis, instead, offers a more realistic measurement of the system performance because it considers the energy degradation due to thermodynamic irreversibilities occurring in the system such as heat losses to the environment and fluid mixing during charging and discharging processes. In addition, efficiency based on exergy analysis compares how close the real and ideal system performances are, identifies the causes and location of thermodynamic losses and therefore, offers fundamental information for the TES system improvement and optimization [12].

Some of the main exergy-destruction factors in TES tank-systems are the heat losses with the surrounding environment, the heat conduction in the tank wall and the mixing of hot and cold portions of the fluid during charging and discharging periods [3]. The first and second factors are predominant when large storing times are required. Improvement of insulation level is essential to reduce exergy destruction via heat losses. In particular, it has been found that a low conducting inner lining material in the tank not only favors the energy storage but also the stratification [13]. The destruction of exergy caused by mixing of hot and cold portions of the fluid can be reduced if a high level of stratification is maintained [14]. It has been found that a high level of stratification inside the tank increases the efficiency of the charging and discharging processes due to a better retention of temperature [14,15]. Numerous studies focused on preserving the stratification condition inside a tank have been done. Some of these works recognize the liquid jets entering the tank as the main reason for destratification [16]. Therefore, different tanks design [17,18], especial inlets design [16,19,20], obstacles with different shapes inside the tank [21], among others alternatives, have been proposed to reduce the mixing effects and consequently, to increase the system efficiency. Considering the difficulties to maintain the stratification condition inside a tank, other alternatives such as dividing the storage tank into several compartments or into a multi-tank system to reduce the exergy destruction have been studied [22,23]. Specifically, some of these studies analyze the performance of series and parallel multi-tank system configurations [24–26], considering submerged heat exchangers [27] and also, as a part of a solar thermal storage system [26,28,29]. In these works, which are focused on particular applications, the efficiency of a multi-tank system is higher when compared with the efficiency of a one-tank system of similar operation conditions and equivalent mass. The main novelty of this work is the exergy analysis of multi-tank systems for uneven mass distribution and mass distribution changing with time. To the authors' knowledge, both situations are still a subject to be developed in the literature and have been just addressed recently. For example, consideration of variable-volume tanks in the context of solar heating and cooling systems has been investigated [1,30]. These studies have shown the advantages of varying the thermal storage capacity of a system of tanks as a function of solar radiation availability and user thermal/cooling energy demands. However, the analysis has been carried out for a fixed number of three tanks and has not included any exergy evaluation. Also, consideration of multi-tank systems in series and parallel configurations with uneven mass distribution and arbitrary number of tanks has been studied [11]. In this work, a very general framework for the study of a large number of systems is developed, however there is no consideration of time-changing mass distributions or any exergy evaluation.

In this work, a systematic generalized framework based on exergy analysis is carried out to study the performance of multi-tank systems for sensible TES discharging processes. The analyzed configuration consists of a multi-tank system with all the storage units connected in series. The dimensionless model developed allows a wide range of operation parameters and heat transfer fluids. Constant heat extraction rate was selected because it is a desirable condition for several applications such as cooling and/or heating spaces, or power supply of several thermal devices. It is well known that this process does not occur naturally, however, a constant heat extraction rate can be achieved implementing a control system linked to the heat exchanger. In this work, not only the even mass distribution situation is analyzed but also the unevenly distributed and time varying mass conditions. These configurations enhance even more the performance of the system compared to the traditional even mass distribution situations considered in previous studies. In addition, optimal times, for which the efficiency during discharge is maximum, are determined for a specific heat extraction rate and different initial temperatures. The considered configurations create the possibility to increase the efficiency of the extraction process in TES respect to the currently known techniques.

The organization of this paper is as follows: a general dimensionless model for a basic multi-tank system is presented in Section 2. In Section 3, the efficiency of multi-tank systems with evenly distributed mass is studied. The uneven mass distribution in two-tank systems is analyzed in Section 4. For these three sections, the instantaneous efficiency as well as the efficiency of the process are determined to measure the system performance. In Section 5, the analysis of a two-tank system with mass distribution changing with time is performed. Furthermore, in Section 6, a pump incorporated into one- and two-tank systems is considered. Similarly, the effects of energy losses for one- and two-tank systems are presented in Section 7 and finally, the most important results are summarized in Section 8.

2. Exergy analysis of multi-tank thermal energy storage systems

A schematic of a multi-tank system with a total mass m distributed among n tanks is presented in Fig. 1. The fluid passes through the system of tanks with a mass flow rate $\dot{m}$. They are connected in series with a temperature T_i (the sub-index i refers to the number of the tank). Then, energy is extracted from the system in a heat extraction unit at a constant rate $\dot{Q}$. Finally, the returning fluid

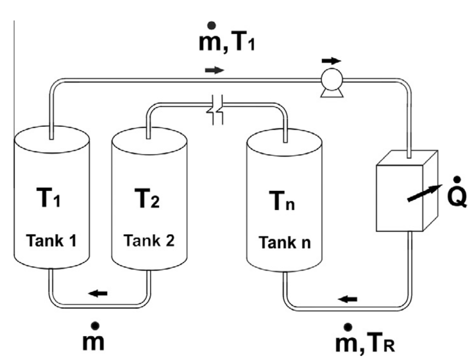

Fig. 1. Schematic of the multi-tank system.