Energy 77 (2014) 871–879

Contents lists available at ScienceDirect

Energy

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

Performance study of a packed bed in a closed loop thermal energy storage system

Lei Chai, Liang Wang, Jia Liu, Liang Yang, Haisheng Chen*, Chunqing Tan

Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, 100190, China

ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form
22 September 2014
Accepted 27 September 2014
Available online 23 October 2014

Keywords:
Thermal energy
Packed bed
Closed loop
Energy efficiency
Exergy efficiency

ABSTRACT

In order to reduce the cost of thermal energy recovery, a packed bed closed loop thermal energy storage system has been proposed and is investigated. The main components of the system include a closed air cycle, a heat exchanger, and a packed bed storage column. This paper is aimed at analyzing the performance of the packed bed in the system. Packed bed column experiments have been carried out to provide a basic understanding of the thermal energy storage process in the closed loop system with different flow directions in the packed bed and different energy storage temperatures. The detailed temperature distributions in the interior of the packed bed and the temperature differences along the axial and radial directions are presented. The influence of flow direction within the packed bed and structure of the gas distributer on the temperature distribution are also analyzed. The performance of packed beds in the closed loop thermal energy storage system is then evaluated based on energy and exergy analyses. These experimental results would be useful in the optimal design of the structure of packed bed columns and thus closed loop thermal energy storage systems.

1. Introduction

In energy systems, where a temporal difference exists between the supply of energy and its utilization, thermal energy storage is necessary to ensure the continuity of many thermal processes, and is of particular interest and significance in solar thermal applications [1,2]. Thermal energy storage systems are classified into three types: sensible heat storage, latent heat storage, and thermo chemical heat storage. Among the three types of thermal energy storage, sensible heat storage is the most simple and inexpensive. Although phase change energy storage has a few advantages over sensible heat storage, the technological and economic aspects of sensible heat storage make it superior [2,3]. Sensible heat storage systems commonly use rocks, water, oil, or salt as the storage medium and are available for short and long-term storage [4]. For a material to be useful in a sensible heat energy storage application, it must be inexpensive and have a good thermal capacity. In addition to the density and specific heat of the storage material, other properties key to sensible heat storage include: operational temperatures, thermal conductivity and diffusivity, vapor pressure, chemical compatibility of the materials, stability, heat loss coefficient as a function of the surface area to volume ratio, and cost [5–7].

Herrmann [5] and Hasnain [8] reviewed the development of available sensible heat energy storage materials and techniques. Sensible heat storage is divided into two classifications based on heat storage media: liquid media storage (such as water, oil based fluids, molten salts etc.), and solid media storage (such as rocks, metals and others). In liquid media storage, water has a higher specific heat than other materials, and while it is cheap and widely available, it cannot be used above 100 °C due to its high vapor pressure. Silicone oil is quite expensive, though it does have the environmental benefit of being a non-hazardous material while synthetic oils usually fall under the hazardous materials classification. And the expense would decrease significantly by the oil/pack bed system. Mawire [9] experimentally measured the volumetric heat transfer coefficient between oil and glass pebbles. At present, molten salt is considered a mature energy storage technology with well understood costs. Unfortunately, the costs for a molten salt thermal energy storage system are still high. Moreover, molten salt is highly corrosive and can be difficult to contain at high temperatures; an important factor as utilities tend to be notoriously reticent when it comes to investing in high risk projects [10,11]. In addition, molten salt generally has a higher melting point, and parasitic heating is required to keep it liquid at night, during low insolation periods, or during plant shutdowns. In solid media

* Corresponding author. Tel.: +86 10 82543148.
E-mail address: chen_hs@iet.cn (H. Chen).

http://dx.doi.org/10.1016/j.energy.2014.09.073
0360-5442/

storage, rock is a good sensible heat storage material due to its wide available temperature range, good mechanical properties, long term stability under thermal cycling, compatibility with its containment and, most importantly, low cost. Difficulties such as the high vapor pressure of water and the limitations of other liquids can be avoided by storing thermal energy as sensible heat in rocks. Moreover, solids do not leak from their container [12].

Kelly [13] studied the thermal storage commercial plant design of two-tank indirect molten salt systems and found that the costs of two tank systems were dominated by the salt expense, which could account for as much as 49% of the system's capital cost. In order to reduce the cost of two-tank storage systems, several schemes involving stratification in liquid tanks and packed beds have been proposed [14–16]. In these storage systems, the molten salt flows uniformly through the packed bed made up of randomly packed particles, and then through a recovery operation. Considering the potential for further cost reductions, we propose a closed loop thermal energy storage system with a rock packed bed substituted for the molten salt solar energy storage system. In the newly proposed storage system, air is used as an intermediate heat transfer fluid, and distributes the energy transferred from the primary HTF (heat transfer fluid) throughout the storage volume at low velocities with the advantages of low expense (much lower cost of thermal storage material), less pump power of HTF and high reliability (no corrosion and blockage under low temperatures). In this paper, we will begin with a brief description of the process using the closed loop thermal energy storage system in the next section and then examine the more comprehensive experimental information regarding the temperature field of the interior of the packed bed. Lastly, energy and exergy analyses are performed based on the experiment's results, investigating the performance of the packed bed.

2. Description of closed loop thermal energy storage system with rock packed bed

The design of the thermal energy storage system under investigation is described in Fig. 1(a). This figure shows the closed air cycle, the heat exchanger, and the packed bed storage column as the three main components of the newly proposed storage system. In the closed air cycle, the air is circulated by a centrifugal fan to absorb the heat from the heat exchanger and carry the heat into the packed bed storage column. The centrifugal fan with frequency converter is used to adjust the speed of the closed air stream and to increase the pressure of the closed air stream to preserve the circulation in the cycle. A plate-fin heat exchanger is used to transfer the heat from the primary heat transfer fluid to the closed air cycle. The plate-fin heat exchanger uses plates and finned chambers to transfer heat between fluids and is often categorized as a compact heat exchanger to emphasize its relatively high heat transfer surface area to volume ratio. The packed bed storage column provides efficient thermal storage due to its high heat transfer effectiveness, which is also simple in design and relatively inexpensive. When the hot air flows through the packed bed, heat is stored in its pebbles. Direct contact between the pebble and the closed air minimizes the cost of heat exchange with the solid storage medium. Furthermore, the use of rocks for thermal storage provides advantages such as being both non-toxic and non-flammable, as well as acting as both heat transfer surface and storage medium.

The packed bed storage set-up used in this newly proposed storage system is shown in Fig. 1(b). The cylinder was made of stainless steel, had an interior diameter of 800 mm, an external diameter of 820 mm, and a height of 1500 mm. The cylinder must both contain the storage material and prevent the loss of thermal energy. In order to decrease the heat loss and heat absorption of the stainless steel wall, 100 mm thick magnesium silicate wool was wrapped around the internal and external wall of the cylinder. In addition, both sides of the thermal insulation layer were coated with silver paper to reduce the radiation heat loss. Thus, the final interior diameter of the packed bed column (bed area) used to contain the porous media was 600 mm. The granite pebbles, serving as the thermal energy storage medium, were packed into the cylinder in a random manner. The thermal energy was stored in the packed bed by forcing heated air into the bed, and was utilized again by recirculating the cooled air back into the heated bed.

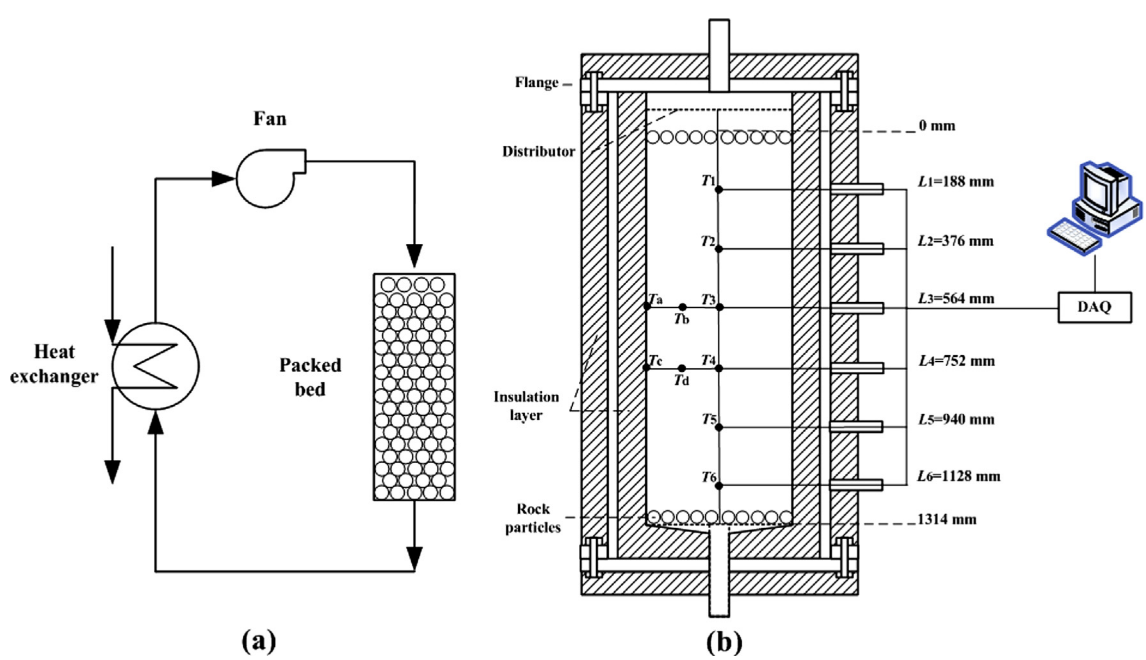

Fig. 1. Thermal energy storage system: (a) closed loop, (b) Packed bed.