Applied Thermal Engineering 112 (2017) 820–831

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Numerical investigation on the heat transfer enhancement of a latent heat thermal energy storage system with bundled tube structures

Jiajia Liu, Chao Xu *, Xing Ju, Bingbin Yang, Yunxiu Ren, Xiaoze Du

Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of MOE, School of Energy Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

HIGHLIGHTS

- The heat transfer of a LHTES with bundled tube structure is investigated.
- A comparison of the charging performance for three LHTES structures is made.
- Effect of air mass flow rate on the heat transfer performance is investigated.
- Effect of different internal fin arrangements in the PCM cylinders is studied.

ARTICLE INFO

Article history:
Received 25 August 2016
Revised 20 October 2016
Accepted 22 October 2016
Available online 24 October 2016

Keywords:
Latent heat storage
Phase change material
Heat transfer enhancement
Staggered tube bundle
Fin arrangement

ABSTRACT

The heat transfer enhancement of a latent heat thermal energy storage system with bundled tube structures using air as the heat transfer fluid (HTF) is investigated numerically. Transient simulations of the charging processes are performed based on a two-dimensional numerical model, and the melting processes of the storage units with staggered tube bundle structure and parallel tube bundle structure are compared with that of flat plate structure. The effects of the air mass flow rate and the internal fin arrangement in the staggered tube bundle storage unit are also investigated. The results show that the heat charging rate of the latent heat storage using air as the HTF can be enhanced by increasing the heat transfer surface, the degree of air turbulence and the gas flow rate; and the storage unit with staggered tube bundle structure is a good choice for its larger heat transfer surface and higher degree of air turbulence. It is also found that the internal fin arrangement has some influences on the PCM melting process, and adding internal outside-in fins that are connected to the tube inner wall can effectively enhance the PCM melting.

1. Introduction

Latent heat thermal energy storage (LHTES) is based on the heat absorption or release when a phase change material (PCM) undergoes a phase change generally from solid to liquid or vice versa. This kind of energy storage system has advantages of a larger thermal storage density and storing/releasing thermal energy at an approximately constant temperature compared to conventional sensible heat thermal storage systems. LHTES has attracted increasing worldwide attentions in the past decades, because it can play an important role on reducing the mismatch between energy supply and demand, and at the same time, improving the efficiency and reliability of energy systems. Specifically, the applications of this technology include: solar energy utilization, "peak load shifting" of electricity, industrial waste heat utilization and recovery and energy-saving of air-conditioning.

The performance of a LHTES system depends highly on the heat transfer processes during the operation. The heat transfer fluid (HTF), which can be liquid (e.g., water, oil, molten salt) or gas (e.g., air, steam, CO_2), exchanges heat with PCM through convection during operation, and the PCM realizes heat charge and discharge through conduction and convection in liquid phase accompanied by phase change. Thus, study of the heat transfer process is very important for improving and regulating performance of the LHTES system, and extensive investigations have been performed both numerically and experimentally in the past years [1].

In previous studies various structures of PCM storage unit have been investigated, including flat plate structure, shell-and-tube structure, packed PCM capsules structure, and bundled tube structure. Pal and Joshi [2] studied numerically and experimentally on the melting process of an organic PCM *n*-triacontane ($C_{30}H_{62}$) in

---

* Corresponding author.
E-mail address: mechxu@ncepu.edu.cn (C. Xu).

http://dx.doi.org/10.1016/j.applthermaleng.2016.10.144
1359-4311/

a rectangular enclosure by supplying a constant heat flux on one side. The results show that natural convection plays a dominant role during the initial melting stage, and the role of natural convection is weakened gradually during the later melting time. Teggar and Mezaache [3] numerically studied the ice banks with the parallel plate type by using the enthalpy method. Water was used as the PCM, and ethylene glycol and indoors warm air were used as the HTFs during the charging process and discharging process, respectively. Darzi et al. [4] carried out a numerical study on simulating a plate type storage filled with Rubitherm as PCM using CFD analysis, and effects of different parameters such as the inlet air mass flow rate on the melting process were analyzed. The results show that the cooling power can be increased by increasing the mass flow rate. Lacroix [5] developed a theoretical model to predict the transient behavior of a shell-and-tube storage unit with the PCM (*n*-octadecane) on the shell side and the HTF (water) circulating through the tubes. Hosseini et al. [6] experimentally and numerically investigated the melting process of the commercial paraffin RT50 inside a shell-and-tube heat exchanger with water flowing through the tube. It was found that natural convection inside the liquid PCM can enhance the heat storage process. The performances of LHTES units with the shell-and-tube structure had also been investigated by Longeon et al. [7], Avci and Yazici [8], and Kibria et al. [9].

Rouault et al. [10] designed a real-scale LHTES device for air cooling in a housing sector. The air passed through a box-section horizontal tube bundle filled with paraffin wax as the PCM. Regin et al. [11] numerically analyzed the behavior of a LHTES system composed of packed spherical capsules filled with paraffin wax as the PCM used in a solar water heating system. Effects of capsule size, inlet water temperature and mass flow rate were discussed. The results indicated that the range of PCM phase change temperature must be accurately known for a good performance prediction of the LHTES system. Bellan et al. [12] developed a numerical model to analyze a LHTES tank filled with sodium nitrate spherical capsules and using the high temperature synthetic oil (Therminol 66) as the HTF. The natural convection effect was considered by using an effective thermal conductivity. Decreasing the capsule size or increasing the oil flow rate was found to enhance the heat transfer rate and decrease the charging/discharging time. The performances of LHTES units with other structures, such as vertical spiral heat exchanger structure [13] and containers with heat pipe [14,15], have also been investigated both experimentally and numerically.

As reported by many researchers, the main issue about the LHTES system is that PCMs (paraffin, hydrated salt, molten salts, etc.) usually have low thermal conductivities, which lead to low charging and discharging rates. To overcome this weak point, various kinds of heat transfer enhancement techniques have been proposed and investigated, and the most regular and cost-effective method is adding fins in the LHTES system. Costa et al. [16] numerically studied the heat transfer enhancement within a rectangular PCM (*n*-octadecane) container by adding aluminum fins using the enthalpy method. Adding fins in the PCM greatly increases the heat transfer rate of the system. Ye et al. [17] numerically investigated a plate-fin LHTES unit with the HTF of water used for rapid heat storage and release by paraffin. Effect of the temperature difference between the heating/cooling plate wall and the mean PCM melting temperature on the heat charging/discharging performance was investigated. Mosaffa et al. [18] developed an approximate analytical model for the solidification process in a shell-and-tube finned TES unit. Cold air flowed through the tube to absorb heat from the PCM ($CaCl_2 \cdot 6H_2O$) in the finned shell. It was found that the inlet air velocity greatly influences the solidification process and the outlet temperature. Al-Abidi et al. [19] numerically studied the heat transfer enhancement technique by using internal and external fins for PCM melting in a triplex tube heat exchanger (TTHX). The outer and inner tubes were used for the HTF (water) flow, whereas the middle tube was filled with paraffin RT82. Both the fin parameters and the PCM unit geometry in the TTHX were changed and their effects on the melting process were investigated. Jmal and Baccar [20] studied the solidification of PCM (Paraffin C_{18}) in coaxial tubes with internal and external horizontal fins for air conditioning systems with two air passages. Effect of natural convection on the PCM solidification time and the impact of fin number on the heat transfer enhancement were discussed. The results showed that the presence of fins contributes to the reduction of the discharging time and the increase of the outlet air temperature, but the heat transfer enhancement becomes insignificant when the fin number increases to 9 due to the restrict of narrow flowing space. Hosseini et al. [21] studied the effect of longitudinal fins in a double pipe LHTES system containing Paraffin RT50 during the charging process by flowing hot water through the inner tube. Fins extension leads to a less melting time, and the heat charging power depends highly on the fin height especially during the initial charging period.

From the above literature review, it can be found that past researches on the LHTES mainly involve liquid HTF which is proper especially for the tube-and-shell structure. While investigations on the LHTES using gas HTF, which requires larger heat transfer surfaces due to the low heat transfer capability of gas, and the corresponding enhancement techniques are relatively rare. In the present study, the heat transfer enhancement of a LHTES unit using air as the HTF is investigated, and the bundled tube structure is adopted since it has larger heat transfer surfaces. Taking the presence of natural convection into account, this work makes a comparison of the charging performance for three unit structures including staggered tube bundle structure, parallel tube bundle structure and flat plate structure. And the heat transfer enhancement effect of different internal fin arrangements in the staggered tube bundle storage unit is also studied.

2. Model descriptions

The following model descriptions are introduced taking the staggered tube bundle structure as an example. Due to the axially symmetric configuration and boundary conditions, a two-dimensional model is adopted in the present work, and the schematic diagram of the LHTES unit with the staggered tube bundle structure is shown in Fig. 1. The bundled aluminum tubes are filled with paraffin PCM to form PCM cylinders. Hot air flows in from the downside entrance, and flows upward (opposite to the direction of gravity, shown as g in Fig. 1) through the void space, exchanging heat with the staggered PCM cylinders. The length, width and depth of the storage unit are $l = 500$ mm, $w = 40$ mm and $d = 1000$ mm, respectively. The inner radius of each container tube is $R = 15$ mm, and the wall thickness is 1 mm. There are totally 11 rows of PCM cylinders in the storage unit, and the distance of x direction between any two neighboring rows is fixed as $D_1 = 34.64$ mm. The entry length shown in Fig. 1 is 50 mm, and the extended downstream in the computational domain is 72.6 mm. In the following analysis, the leftmost cylinder as shown in Fig. 1 is termed as Tube 1, and the cylinder neighboring Tube 1 is termed as Tube 2, and so on.

2.1. Conservation equations

The governing equations for the air flow through the void region of the computational domain are given by [22]: