Engineering Science and Technology, an International Journal 19 (2016) 619–631

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material

Ashish Agarwal *, R.M. Sarviya

Department of Mechanical Engineering, Maulana Azad National Institute of Technology, Bhopal, MP, India

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
5 September 2015
Accepted 29 September 2015
Available online 18 November 2015

Keywords:
Latent heat storage
PCM
Melting and solidification process
Paraffin wax

ABSTRACT

In the presented study the shell and tube type latent heat storage (LHS) has been designed for solar dryer and paraffin wax is used as heat storage material. In the first part of the study, the thermal and heat transfer characteristics of the latent heat storage system have been evaluated during charging and discharging process using air as heat transfer fluid (HTF). In the last section of the study the effectiveness of the use of an LHS for drying of food product and also on the drying kinetics of a food product has been determined. A series of experiments were conducted to study the effects of flow rate and temperature of HTF on the charging and discharging process of LHS. The temperature distribution along the radial and longitudinal directions was obtained at different time during charging process to analyze the heat transfer phenomenon in the LHS. Thermal performance of the system is evaluated in terms of cumulative energy charged and discharged, during the charging and discharging process of LHS, respectively. Experimental results show that the LHS is suitable to supply the hot air for drying of food product during non-sunshine hours or when the intensity of solar energy is very low. Temperature gain of air in the range of 17 °C to 5 °C for approximately 10 hrs duration was achieved during discharging of LHS.

1. Introduction

In the recent years, most of the developing countries around the world were facing the problem of energy crisis because of the large gap between demand and supply of energy. This problem can be minimized to some extent by utilizing renewable energy sources. Solar energy is the attractive form of the renewable energy. Solar energy is available abundantly in the world, but it is not continuous and its intensity also varies with time. Due to above reason the acceptability and reliability of solar based thermal system is lower than conventional systems. A properly designed heat storage system increases the reliability of solar thermal system by bridging the gap between the energy demand and availability. The thermal energy can be stored in the form of sensible heat, latent heat or thermochemical energy. Latent heat storage is a more attractive form because of high energy storage capacity per unit volume, absorbing and releasing heat at constant temperature, chemical stability, non-corrosiveness, low vapor pressure, small volume change during phase transformation etc. [1].

A number of experimental and computational studies have been reported in the literature to evaluate the thermal performance of numerous latent heat storage systems. A detail review of phase change materials (PCMs) used in the thermal heat storage system has been given by Abhat [1], Lane [2], Zhou et al. [3], Garg et al. [4], Zhang et al. [5], Tyagi and Buddhi [6], Riffat et al. [7], Sethi and Sharma [8], Verma et al. [9], and Agrawal and Sarviya [10]. Many researchers have reported the thermal and heat transfer characteristics of latent heat storage systems with different geometrical configuration during charging and discharging. Khodadadi and Zhang [11] numerically studied the melting process of PCM in spherical container. The results of the numerical study show that the rate of melting is higher at top region of a sphere than at the bottom region. They investigate the effect of convection on the melting rate.

Medrano et al. [12] experimentally studied the heat transfer characteristics of five small heat exchangers working as latent heat thermal storage systems, during the charge and discharge processes. The results indicated that the double pipe heat exchanger with the PCM embedded in a graphite matrix had the highest values of heat storage. Liu et al. [13] experimentally investigated the thermal and heat transfer characteristics of stearic acid during the solidification processes in a vertical annulus energy storage system. They studied the movement of the solid–liquid interface in the radial direction, and the effects of Reynolds number on the heat transfer parameters. Also, the effects

Abbreviations: DSC, Differential scanning calorimetry; HTF, Heat transfer fluid; LHS, Latent heat storage; PCM, Phase change material; PID, Proportional-integral-derivative; wb, Wet basis.

* Corresponding author. Tel.: +91 9425680418, fax: +91 7552670562.
E-mail address: er_ashishagarwal@yahoo.com (A. Agarwal).

Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.09.014

of the fin with various widths on the enhancement were reported. Their results indicated that the fin can enhance both the conduction and the natural convection heat transfer of the PCM.

Ezan et al. [14] experimentally investigated the thermal performance of shell and tube system during charging and discharging cycle using water as HTF. They evaluate the performance of the system under different operating conditions. They studied the effects of inlet temperature, flow rate, shell diameter and thermal conductivity of the tube material on the storage capacity of the system. The results show that the natural convection mode of heat transfer is dominant over conduction during melting and solidification. The conduction was dominant only during the beginning of melting and solidification processes. The effect of inlet temperature of HTF on rejected energy is more, compared to flow rate of HTF. Akgün et al. [15] experimentally evaluated the melting and solidification behaviors of PCM in a vertical shell and tube heat exchanger. The results of the study show that the melting time greatly decreased by increasing the temperature of HTF. Low value of mass flow rate of HTF leads to lower consumption of energy. Seeniraj et al. [16] conducted a numerical study of a finned tube latent heat thermal storage (LHTS) module. The shell side of the module is filled with PCM while the tubes carry the heat transfer fluid (HTF). The influence of various parameters viz. geometrical, thermophysical and various non-dimensional numbers on the performance of the unit is studied. They observed that some quantity of PCM at the end of the exit of the HTF tube have remained in the solid state in case of an unfinned tube. An appreciable enhancement in the energy storage process was observed with the addition of fins in the module.

Hosseini et al. [17] performed an experimental investigation to evaluate the melting behavior of PCM in horizontal shell and tube heat storage. They found that the high temperature region exists in the uppermost section due to buoyancy effects. They claimed that by increasing the temperature from 70 to 80 °C, the total melting time is reduced to 37%. Adine and El Qarnia [18] reported numerical study of melting of PCM in latent heat storage unit. The shell-and-tube type heat storage system was selected in this study. The effect of multiple PCMs on thermal performance was studied numerically. *n*-octadecane and P116 of melting temperatures of 50 °C and 27.7 °C was selected as a heat storage material and filled in shell side. Water was used as heat transfer fluid and flow through the inner tube. Water flow under forced convection and transfers the heat to PCM. The thermal performance of the latent heat thermal energy storage unit was numerically studied using multiple phase change materials and a phase change material during charging process (melting). The parametric studies were conducted to optimize the design and to evaluate the thermal performance of the system. The key parameters considered during the study were: the mass flow rate and temperature of the HTF and the proportion mass of Phase change materials.

Li and Kong [19] performed a numerical study for evaluating the thermal performance of a shell and tube heat storage unit using paraffin as PCM. The study was conducted using air and water as HTF. Parametric analysis has been conducted to evaluate the effect of HTF inlet velocity on the HTF outlet temperature, Nu, and melt fraction. Results indicate that the air inlet velocity has a great effect on the air outlet temperature and heat transfer rate, and the water inlet velocity has little effect on the water outlet temperature. Trp [20] conducted an experimental and numerical investigation of the shell-and-tube type latent thermal energy storage system during charging and discharging. The aim of the study is to provide guidelines for system performance and design optimization. The unsteady temperature distributions of the HTF, tube wall and the PCM have been obtained by a series of numerical calculations for various HTF working conditions and various geometric parameters. Zhang and Faghri [21] numerically studied freezing in an eccentric annulus using a temperature-transforming model. They investigated the effect of the eccentricity on the freezing process. Sari and Kaygusuz [22–24] performed experimental investigations during melting and solidification of some acids including stearic acid, eutectic mixture of lauric and stearic acids and myristic acid. They claimed that the temperature and mass flow rate of HTF is more effective on the solidification behavior than the melting behavior of PCM.

Avci and Yazici [25] reported melting and solidification behaviors of paraffin in a horizontal tube-in-shell storage system. The effect of the inlet temperature on the melting and solidification time was determined. The focus of the study is to understand the physics of the process based on the temporal variation of temperature field inside the PCM. Wang et al. [26] numerically studied melting and solidification characteristics of a shell-and-tube phase change heat storage unit. Yusuf Yazici et al. [27] reported solidification characteristics of paraffin in a horizontal shell-and-tube type-storage system. In this study the effects of the eccentricity of the inner tube on the solidification were determined and discussed. The inner tube has been moved upward/downward according the center of the outer shell. Six different values of the eccentricity from the center of the outer shell are considered: $e = -10, -20, -30, 10, 20, 30$ besides the concentric geometry ($e = 0$). The focus of the study was to understand the solidification behavior of PCM based on the transient temperature fields inside the PCM. Eccentricity is shown to affect the total solidification time considerably. The eccentricity, either upward or downward, was found to make the total solidification time longer. Pandiyarajan et al. [28] conducted an experimental study in order to evaluate the performance of heat recovery system for diesel engine exhaust. The finned shell and tube heat exchanger was used in this study. The reported heat recovery of the system was 10–15%. The effect of velocity and temperature of HTF, on the heat transfer was studied and reported.

Several investigations were carried out in the past for observing the dynamic characteristics of the latent heat storage system during charging and discharging [29–31]. Wu and Fang [29] developed numerical model to analyze the influence of mass flow rate and inlet temperature of HTF on the transient thermal characteristics of latent heat thermal storage system coupled with a solar heating collector, during the discharging process. The heat storage system consists of a cylindrical storage tank filled with spherical capsules containing a phase change material (PCM). Myristic acid was used as a PCM and water was used as heat transfer fluid (HTF). The mass flow rate and inlet temperature of HTF have strong influences on complete solidification time and the heat removal rate compared to the initial temperature of PCM. The heat release during solidification is divided into three stages, namely, liquid sensible heat release, solidifying latent heat release and solid sensible heat release. The temperature of PCM drops very rapidly at the liquid sensible heat release stage, then it stabilizes at the solidification temperature until the solidification process is completed.

Veerappan et al. [30] analytically studied the phase change behavior of different PCMs encapsulated in spherical enclosures to identify a suitable heat storage material. The developed model is useful for finding the interface positions and complete phase change time for solidification and melting of PCM in spherical enclosure. Results indicated that the solidification time and the solidified mass fraction was greatly influenced by the thermal conductivity of PCM. The results of the study show that the conduction is the dominant mode of heat transfer during initial stage of melting. After that, melting is greatly influenced by natural convection phenomena. Liu et al. [31] simulate the dynamic characteristics of the latent heat storage device with heat pipe during charging process. The dynamic charging process model has been developed to analyze the effects of initial temperature of the PCM and inlet temperature of heat pipe medium on the transient thermal performance of the system. Paraffin was used as phase change material (PCM) and water was used as heat transfer fluid (HTF). The thermal performance of the heat storage is measured in terms of total heat storage capacity, heat