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Effect of eccentricity on melting behavior of paraffin in a horizontal tube-in-shell storage unit: An experimental study

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Abstract

In this study, melting behavior of paraffin in a horizontal shell-and-tube type-storage unit is experimentally studied. Both the concentric and eccentric orientations of the inner tube according the center of the outer shell are considered. Three different values for the eccentricity from the center of the outer shell is investigated: $e = 10$, 20 and 30 mm besides the concentric geometry ($e = 0$). For each geometric orientation, effect of the inlet temperature on the melting behavior is also obtained. A special attention is paid to understand the melting behavior based on the temporal variation of temperature field inside PCM. Eccentricity is shown to respond much well to the melting behavior and hence enhance melting behavior due to intensified natural convection intensity inside PCM.

Keywords: Thermal energy storage; Tube-in-shell; Eccentricity; Paraffin; Melting

1. Introduction

Thermal energy storage (TES) has recently become popular as an energy saving method to conserve available energy and to improve its utilization overcoming the imbalance between energy supply or availability and demand through the implementation of a proper energy storage system (Aydın et al., 2007).

Among various thermal energy storage methods, the latent heat thermal energy storage (LHTES) systems utilizing phase change materials (PCM) have been the most attractive due to its advantages of high energy storage density and its isothermal operating characteristics during solidification and melting processes. Therefore, use of the latent heat of a PCM as a thermal energy storage medium has gained considerable attention recently by finding applications in conservation of energy and natural resources, recovery and use of waste industrial energy, space craft, refrigeration and air conditioning systems, solar energy systems, heating and cooling of buildings, cooling of electronic devices, cooling vest for athletes, etc.

Latent heat thermal energy storage has been receiving a great deal of research attention. The research focus has generally been on the investigation of the overall thermal behavior and performance of various latent heat thermal energy storage systems. In order to have a better view on the studies existing in the literature, we refer readers to see the excellent reference books by Lane (1983), Garg et al. (1985), and Dincer and Rosen (2002) and the comprehensive review articles by Abhat (1983), Hasnain (1998), Faith (1998), Zalba et al. (2003), Ettouney et al. (2004), Farid et al. (2004), Sharma and Sagara (2005), Felix Regin et al. (2008), Jegadheeswaran and Pohekar Sanjay (2009), Haller et al. (2009), Agyenim et al. (2010).

Various configurations have been suggested for PCM storage. The tube-in-shell storage units, either horizontal

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or vertical, are very common, in which the PCM is kept in the concentric annular space while the heat transfer fluid (HTF) flows through the inner tube. Many studies have been conducted on this geometry. Extensive investigations have been made on predicting performance of various PCMs. Effects of various working parameters such as inlet temperature or mass flow rate of heat transfer fluid have been studied (for horizontal tube-in-shell storage geometries: e.g. Dutta et al., 2008; Hosseini et al., 2012; Jian-you (2008) and, for vertical tube-in-shell storage geometries: e.g. Trp, 2005; Jesumathy et al., 2012; Sarı and Kaygusuz, 2001; Akgun et al., 2007a; Shmueli et al., 2010). Sarı and Kaygusuz (2001) experimentally studied thermal energy storage performance of myristic acid. Trp (2005) experimentally and numerically investigated transient melting and solidification behaviors of paraffin in a vertical shell-in-tube latent thermal energy storage unit. Akgun et al. (2007a) experimentally investigated charging and discharging characteristics of paraffin in a vertical tube-in-shell storage unit. Dutta et al. (2008) experimentally and numerically studied solid–liquid phase change heat transfer of paraffin was encapsulated in the annulus of two coaxial circular cylinders with variable heat flux. Jian-you (2008) numerically and experimentally investigated melting and solidification of PCM in a triplex concentric tube used as thermal energy storage unit. Shmueli et al. (2010) numerically investigated melting of PCM in a vertical cylinder using an enthalpy-porosity formulation. They showed that as the melting progressed, natural convection in the liquid become dominant, changing the solid to a conical one, which shrank in size from the top to the bottom. Jesumathy et al. (2012) experimentally studied melting and solidification characteristics of paraffin wax in a vertical shell-in-tube storage system. Hosseini et al. (2012) obtained that heat transfer from the HTF tube to the PCM was largely influenced by natural convection at the HTF tube to the PCM was largely influenced by natural convection at the melting layer section and strong thermal stratification of the molten liquid existed in the upper half of the horizontal tube-in-shell storage geometry.

From either scientific or practical viewpoint, research concentration should be directed to improving or enhancing storage performance. By enhancing, our ultimate goal is "*storing energy as much as possible in a time as short as possible*". Enhancing storage performance can be via active or passive ways. Active methods such as mixing require usage of additional energy. However, passive methods just require some geometrical orientations without any external energy mean.

Using extended surfaces is a passive way to improve performance, which is an approach followed by some researchers (e.g. Lacroix, 1993; Zhang and Faghri, 1996a,b; Velraj et al., 1999; Seeniraj et al., 2002; Liu et al., 2005a,b; Balikowski and Mollendorf, 2007; Castell et al., 2008; Tao et al., 2012).

Lacroix (1993) numerically and experimentally studied the tube-in-shell storage geometry with annular fins. Zhang and Faghri (1996a,b) numerically analyzed latent heat thermal energy storage system of internally or externally finned tube. Velraj et al. (1999) experimentally studied three different methods to augment heat transfer in a latent heat storage system. Seerinaj et al. (2002) investigated transient behavior of a finned tube latent heat thermal storage module. Liu et al. (2005a,b) experimentally investigated melting and solidification characteristics of stearic acid in a vertical annulus energy storage system with fins. They showed that attaching a conducting fin on the electrical heating rod of the annular storage geometry improved the melting process inside. Balikowski and Mollendorf (2007) experimentally investigated two PCMs in smooth-piped and spined heat exchangers comparatively. They obtained that spined fins accelerated charging and discharging performance. Tao et al. (2012) numerically studied high temperature molten salt phase change thermal energy storage using three different tubes: dimpled tube, cone-finned tube and helically – finned tube.

Without increasing heat transfer area, for a specified area, storage performance could be enhanced through optimizing geometries. In this way, investigating geometries to be very convenient to phase change behavior of PCM is the focus. Hence, it is aimed to have increased heat transfer coefficients. For a vertical tube-in-shell storage geometry, motivated by the structure of the melting behavior of the PCM in the annular space, Akgun et al. (2007b, 2008) suggested an innovative design in which the outer surface of the shell was inclined. The new geometry was shown to respond well with the melting characteristics of the PCM and to enhance heat transfer inside the PCM for a specific range of the shell inclination angle.

Similar to the above approach followed for the vertical shell-in-tube geometry by our group, we investigate a geometric modification for the horizontal tube-in-shell storage unit responding melting behavior of PCM inside the annulus. In order to enhance natural convection currents inside, inner tube is moved eccentrically towards down to the center. This modification has been recognized by other researchers (Yao and Chen, 1980; Dutta et al., 2008; Darzi et al., 2011), who studied melting behavior in an eccentric annulus numerically. To the best knowledge of the authors, this is the first experimental study investigating the influence of the eccentricity on the melting behavior of paraffin in a horizontal tube-in-shell geometry.

2. Experimental study

2.1. Heat storage material

In the present study, paraffin of P56-58 is used as PCM, which is supplied from the MERCK. Paraffin is known to be an attractive, chemically stable and non-toxic material without regular degradation and it has high latent heat storage capacities over a narrow temperature range. The thermo-physical properties of the paraffin used in the study