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Experimental study on the melting and solidification behavior of erythritol in a vertical shell-and-tube latent heat thermal storage unit

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ABSTRACT

An experimental study on a vertical shell-and-tube latent heat thermal storage unit with erythritol as storage media and air as heat transfer fluid (HTF) is conducted to evaluate the thermal behavior and heat transfer performance of the unit. The thermophysical properties of erythritol, such as melting temperature, melting enthalpy, thermal conductivity, and viscosity, are obtained. During charging, the molten phase change material (PCM) first occupies the top region and then spreads from top to bottom. During discharging, the PCM initially solidifies from the bottom region, and then the solid–liquid interface progresses uniformly from the inner tube to the outer shell, where natural convection plays a dominant role in the heat transfer at the liquid region. Moreover, increasing the inlet temperature and the mass flow rate of the HTF during charging obviously enhances the heat transfer in the PCM and shortens the charging time. Increasing the pressure of the HTF with the same mass flow rate shows little effect on the heat transfer in the PCM. In addition, increasing the mass flow rate of the HTF helps enhance heat transfer during discharging.

1. Introduction

Thermal energy storage is important in overcoming the mismatch between energy supply and demand in a wide range of applications, such as solar energy utilization, compressed air energy storage, waste-heat utilization, heating, cooling, and air-conditioning [1–3]. Latent heat thermal storage (LHTS) using phase change material (PCM) has received tremendous attention in the last decades because it has the advantages of high energy density and near isothermal characteristic during melting/solidification.

For decades, research on LHTS focused mainly on PCM and heat exchanger design [1]. Several studies summarized the PCM on thermophysical properties [1,2,4,5]. Designing a suitable heat exchanger is equally important as material investigation. Two types of heat exchangers are primarily used for LHTS, namely, direct-contact heat exchanger and indirect-contact heat exchanger. For the indirect-contact heat exchanger, the plate, shell-and-tube, and packed-bed types are typically used because other complicated forms of heat exchangers can be developed from these types. Shell-and-tube heat exchanger is commonly employed in LHTS because of its simple structure and relatively small heat loss [5]. Considerable research on the melting/solidification behavior and thermal performance of shell-and-tube LHTS [6–15], including theoretical, numerical, and experimental studies, has been conducted.

For theoretical studies, thermodynamic optimization theory is the main tool. Conti et al. [6] performed a theoretical analysis on irreversibility during the heat transfer process in a shell-and-tube LHTS unit by a mathematical model neglecting the natural convection in liquid PCM. Erek and Dincer [7] conducted an entropy and exergy analysis of a shell-and-tube LHTS unit during charging. They investigated the timewise variations of melting fronts, heat stored, heat transfer rates, and exergy efficiency. Their results indicated that the efficiency analysis is important for the assessment and optimization of an LHTS unit.

Without gravity, pure conduction model used in numerical studies without considering the natural convection during melting is applicable. Zhang and Faghri [8] numerically studied a shell-and-tube LHTS unit through an analytical method. They concluded that the convective heat transfer in the tube will not reach a fully developed state regardless of the length of the tube. Thus, heat transfer between the heat transfer fluid (HTF) and the PCM must be solved simultaneously. Gong and Mujumdar [9] performed a numerical study of cyclic heat transfer in a shell-and-tube LHTS exchanger with a pure conduction model. The mode of charging and discharging from the same direction showed a more desirable performance than that from different directions.

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Though the simulation results of Trp [10] on a vertical shell-and-tube LHTS unit ignoring the natural convection in liquid PCM agreed with the experiment well, it becomes acknowledged to consider the natural convection in the liquid PCM with gravity [11–15]. Rathod and Banerjee [11] analyzed the charging and discharging of a shell-and-tube LHTS with air as the HTF and paraffin as the PCM. The charging and discharging directions are all from bottom to top. They concluded that natural convection is significant during melting, and conduction is dominant during solidification. For vertical shell-and-tube LHTS unit, Longeon et al. [12] performed an experimental and numerical study to investigate the effects of natural convection during melting and solidification. Paraffin RT 35 was adopted as the storage media in an annular space, and water circulated in the inner tube. The unit showed a faster charging rate with top HTF injection than that with bottom HTF injection. Conversely, Ettouney et al. [13] conducted an experimental study of a vertical double pipe LHTS unit and concluded that the effects of natural convection are negligible during melting for the HTF flow direction from top to bottom.

For horizontal shell-and-tube LHTS unit, Ng et al. [14] conducted a numerical simulation and investigated the effect of Rayleigh number on the flow pattern. They found that the natural convection mainly affects the PCM in the upper part of the annulus. Ezan et al. [15] performed an experimental investigation of a horizontal double pipe LHTS unit. The effects of inlet temperature, mass flow rate, eccentric position, tube material, and shell diameter on the temperature distribution, phase change time, and energy charging/discharging process were investigated.

The studies discussed above provided basic research methods for LHTS. However, most of these studies focused on the charging and discharging performance of paraffin with melting points lower than 100 °C. The thermal properties, crystallization period, and subcooling is much different from that of sugar alcohol with the melting temperature over 100 °C. And it will leads to different heat transfer and heat storage characteristic. Erythritol is a common sugar alcohol used as a low-calorie sweetener in the food industry. With a melting point of about 120 °C, erythritol is a very promising PCM for thermal energy storage in medium temperature owing to its advantages, such as large melting enthalpy, low volume expansion of approximately 10%, low corrosiveness with metal, and good cycle stability. Several studies have analyzed the thermophysical properties of this material [16–22]. These studies only gave a few measurement points of conductivity and viscosity on erythritol, so detailed measurements and the effects of temperature are needed. Studies on the thermal performance of LHTS with erythritol as the PCM include several types, such as direct-contact [22–28], horizontal shell-and-tube [29–31], and encapsulated packed bed [32]. Agyenim et al. [29–31] conducted experimental studies on thermal storage using erythritol as the PCM in a horizontal shell-and-tube unit. The heat transfer enhancement methods that use multi-tubes, circular fins, and longitudinal fins were compared with those using plain inner tube forms, where natural convection still plays an important role during melting. However, no study on the vertically placed shell-and-tube type LHTS has been conducted with erythritol as the PCM, where the effect of natural convection on the flow and heat transfer may be different from that on the horizontal type. In addition, the effect of natural convection when HTF flows from top to bottom needs to be studied further. Thus, detailed experimental and theoretical studies must be carried out to reveal the physical phenomena and design of vertical shell-and-tube heat storage unit with erythritol as storage media.

In the present study, detailed thermophysical properties such as thermal conductivity and viscosity of erythritol at temperatures ranging from 15 to 160 °C were carried out, an experimental investigation on a vertical shell-and-tube LHTS unit without heat transfer enhancement with erythritol as the PCM was conducted, the HTF flows from top to bottom, and the heat transfer of erythritol during melting and solidification was analyzed. Moreover, the effects of inlet temperature, mass flow rate, and pressure of the HTF on thermal performance were studied.

2. Analysis of thermophysical properties

Thermophysical properties including solidification/melting temperature, latent heat, and thermal conductivity play very important roles in utilization of PCMs. Before the thermal storage experiment, a series of thermophysical properties tests on the PCM erythritol were conducted first.

Erythritol with labeled purity >99.5% mass fraction on dry basis was purchased from Shandong Sanyuan Biotechnology Co. Ltd., in PR China. Before the thermophysical property tests, the samples were dried at 80 °C in a drier for about 1 h.

A differential scanning calorimeter (DSC Q2000, TA Instruments) was used to measure the melting enthalpy and heat capacity of erythritol. T-zero calibration with sapphire and cell constant and temperature calibration with indium for the instrument were performed before the experiment with erythritol, and an accuracy of ±5% was reached. The heating rate was 5 °C/min. A constant stream of high-purity helium (25 mL/min) was applied as purge gas during the entire experiment. Fig. 1 shows the heat capacity and melting enthalpy curve of erythritol. The melting point of erythritol is about 120.39 °C, and its melting enthalpy is about 319.5 kJ/kg.

The thermogravimetric analysis was conducted using SDT Q600, TA Instruments. The heating rate was set to 3 °C/min during the experiment, and nitrogen was used as the purge gas. The weight was measured during the experiment, as shown in Fig. 2. The onset decomposition temperature was 183.66 °C when the weight loss was 3.82%, and the complete decomposition temperature was about 250 °C.

The thermal conductivities of erythritol were measured with a hot-disk thermal constant analyzer (TPS2500S, Hot Disk Inc., Sweden). Thermal conductivity can be measured ranges from 0.005 W/(m K) to 1800 W/(m K) with an accuracy of ±5%. Fig. 3 plots the thermal conductivity of erythritol at the solid state between 15 °C and 60 °C and at the liquid state between 120 °C and 160 °C. The thermal conductivity result shows good agreement with the literature data [16]. The thermal conductivity of solid erythritol decreases linearly with temperature increasing at the temperature range between 15 °C and 60 °C. Conversely, the thermal conductivity of liquid erythritol increases linearly with the increase in temperature between 120 °C and 160 °C. The tendency is in accordance with the measurement of $C_{25}H_{52}$ [33]. Linear

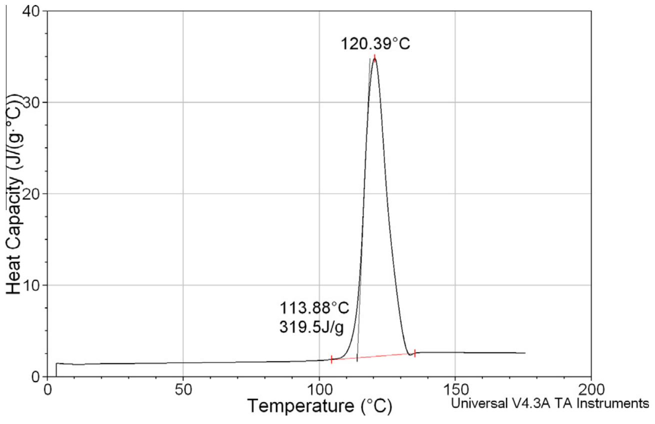

Fig. 1. Heat capacity and melting enthalpy curve of erythritol.