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Heat release performance of direct-contact heat exchanger with erythritol as phase change material

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HIGHLIGHTS

- Direct-contact heat exchanger with a phase change material and heat transfer oil.
- We examined effects of operating conditions on performance of latent heat release.
- We found the optimum conditions to flow heat-transfer-oil uniformly.
- The uniform flow improved the performance of latent heat release.
- Heat release rate increased with the flow rate of the inlet heat-transfer-oil.

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ABSTRACT

This paper describes heat-release performance of a direct-contact heat exchanger using erythritol as a phase change material (PCM) along with a heat-transfer oil (HTO). A vertical cylinder with an inner diameter of 200 mm and a height of 1000 mm was used as a heat-storage unit (HSU). A nozzle with nine holes in diameter of 3.0 mm facing vertically downward was placed at the bottom of HSU. We examined the effects of flow rate of HTO and the height of PCM layer in the HSU, on three characteristic parameters of heat release—temperature effectiveness, heat release rate, and volumetric heat transfer coefficient. Consequently, we determined optimum conditions under which the HTO uniformly flowed in the PCM. When the HTO uniformly flow and the height of PCM was constant, the temperature effectiveness was high and the heat release rate was proportional to the flow rate of HTO. In addition, a high temperature effectiveness over 0.83 was observed even when the height of PCM was 0.2 m. Further, the average volumetric heat transfer coefficient increased with increasing the flow rate of HTO and decreasing the height of PCM. These results revealed that the direct-contact heat exchanger can rapidly, efficiently, and compactly release the latent heat of PCM provided that HTO uniformly flows.

1. Introduction

Latent heat storage (LHS), to utilize unused thermal energy, has recently attracted considerable attention. LHS is based on the storage or release of latent heat when a phase change material (PCM) undergoes a phase change from solid to liquid and liquid to solid. LHS has the following three advantages [1]:

(1) Constant-temperature heat source: The PCM first stores heat in the form of latent heat of fusion and then releases thermal energy at a fixed melting point of the PCM during solidification.
(2) High storage density: In general, the latent heat of the PCM is 50–100 times higher than the sensible heat.
(3) Repeatable process: The melting and solidifying processes of the PCM can be repeated.

These features of the LHS are suitable for utilize solar energy and industrial waste heat which generate intermittently. Therefore, LHS can apply various fields [2] such as building materials [3,4], domestic solar water heater [5,6], solar power plant [7,8], waste heat recovering system [9,10].

High heat exchange performance and high thermal storage density of the system are important for design of thermal energy storage (TES) system. The former increases in the amount of the recovering heat and profits due to introduction of the TES, and the latter brings benefits to downsizing of the heat storage unit and saving initial cost of TES system.

An indirect heat exchanger and a direct heat exchanger for LHS have been proposed. In the indirect heat exchanger such as shell &

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tube and packed bed types, heat exchange proceeds through a heat transfer wall between the PCM and the heat transfer medium. On the other hand, direct-contact heat exchange (DCHEX) between the PCM and the heat transfer medium proceeds without any heat transfer wall. Here, the PCM is required to be insoluble in the heat transfer medium and the density of the PCM is required to be high enough to ensure that a phase separation is possible.

Comparing indirect heat exchanger with DCHEX, DCHEX has the following three advantages [11]. First, DCHEX can exchange heat more rapidly than indirect-contact heat exchangers, because it can afford a large heat transfer area, and the thermal resistance of the heat transfer wall can be negligible. Second, it has a very simple structure and a high thermal storage density, because only the inlet and outlet nozzles for the heat transfer medium are required. Indirect-contact heat exchangers need a lot of heat transfer pipes and capsules. Third, DCHEX can be carried out using not only a stationary system but also a heat transport system, because the DCHEX is light and can hold a large amount of PCM.

Early works were mainly focused on DCHEX using a PCM with a melting point, T_m, lower than 373 K [12–18]. In these studies, some important objectives, such as the establishment of a porous PCM and layer of the heat transfer medium [17,18], dimensionless equations [12,13,15], and various concepts [14], were achieved.

Recently, DCHEX using PCMs with T_m of medium-to-high temperatures, that is, at temperatures higher than 373 K, has been studied. In particular, DCHEX for a latent heat transportation system has been primarily studied [11,19–23]. In a latent heat transportation system, a mobile latent heat accumulator recovers industrial waste heat from the heat source at temperatures below 473 K and distributes it over a large area. The industrial waste heat is compactly stored in the form of latent heat by melting the PCMs, and it is then transported to office buildings, hospitals, hotels, etc. Kaizawa et al. revealed that sodium acetate trihydrate (T_m: 331 K) and erythritol (T_m: 391 K) can be used as PCMs for such a system [21]. Especially, erythritol is a promising PCM for recovering solar energy and industrial waste heat at temperatures below 473 K owing to its high latent heat and adequate melting point. In addition, Kaizawa et al. performed bench-scale experiments on heat storage and release using erythritol and revealed the heat and fluid flows in a heat transportation container [11]. Guo et al. developed 2-dimensional numerical simulation model of the container for the heat storage mode of DCHEX [23]. Tagashira et al. studied a latent heat transportation system using a PCM storage cassette and investigated the use of erythritol as a heat medium in a lab-scale reactor. They charged a storage cassette with 400 kg of erythritol and investigated the heat transportation system using the PCM [19]. Note that, latent heat transportation systems have also been used in practical applications in Japan [24].

The development of a latent heat transportation system indicates that DCHEX may be applied for LHS on a conventional scale. However, inefficient design of such heat exchangers in the past has lead to low efficiency and heat exchange rate [11], and the conventional-scale experiments have not investigated the potential heat exchange rate achieved by DCHEX for LHS, despite the engineering significance of this rate. In the previous study [25,26], we studied the performance analysis of latent heat storage by DCHEX to achieve rapid latent heat storage. The study revealed latent heat can be rapidly stored under large flow rate and high inlet temperature of heat transfer medium in the DCHEX.

On the other hand, latent heat release and storage are different phenomena because the former is related to solidification of PCM and the latter is melting of PCM. Therefore, the present study investigated the characteristics of the latent heat release by DCHEX between erythritol as the PCM and a heat transfer oil (HTO) to achieve rapid latent heat release. We used a vertical cylinder with an inner diameter of 200 mm and a height of 1000 mm as the heat storage unit (HSU); a nozzle oriented vertically downward was set at the bottom of the unit, and the unit was filled with melting erythritol. We observed the effects of the flow rate of the HTO and the height of the PCM layer in the HSU on the characteristics of heat release, such as temperature effectiveness, heat release rate, and volumetric heat transfer coefficient. The results indicate techniques that can improve the heat release performance of DCHEX for LHS.

2. Materials and methods

2.1. Materials

Table 1 lists the thermophysical properties of erythritol as PCM and HTO. Erythritol has a high latent heat of 340 kJ/kg and a T_m of 391 K. Because of the high T_m of erythritol, it can be used as a heat source for various devices, such as adsorption chillers, steam generators, and solar cookers [27]. HTO was selected because of three features: safety, excellent chemical stability even after mixing with erythritol, and facile separation from erythritol.

2.2. Experimental setup and procedure

Fig. 1 shows a schematic of the experimental setup. It consisted of an HSU, a separator between the HTO and the PCM overflowing from the HSU, an HTO cooler, an HTO tank, an HTO heater, a flow meter, and a circulation pump. The details are as follows.

HSU; A stainless steel cylinder with an outer diameter of 204 mm, an inner diameter of 200 mm, and a height of 1000 mm was used. Two glass windows were used for observation, and six K-type thermocouples were installed for measuring local temperatures in the HSU. The HSU was thermally isolated with glass wool of 50 mm thickness. K-type thermocouples were installed at the inlet and outlet nozzles of the HSU for measuring the temperatures of the HTO flowing into and out of the HSU. In addition, six heat flow meters were set on the wall of the HSU at uniform intervals in the vertical direction for measuring the heat loss from the HSU wall. A ring-shaped injector, with nine holes positioned vertically downward, was placed 50 mm above the bottom of the HSU, and each hole had a diameter of 3.0 mm.

Separator between the PCM overflowing from the HTO outlet and the HTO; A stainless steel cylinder with an inner diameter of 160 mm and a height of 300 mm was used. The separator was placed adjacent to the HSU to prevent the PCM from overflowing toward the downstream of the separator.

HTO cooler; A tubular heat exchanger was used as a HTO cooler. The HTO cooler was connected with a chiller, and coolant water were circulated for cooling HTO.

HTO heater; A electro-thermal type heater was used as a HTO heater. Maximum heating capacity of the heater was 12 kW.

Flow meter; A rotary flow meter was used as a flow meter.

Circulation pump; A trochoid pump was used as a HTO circulation pump.

Table 1
Thermophysical properties of PCM and HTO used in this study.

Property	Erythritol	Heat transfer oil (HTO)
Latent heat [kJ/kg]	340	–
Melting point [K]	391	–
Density [kg/m^3]	1480 (at 293 K) 1300 (at 413 K)	780
Specific heat [kJ/kg K]	1.35 (at 293 K) 2.74 (at 413 K)	2.35
Viscosity [Pa s]	2.90×10^{-2} (at 393 K) 1.60×10^{-2} (at 413 K)	6.53×10^{-3}(at 363 K)