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A combined experimental and simulation study on charging process of Erythritol–HTO direct-blending based energy storage system

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ABSTRACT

Thermal energy storage (TES) system is essential to recover and use intermittent heat, such as industrial waste/excess heat or solar energy. In this paper, a direct-contact erythritol/heat transfer oil (HTO) energy storage system has been studied experimentally, consisting of a thermal energy storage unit, electrical heaters, heat exchanger and water cycle. In the system, erythritol has been used as an energy storage media (melting point = 118 °C, heat enthalpy = 330 kJ/kg), and HTO is used as a heat transfer material. Moreover, simulation has been conducted to understand heat transfer enhancement mechanisms of direct-contact heat storage. It is noticed that, at the beginning of heat storage, heat transfer oil has a small flow rate due to the block of solid part. PCM in the middle area of the storage unit melts faster than other parts due to the greater heat transfer on the liquid–solid interface of the both sides, and erythritol attached on the storage unit wall melts slowly since small heat conductivity plays a key role for heat transfer. It is also found that increasing the flow rate of HTO can significantly decrease the melting time by increasing fluid turbulent degree.

1. Introduction

The energy usage for total residential and service sector accounts for 35.3% of the total global energy consumption, of which 75% is used for space and domestic water heating purpose [1–3]. This part heat mostly comes from coal/oil combustion or electricity heaters, resulting in environmental and low energy-utilization-efficiency consideration [4,5]. Meanwhile, a large amount of low-grade heat are produced from various industrial processes, most of which directly are rejected to the closed-by environment, which increases the surrounding temperature. For industrial heat recovery, most work has been done to use heat on-site to improve system efficiency, which focuses on the medium/high-temperature heat extracting integration. However, low grade industrial heat recovery draws less attention due to its low temperature and intermittent features. Hence, it is constructive to bridge the gap between intermittent heat utilization and residential heat demand from the viewpoints of environment and economy. Facing to the major challenges of the mismatch between heat source and end users, thermal energy storage technology has been considered as a potential way, and most work has been done including the development of energy materials, specific storage components and system design. Recently, we proposed an alternative flexible heat transporting system, called 'mobilized thermal energy storage system (M-TES)' for industry heat recovery for heat distribution instead of transporting heat by district heating (DH) networks [6–8], due to its unsatisfied economic benefits for low-density heat supply regarding the infrastructure construction investment [9–11].

In this heat storage and transport system, the performance of energy storage units decides the energy-utilization efficiency of entire systems. It is of importance to improve heat storage processes in order to achieve a low cost for storage systems by decreasing storage time and enlarging heat storage capacity. Over three decades, most efforts have been done to increase the storage efficiency, such as solid–solid energy storage materials [12–15], encapsulation [16–18] and metal matrix [19–21]. Consequently, energy utilization and heat transfer have been improved based on indirect-contact storage systems, where heat is transferred through a built-in tube- and shell-heat exchanger between storage materials and heat transfer media [22,23]. Recently, some direct-contact heat transfer and storage system has been put forwards as an alternative construction to improve the energy efficiency of storage units, in which the PCM mixes with the heat transfer media

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Nomenclature

CFD	computational fluid dynamics
DH	district heating
HTO	heat transfer oil
LTES	latent thermal energy storage
M-TES	mobilized thermal energy storage
PCM	phase change materials
TES	thermal energy storage

Symbols

ρ_{oil}	fluid density of HTO (kg/m^3)
λ_{oil}	thermal conductivity of HTO (W/m K)
μ_{oil}	dynamic viscosity of HTO
$c_{p,oil}$	specific heat of the HTO (kJ/kg K)
ρ_{pcm}	density of PCM (kg/m^3)
λ_{pcm}	thermal conductivity of PCM (W/m K)
μ_{pcm}	dynamic viscosity of PCM
h	enthalpy of PCM (kJ/kg)
$h_{sensible}$	sensible heat of PCM (kJ/kg)
L	latent heat of PCM (kJ/kg)
β	melted mass fraction of PCM
A_{mush}	mushy zone constant
η	heat utilization ratio
F_{oil}	volumetric flow rate of thermal oil (m^3/h)

directly, including water/paraffin TES cooling system, water/concrete system, etc. [24–26]. To our best knowledge, there are still quite few reports and studies regarding this direct-contact storage system performance. Especially, the mechanism of heat transfer on this structure is lack of study.

The purpose of this paper is to investigate the performance and phase change behavior of PCM in the direct-contact structure of energy storage units, focusing on the contributions of the structure to heat transfer and heat storage efficiency under various conditions. Moreover, the heat transfer mechanism by using CFD simulation is further carried out to seek for the structure–performance relationship.

2. Methodology

2.1. Experimental

Fig. 1 shows the parts of TES system during the construction, including a storage unit, oil boiler, oil pump, water pump, heat exchanger, etc. The direct-contact storage unit is the major unit with the dimension of 200 mm of length and 800 mm of diameter. There are two inlet pipes with five holes on the bottom surface, located at 60 mm above the TES storage unit bottom. The third pipe with three holes on the top surface, working as an outlet channel, is installed 60 mm below the top of TES storage unit. The phase change materials and heat transfer oil are packed inside, taking up 50% of the entire storage unit volume, respectively.

The detailed location of thermocouples and the sketch of the TES system can be seen in Fig. 2. In the system, an electrical boiler is used to heat HTO to 140 °C before pumping HTO into the storage unit to heat materials inside, and HTO flows in and out via the bottom/top pipes in the container. In the cooling process, the heat in the storage unit can be transferred to water cycles through the plate heat exchanger. In the experiments, the phase change behavior of PCMs is investigated in the Erythritol–HTO direct-blending based energy storage system. The effects of the different HTO flow rates (0.5, 0.96, and 1.26 m^3/h) on melting processes in the direct-contact storage unit have been discussed.

2.2. Simulation

2.2.1. Modeling

A two-dimensional CFD model using commercial software of ANSYS FLUENT is built to analyze the melting behavior of the PCM in the direct-contact storage unit, as illustrated in Fig. 2. According to experimental results, the model has been simplified by ignoring the melting behavior difference in the axial direction. The PCM below the inlets on the bottom is neglected due to its little stored thermal energy and the inlet pipes are replaced by two edges avoiding using the complicated mesh for the bottom pipes.

The mesh is created by the commercial pre-processor GAMBIT 2.3.16 (shown in Fig. 3). To obtain a high quality mesh, the computational domain is divided into three zones, and the boundary between zones is set as interior. The central zone is structured by quadrilateral mesh, while the rest uses unstructured quadrilateral mesh. To check the grid independence, several mesh distributions have been tested and the maximum discrepancies are less than 1.2%. By comparison, the mesh including 5518 elements is chosen to carry out for the melting simulation.

2.2.2. Governing equations

The heat transfer fluid (HTF) is thermal oil, and a forced convection Newtonian laminar flow with the conservation equations of mass, momentum and energy are given by:

$$\frac{\partial \rho_{oil}}{\partial t} + \rho_{oil}\frac{\partial u_k}{\partial x_k} = 0 \tag{1}$$

$$\rho_{oil}\frac{Du_j}{Dt} = \mu_{oil}\frac{\partial^2 u_j}{\partial x_i^2} - \frac{\partial p}{\partial x_j} + \rho_{oil} g_j \tag{2}$$

$$\rho_{oil} c_{p,oil}\frac{DT}{Dt} = \frac{Dp}{Dt} + \lambda_{oil}\frac{\partial^2 T}{\partial x_j^2} + \mu_{oil}\left(\frac{\partial u_j}{\partial x_j}\right)^2 + \frac{\mu_{oil}}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 \tag{3}$$

where ρ_{oil} is the fluid density of the HTO, λ_{oil} is the thermal conductivity of the HTO, μ_{oil} is the dynamic viscosity of the HTO, $c_{p,oil}$ is the specific heat of the HTO, p is the pressure, u is the fluid velocity and T is the temperature.

From the storage aspect, fluid flow, heat transfer and phase change processes of the PCM are also taken into consideration. The governing equations are given by:

$$\frac{\partial \rho_{pcm}}{\partial t} + \frac{\partial(\rho_{pcm} u_k)}{\partial x_k} = 0 \tag{4}$$

$$\rho_{pcm}\frac{Du_j}{Dt} = \frac{\partial}{\partial x_j}\left(\mu_{pcm}\frac{\partial u_k}{\partial x_k}\right) + \frac{\partial}{\partial x_i}\left[\mu_{pcm}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial p}{\partial x_j} + \rho_{pcm} g_j + S \tag{5}$$

$$\rho_{pcm}\frac{Dh}{Dt} = \frac{Dp}{Dt} + \frac{\partial}{\partial x_j}\left(\lambda_{pcm}\frac{\partial T}{\partial x_j}\right) + \mu_{pcm}\left(\frac{\partial u_j}{\partial x_j}\right)^2 + \frac{\mu_{pcm}}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 \tag{6}$$

where ρ_{pcm} is the density of the PCM, λ_{pcm} is the thermal conductivity of the PCM and μ_{pcm} is the dynamic viscosity of the PCM.