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Numerical simulation study on discharging process of the direct-contact phase change energy storage system

Weilong Wang[a], Hailong Li[b], Shaopeng Guo[c], Shiquan He[d,*], Jing Ding[a], Jinyue Yan[b,e,*], Jianping Yang[f]

[a] School of Engineering, Sun Yat-sen University, Guangzhou, China
[b] School of Business, Society and Energy, Mälardalen University, Västerås, Sweden
[c] School of Energy and Environment, Inner Mongolia University of Science and Technology, Baotou, China
[d] Academy of Building Energy Efficiency of Guangzhou University, Guangzhou, China
[e] Energy Process Division, Royal Institute of Technology, Stockholm, Sweden
[f] School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou, China

HIGHLIGHTS

- Discharging process of the direct-contact TES container are studied experimentally.
- Direct-contact solidification process are modeled and simulated by CFD.
- Effects of HTO flow rate and inlet temperature on solidification rate of PCM are clarified.

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ABSTRACT

The mobilized thermal energy storage system (M-TES) has been demonstrated as a promising technology to supply heat using waste heat in industries to distributed users, where heat discharging determines whether M-TES system can satisfy the required heating rate. The objective of this work is to investigate the solidification mechanism of phase change materials (PCM) for heat discharging in a direct-contact thermal energy storage (TES) container for M-TES. A 2-dimensional (2D) numerical simulation model of the TES tank is developed in ANSYS FLUENT, and validated with the experimental measurement. Effects of flow rate and inlet temperature of heat transfer oil (HTO) were studied. Results show that (a) the discharging process includes the formation of solidified PCM followed by the sinking of solidified PCM; (b) the discharging time of M-TES can be reduced by increasing the flow rate of heat transfer oil. When the flow rate is increased from 0.46 m^3/h to 0.92 m^3/h, the solidified PCM is increased from 25 vol.% to 90 vol.% within 30 min; (c) the discharging time can be reduced by decreasing the inlet temperature of HTO. While the inlet temperature is reduced from 50 °C to 30 °C, the solidified PCM is increased from 60 vol.% to 90 vol.% within 30 min. This work provides engineering insights for the rational design of discharging process for M-TES system.

1. Introduction

Enormous amount of low-temperature heat produced in industrial process is rejected to ambient surrounding directly without further usage [1]. The district heating (DH) network provides a viable path to deliver such kind of excess heat to cover daily heat consumption in residential sectors [2–4]. However, building a DH is not always cost-efficient due to tremendous investments on pipeline construction, especially when the local heat demand is small [5,6]. As an alternative, mobilized thermal energy storage (M-TES) system, supplying heat by thermal energy storage (TES) container in a truck, has been proposed as a new energy transportation system, in which high energy–density TES technology is the key factor for system's energy-utilization efficiency [7–9].

Two kinds of M-TES system using a direct- /indirect- contact TES container have been built in Yan's laboratory to test their energy transfer and storage performance [10–13]. Till now, for indirect-contact TES container in M-TES system, studies have been carried out on developing effective TES materials, as well as enhanced heat transfer from the aspects of both TES container

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[*] Corresponding authors at: School of Business, Society and Energy, Mälardalen University, Västerås, Sweden (J. Yan), Academy of Building Energy Efficiency of Guangzhou University, Guangzhou, China (S. He).

E-mail addresses: heshiq@mail2.sysu.edu.cn (S. He), jinyue.yan@mdh.se (J. Yan).

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Nomenclature

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
VOF	volume of fluid

Symbols

α_i	volume fraction of HTO
$\underline{p}$	pressure
$\underset{\rightharpoonup}{g}$	gravitational acceleration
H	enthalpy
S	energy source term
$\dot{m}_{j\to i}$	rate of mass transfer
T_{sat}	freezing point of PCM
Q_r	heat release capacity
m_{PCM}	mass of PCM
m_{oil}	mass of HTO
T_0	initial temperature
$\backslash\rho_{oil}$	fluid density of HTO
λ_{oil}	thermal conductivity of HTO
μ_{oil}	dynamic viscosity of HTO
$c_{p,oil}$	specific heat of the HTO
ρ_{pcm}	density of PCM
λ_{pcm}	thermal conductivity of PCM
μ_{pcm}	dynamic viscosity of PCM
$h_{sensible}$	sensible heat of PCM
L	latent heat of PCM
β	melted mass fraction of PCM
A_{mush}	mushy zone constant.
η	heat utilization ratio
$\underline{F}_{oil}$	volumetric flow rate of HTO
$\underline{v}$	velocity

structure and materials. By comparison, the direct-contact TES container shows higher efficiency with larger energy storage capacity and shorter charging and discharging time needed. In Yan's latest work, the charging process has been simulated to understand the melting behavior of phase change material (PCM) and heat and mass transfer mechanism in the direct-contact TES container [14]. In contrast, discharging process of direct-contact TES system has not been fully understood, which is essential for the optimization of the M-TES system. However, to our best knowledge, due to its complicated mass and heat transfer process [15], few experimental and simulation works have been carried out on the direct-contact discharging process.

Herein, the solidification mechanism of PCM for heat discharging in a direct-contact container for M-TES has been studied in this work. A 2-dimensional numerical simulation model for the discharging process of the direct-contact TES system is developed in ANSYS FLUENT, and verified by the experimental data. With the verified model, the effects of the heat transfer oil (HTO) flow rate and inlet temperature on the discharging time and phase change behavior of the PCM are investigated. The results provide insights and guidelines for the rational design and optimization of the direct-contact M-TES system.

2. Experiments

Lab-scale M-TES system with the direct-contact TES container was constructed in the lab, as shown in Fig. 1. The direct-contact container is composed of a cylinder tank. The diameter and length of the tank are 800 mm and 200 mm, respectively. There are two pipes with five holes downwards located at 60 mm above the bottom of the container and one pipe with three holes upwards located at 60 mm below the top of container. Initially, the container is filled with erythritol and HTO (each for 50 vol.%, respectively).

An electrical boiler serves as a heat source and tap water is used as a cooling sink. Ten thermocouples are mounted on the TES container and pipes, as shown in Fig 2. During the heat charging process, HTO was heated by an electrical boiler to 140 °C, and pumped into the TES container through the two bottom pipes. Due to different densities, HTO and erythritol can be easily separated in the tank, where HTO moves out of the container through the top pipe. During the heat discharging process, HTO was cooled by the tap water to around 30 °C, and reheated by the TES container. HTO flow rate was measured by a turbine flow meter with a range of 0.6–6.0 m^3/h (uncertainty of 0.5%). Temperature changes during the experiments were measured using K-type thermocouples with the uncertainty of 0.5 K.

3. Simulation model

Since considering simulation with three-dimensional model is time-consuming, a two-dimensional model is developed to compute the solidification process of the PCM. To obtain a high quality mesh, the ideal model is developed ignoring the small amount (about 1.5 vol.%) of PCM below the inlet pipes, which has a negligible effect on the discharging process. Inlets of HTO are simplified to two edges below two tubes.

4. Governing equations

The volume of fluid (VOF) model is employed to simulate the discharging process. Fluid flow and convective heat transfer are taken into consideration in the HTF. Instead of using a melting

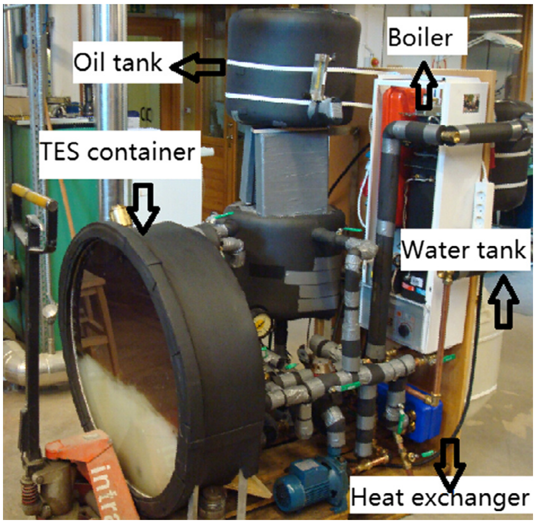

Fig. 1. The photo of the direct-contact container system.