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Experimental and numerical investigation of discharging process of direct contact thermal energy storage for use in conventional air-conditioning systems

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HIGHLIGHTS

- The discharging process of a direct contact TES system with a new PCM is modeled.
- Effects of HTF flow rate and inlet temperature on discharging process are clarified.
- A novel PCM with higher latent heat for conventional air-conditioning system is prepared.
- An experimental direct-contact TES system is designed and built.
- Good agreement is observed between simulation results and experimental data.

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ABSTRACT

Direct contact thermal energy storage (TES) for use in conventional air-conditioning systems is proposed to reduce the operational energy demand. Thermal performance of a novel kind of phase change material (PCM) prepared for use in conventional air-conditioning systems with the proposed direct contact TES tank, is evaluated. A 3-dimensional (3D) numerical model is built using ANSYS FLUENT to investigate dynamic characteristics of the discharging process of TES system. The model is validated by comparing the numerical with the experimental results. The effects of heat transfer fluid (HTF) flow rate, HTF inlet temperature, liquid PCM volume fraction, complete discharging time, discharging capacity of the tank, and temperature distribution in direct contact TES tank are investigated. The results indicate that increasing the HTF flow rate speeds up the discharging capacity and the discharging time of the direct contact TES system reduces. When the flow rate increases from 0.503 m^3/h to 0.936 m^3/h, the melting PCM increases from 63.33 vol.% to 70.74 vol.% within 600 s. The discharging capacity increases with HTF inlet temperature; however, the whole discharging capacity does not change obviously by changing HTF inlet temperature.

1. Introduction

At present, conventional central air-conditioning system of commercial building consumes about 50% of electrical demand, which leads to high electricity costs. Air-conditioning using TES is currently seen as a way to solve this problem. Studies on ice-based TES air-conditioning systems using cheaper electric power at night have been carried out [1–3]. However, the low melting point of ice leads to the evaporation temperature of the chiller and the coefficient of performance (COP) much lower than in conventional air-conditioning. Therefore, a novel PCM having a melting point temperature higher than that of ice, has been used in indirect-contact TES tank filled with spherical capsules [4]. In indirect-contact TES systems, heat flows through a heat transfer wall set between the HTF and the PCM increasing the thermal resistance of the system, thus the time to complete the charging and discharging process of the TES system increases [5,6]. Contrary to the indirect-contact TES system, the direct-contact heat transfer and storage system has a larger heat transfer area, in which the PCM directly mixes with a heat transfer media, such as water/paraffin and water/concrete. Therefore, direct-contact TES system with appropriate PCM has higher efficiency and greater energy storage capacity [7–9].

Direct contact TES systems have received increasing attention for many applications such as solar thermal energy storage [10],

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Nomenclature

Abbreviation

HTF	heat transfer fluid
PCM	phase change material
TES	thermal energy storage
VOF	volume of fluid
DSC	differential scanning calorimeter

Symbols

T	temperature (°C)
k	thermal conductivity (W/m °C)
L	PCM latent heat (kJ/kg)
c_p	constant-pressure specific heat (kJ/kg °C)
t	time (s)
v	velocity (m/s)
H	enthalpy (kJ)
h	sensible enthalpy (kJ)
$T_{solidus}$	solidus temperature (°C)
$T_{liquidus}$	liquidus temperature (°C)
p	pressure (N/m^2)
A_{mush}	mushy zone constant
S	source term
g	gravity vector (m/s^2)
Q_{PCM}	cool release capacity of the PCM (kJ)
M	mass (kg)
Q	discharging capacity of the TES system (kJ)
W	flow rate (kg/s)

Greek symbols

ρ	density (kg /m^3)
α	volume fraction
β	liquid fraction
μ	dynamic viscosity coefficient (N/m^2 s)

Subscripts

m	melting point
l	liquid
s	solid
a	phase a
b	phase b
ref	reference value
in	inlet
out	outlet
max	maximum
ini	initial

solar heating system [11], water desalination [12], latent heat energy storage system [13], and waste heat recovery systems [14]. The heat transfer in the storage system determines the thermal storage characteristic of such systems. Several experimental and simulation studies have investigated the thermal performance of direct contact TES systems [15,16]. Kaizawa et al. [17] carried out lab-scale experiments on heat release and storage using PCM (erythritol) and investigated thermal and flow behaviors in a heat transportation container. The studies have shown that the design of container's shape (i.e. the nozzle angle, the position and the number of inlet pipes) can affect both the heat transfer rate and heat storage capacity. However, these studies [15–17] did not provide a further discussion on heat-storage performances of direct-contact heat transfer for latent heat storage (LHS). To examine the performance of the direct-contact heat transfer in LHS, Lemenand et al. [18] investigated the axial evolution of the temperature for different conditions in a high-efficiency vortex (HEV) static mixer using a one-dimensional model. The group also validated the model experimentally. The study found that the vortex pairs were very efficient for heat and mass transfer and the HEV direct-contact heat exchanger (DCHE) showed the best heat transfer performance. Wang et al. [19] developed a 2-dimensional numerical simulation model of the direct-contact TES tank using ANSYS FLUENT. The solidification behavior of the PCM for discharging process in the direct-contact TES system was simulated and further verified through comparison with experimental data. The study showed that the HTO flow rate and inlet temperature affected the performance of direct-contact TES container, which provides guidelines for M-TES system improvement and rational design. According to the present literature, charging and discharging processes improvement is a key issue to be solved for the development of TES system to achieve low operation costs. A 3D numerical simulation model is suggested for future study by Ref. [20] because the simulated results based on a 2D model can neither show the complete discharging time nor the melting differences exactly [21]. In our previous study [22], the charging process of direct contact TES was investigated, but the discharging process, which is important for the performance of the TES system, has not been fully understood. Especially, a 3D analysis on the discharging process of the direct contact LHS system with multiple nozzles has not been deeply investigated and few studies have dealt with. In addition, a PCM with higher latent heat and higher melting point temperature, which increases discharging capacity and COP and reduces cost of such a system, is still needed. Therefore, the present investigation was undertaken.

In this article, a novel PCM (melting point temperature = 6.7 °C) with higher latent heat fitted to conventional central air-conditioning systems is studied. More specifically, the system is fitted with a direct contact TES tank with multiple nozzles, in which the PCM and HTF transfer heat directly. A 3D simulation model on the discharging process of the direct-contact TES is developed using ANSYS FLUENT. The simulation results are compared with those of the experimental measurements. The performance of PCM and the heat transfer mechanism of discharging process are studied. The effects of HTF inlet temperature, HTF flow rate, complete discharging time, discharging capacity, and temperature distribution of TES tank are investigated with respect to the discharging process. The results provide guidelines for the design and optimization of direct contact TES tank for use in conventional air-conditioning systems.

2. Thermal properties of the novel PCM

A novel PCM (HS-C2) was developed for use in direct contact TES of conventional air-conditioning systems. Its thermal properties were determined using DSC measurements of heating and cooling cycles. Before measurements, a calibration of the system (i.e. sensitivity and temperature) is required. The sensitivity calibration consists of a baseline run and a calibration run. The calibration measurement was run on a sapphire standard. Measurement acquired the sapphire and the baseline heat flow curves to determine the accuracy of the instrument for the whole measuring range. Indium was the calibration reference material. Its phase change temperature is 156.5 °C (standard value 156.6 °C, deviation 0.1 °C), Indium latent heat is 28.58 kJ/kg (standard value 28.6 kJ/kg,