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Research paper

Investigation on the dynamic characteristics of a direct contact thermal energy storage charging process for use in conventional air-conditioning systems

Xiao-Yan Li*, Qiao-Qiao Zhao, Dong-Qi Qu

School of Energy and Building Engineering, Harbin University of Commerce, No. 1 Xuehai Street, Songbei District Harbin, Heilongjiang 150028, China

HIGHLIGHTS

- A charging process model of a direct contact TES system with a PCM is developed.
- The dynamic characteristics of a new direct contact TES system are presented.
- Investigating different conditions to shorten the charging time of the TES system.
- A novel PCM for use in a direct contact TES air-conditioning system is prepared.
- PCM properties experimentally validated on a new direct contact cold storage system.

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ABSTRACT

This study proposes a 3-dimensional (3D) mathematical model to simulate the heat transfer process in a direct contact latent heat thermal energy storage (TES) tank for conventional air-conditioning systems. The thermal performance, including the congealing point and congealing latent heat of a new phase change material (PCM), which is developed for use in conventional air-conditioning systems with a direct contact TES tank, is studied. To improve the charging performance of direct contact TES system and further understand the freezing process, a 3D numerical model was developed in ANSYS FLUENT. The volume of fluid (VOF) method tracked the volume fraction of each of the phases. The Navier-Stokes equations were solved using a finite-volume formulation, and energy equation was modeled by using an enthalpy-based formulation. The method provided a comprehensive model of the dynamic and thermal aspects of the impact process. To validate the analytical model an experimental cool storage air-conditioning system with a direct contact TES tank was designed and setup. The effects of the heat transfer fluid (HTF) inlet temperature, the flow rate of the liquid PCM, the complete charging time, cold storage capacity of the direct contact storage tank and distribution of temperature in the direct contact cold storage device were investigated. The results indicate that the charging capacity increases more rapidly when the PCM flow rate is greater. The complete charging time can be reduced by increasing the flow rate of the liquid PCM and decreasing inlet temperature of the HTF when charging the same quality of PCM. The charging capacity is larger with a lower HTF inlet temperature, however, changing the HTF inlet temperature does not appreciably change the total storage capacity.

1. Introduction

The extensive use of conventional central air-conditioning systems leads to high electrical costs. To overcome this problem, air conditioning using ice-based thermal energy storage has been considered. During off-peak electrical load periods, ice forms in a storage tank; then, during on-peak electrical load periods, the circulation of cool water from the storage tank is used for air-conditioning purposes, effectively shifting the on-peak demand to the off-peak periods and taking advantage of the lower off-peak electricity rates [1]. However, ice-based thermal energy storage air-conditioning uses low freezing point water, which makes the evaporation temperature of the chiller, the coefficient of performance, and the cold storage capacity significantly lower than those

* Corresponding author. Tel.: +86 18645042691.
E-mail address: mylxy6168@sina.com (X.-Y. Li).

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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
g	gravity vector (m/s^2)
Q_{PCM}	cool storage capacity of the PCM (kJ)
M	mass (kg)
Q	charging capacity of the TES system (kJ)
W	flow rate (m^3/s)
$T_{initial}$	initial temperature of HTF in the storage tank (°C)
Greek symbols	
ρ	density (kg/m^3)
α	volume fraction
β	liquid fraction
μ	dynamic viscosity coefficient (N/m^{2}s)
Subscripts	
c	congealing point
l	liquid
s	solid
q	phase q
p	phase p
ref	reference value
in	inlet
out	outlet
min	minimum

of conventional air-conditioning systems. Therefore, an appropriate phase change material (PCM) whose melting point is higher than ice should be identified. Li et al. investigated a PCM fitted to a conventional air-conditioning system, fitted with a latent heat thermal storage tank filled with spherical capsules containing the PCM [2]. Hosseinizadeh et al. conducted numerical investigations of unconstrained melting of nano-enhanced phase change materials (NEPCM) inside a spherical container [3]. However, in a capsule-type latent heat thermal energy storage system, heat flows through the capsule wall from heat transfer fluid (HTF) to PCM; the completion of latent-heat energy storage takes long time and the size of the heat energy storage tank increases. However, a direct contact thermal energy storage system has many advantages [4]: because of its large heat transfer area, large thermal storage density, and negligible thermal resistance without a heat transfer wall, heat exchange is more rapid than that of indirect-contact heat exchanger [5].

Direct contact thermal energy storage can apply to various fields, such as solar thermal energy storage [6], waste heat recovery systems [7], water desalination [8] and latent heat cold energy storage [9]. The heat transfer inside the direct contact storage tank determines the thermal performance of these systems. Nomura et al. investigated the characteristics of latent heat release and storage by a direct contact heat exchanger using erythritol (melting point = 118 °C) as PCM. They also reported that the heat storage rate accelerates with increasing the flow rate and inlet temperature of the heat transfer oil [10,11]. Gulawani et al. investigated the heat transfer performance of direct contact steam condensation using both engineering fluid dynamics and computational fluid dynamics (CFD) approaches. The results show that the longitudinal and transverse velocity increases with increasing upstream nozzle pressure and initial bath temperature [12]. Several studies reported on heat transfer characteristics during the formation of ice slurry by direct contact heat transfer between two immiscible liquids used in ice thermal energy storage [13–16]. Inaba et al. studied the performance of a direct contact heat exchanger in which the formed droplets freeze by injecting tetradecane oil from a single-hole nozzle into cold water solution and establish the non-dimensional empirical equations to predict the solidification fraction [17]. Mahood et al. investigated numerically and analytically the temperature distribution prediction of a three-phase bubble-type direct-contact condenser, using the analytical model based on the one-dimensional mass and energy equations [18]. Guo et al. developed a 2-dimensional (2D) numerical simulation model of the direct contact thermal energy storage container using ANSYS FLUENT, simulating the blocking in charging process by a 'two-stage' simulation strategy and validated the model experimentally [19]. According to presented literature, the 2D model may have some limitations for the charging problem when compared to 3-dimensional (3D) analysis, and the 3D case can be considered as higher fidelity simulation. However, few studies have investigated a 3D analysis on the dynamic characteristics of the direct contact latent heat storage system with multiple nozzles. Therefore, the present computational study was undertaken.

In this paper, we study a PCM fitted to a conventional air-conditioning system. The system was fitted with a direct contact latent heat thermal energy storage (TES) tank with multiple nozzles, in which there was a direct contact heat transfer between the liquid PCM and the HTF. We developed a 3D numerical model simulating the charging process of the direct-contact TES system using ANSYS FLUENT, and verified it by experimental test. The effects of the HTF inlet temperature, the flow rate of the liquid PCM, the complete charging time, the cold storage capacity of the direct contact storage tank, and the distribution of temperature in the direct contact cold storage device were investigated both numerically and experimentally, with respect to the charging processes.

2. Thermal performance of a new PCM

We developed a new organic PCM (HS-E2) for use in conventional air conditioning systems using direct contact thermal energy storage, and we investigated its thermal performance. Meanwhile, we also measured the thermal properties of the new organic PCM with a differential scanning calorimeter (DSC). Before the DSC measurements, we investigated the temperature and sensitivity calibration. Calibration material is Indium. The phase change