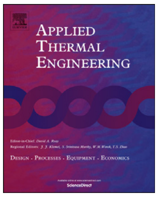
Applied Thermal Engineering 91 (2015) 547–555

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Research paper

Visualization of the phase change behavior of sodium acetate trihydrate for latent heat storage

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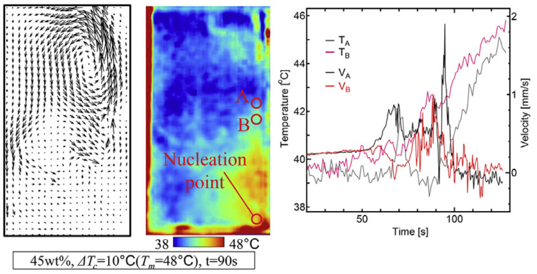
HIGHLIGHTS

- The velocity and temperature during the solidification of a PCM were visualized.
- The temperature around crystals was lower than the melting point with the convection.
- The temperature increased to the melting point after the solidification.
- Solution flow into the needle-shaped crystals was observed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 June 2015
Accepted 18 August 2015
Available online 29 August 2015

Keywords:
Phase change
Latent heat
Visualization
Temperature
Velocity
Sodium acetate trihydrate

ABSTRACT

A latent heat storage system has higher storage capacity than a sensible heat storage system. Sodium acetate trihydrate has large latent heat at its melting point of 58 °C, which is suitable for a hot-water supply system. The crystal growth rate, convective flow and temperature fields during the phase change of sodium acetate trihydrate were quantitatively visualized using PIV analysis with temperature sensitive particles (TSPs) which has enabled a simultaneous measurement of the velocity and temperature fields. The velocity field was obtained by the PIV analysis of TSPs and the temperature field was simultaneously visualized from the intensity decay of TSPs. The visualized temperature of the solid–liquid multiphase flow increased slowly as crystals grew. The temperature around the crystal was lower than the melting temperature during the phase change process with the convection because the crystal was needle-shaped and a liquid phase was also present between crystals. After the convective velocity rapidly decreased due to the solidification, the temperature started to increase to around the melting point. Buoyancy-driven convection occurred under certain conditions of supercooling temperature and concentration of sodium acetate trihydrate. However, convection could not be fully developed over a certain range of concentration and supercooling temperature because the crystal growth rate was too fast and solidification was completed quickly.

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1. Introduction

The development of thermal energy storage will play an important role in the conservation of energy and optimization of its utilization. Many kinds of cogeneration systems have been reported. There are three types of storage system with different

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http://dx.doi.org/10.1016/j.applthermaleng.2015.08.056
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mechanisms that are generally employed; sensible, latent and thermochemical storage. Latent storage uses a phase change material (PCM) and promises high thermal efficiency, high storage capacity and density, and almost constant thermal energy compared with a sensible storage system. In addition, this system has a simpler structure than a thermochemical storage system. Latent storage systems are used in various applications, such as thermal storage in building structures, household hot water supply systems, domestic space heating and air conditioning, and absorption refrigeration.

PCMs are classified into organic materials (paraffins, fatty acids, etc.) and inorganic materials (salt hydrates, metals, etc.), each of which have several advantages and disadvantages. It is necessary to select an appropriate PCM from several materials for a particular system. Liu et al. [1], and Karthikeyan and Ramachandran [2] have recently reviewed and summarized the thermal properties of PCMs.

In the present study, sodium acetate trihydrate is selected as the PCM for use in a household hot water supply system or an indoor heating system. Sodium acetate trihydrate has a large latent heat (264 kJ/kg) with a melting point of 58 °C; however, it has several problems for such applications, such as a large degree of supercooling and phase segregation. Therefore, many studies have focused on the nucleation agents and the use of thickeners [3–6]. The addition of nucleation agents and thickeners often lowers the storage capacity. However, adding a small amount of carboxymethyl cellulose could keep the storage capacity high enough [3,4] without the phase segregation.

There have been many studies on the improvement of heat exchange to achieve an efficient charge and flexible discharge of thermal energy during the solidification and melting processes [7–9]. The heat transfer performance between PCMs and their containers has been extensively studied [10,11]. There have also been many visualization studies on the phase change behavior. Y. Du et al. [12] experimentally visualized the boundary of liquid–solid phase by a CCD camera and compared with numerical result. H. Shokouhmand et al. [13] and B. Kamkari et al. [14] visualized a melting process of PCM in rectangular enclosure with and without fins. The temperature distribution was measured by thermocouple and the boundary of phase was pictured. Y.K. Oh et al. [15] measured temperature distribution at a wall of PCM container using an infrared thermal camera. All these researches insisted that the temperature change and crystal growth in the PCM container had an important role for the convection. These studies have indicated that the natural convection plays an important role in heat transfer inside the PCM container. Therefore, the occurrence of natural convective heat transfer during a phase change should be taken into account. Different latent storage system geometries must be tested and optimized individually, although it takes a long time to develop and optimize a system. However, the boundary of solid phase at the wall was the only information experimentally visualizable in previous researches [12–15].

It is very important to understand the heat and fluid flow and to verify the numerical simulation code for the design of a latent heat storage system. The quantitative visualization of natural convection during the phase change of a PCM may be helpful for these purposes. The temperature distribution, natural convection of the liquid phase and the crystallization process are important for developing and controlling PCM applications. The relationships among the phase change process, temperature and velocity fields may be strongly related to the supercooling temperature and the concentration of solution, especially in the case of hydrated salts such as sodium acetate trihydrate.

Particle image velocimetry (PIV) is a useful tool for measuring the velocity field in a single-phase flow, while measurement of that in a multiphase flow is not easily achieved. The temperature of a PCM could be measured with a thermocouple at a certain point; however, it does not provide information on the entire field. An infrared camera can be used to capture temperature two-dimensionally; however, it measures only the surface temperature. It is difficult to measure temperature two-dimensionally in a multiphase flow. Particle-based visualization methods such as the PIV have rarely been applied to measure velocity during a phase change, especially for that of a supercooled PCM solution during the phase change. It has been considered that the particles could influence the release of a supercooling state. Therefore, there is very little data regarding the temperature and velocity field of PCM solutions during a phase change.

In the present study, PIV analysis was conducted using temperature sensitive particles (TSPs) [16–19] for the simultaneous visualization of the temperature and velocity fields in order to investigate thermal convection during solidification of a sodium acetate trihydrate solution. The TSPs do not affect the release of the supercooling state. The convection, temperature distribution and crystal growth rate for a PCM in a rectangular container were investigated, and the transient velocity and temperature were measured during solidification.

2. Experimentation

2.1. Phase change material

Sodium acetate trihydrate ($CH_3COONa \cdot 3H_2O$) with a large latent heat and the melting point T_m, of 58 °C was selected as the PCM. The thermophysical properties of sodium acetate trihydrate at 61 °C as given by the supplier (Wako Chemical Co. Ltd.) and from the literature [20] are listed in Table 1. The concentration of saturated sodium acetate trihydrate solution is 60.3 wt%, which was adjusted to 45 wt% ($T_m = 48$ °C), 50 wt% ($T_m = 54$ °C) and 55 wt% ($T_m = 57$ °C) for the present experiments. No viscosity bodying agent was added to the solutions and sodium acetate anhydrate was not generated during the experiments.

TSPs (15 μm diameter) were dispersed into the solutions for temperature and velocity measurements. The method for the fabrication of the TSPs was as follows. Dried adsorbent particles (MCIGEL, Mitsubishi Chemical Co. Ltd.) were added to an ethanol solution of the dye europium(III) thenoyltrifluoroacetonate, trihydrate (EuTTA; $C_{24}H_{12}EuF_9O_6S_3 \cdot 3H_2O$, 95%, formula weight: 869.54, Acros Organics). The dyed particles were then removed from the solution and sintered at 100 °C for 8 h. The melting points of EuTTA and the adsorbent particles were 142 and 130 °C, respectively. EuTTA is insoluble in water.

The influence of the TSPs on the nucleation of sodium acetate trihydrate in solution was investigated. Particles or other impurities are sometimes considered to influence the nucleation of crystals and the stability of supercooled solutions. However, the addition of TSPs did not affect the nucleation of crystal growth or the supercooling stability of sodium acetate trihydrate in solution. No crystal growth from the particles was observed. The solution with TSPs could be kept in a stable supercooled state at 10 °C for several days.

Table 1
Thermophysical properties of sodium acetate trihydrate.

Thermophysical property	Value ($T = 61$ °C)
Density, ρ [kg/m^3]	1287
Viscosity, μ [mPa s]	7.49
Kinematic viscosity, ν [mm^2/s]	5.81
Specific heat, C_p [J/(kg K)]	2998.3
Thermal conductivity, λ [W/(m K)]	0.416

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