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Transient thermal response of a PCS heat storage system

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ABSTRACT

Over the last years the use of phase change slurries (PCSs) based on microencapsulated phase change material (MEPCM) increased considerably due to their capacity of adaptation to various heat storage systems. PCSs are obtained by dispersing a microencapsulated PCM (particle diameter 5–20 μm) into a heat carrier fluid (e.g. water). Heat storage systems are used in applications where the available energy supply is not synchronous with the demand, such as solar thermal and waste heat recovery systems. The theoretical study conducted here – based on heat transfer and energy conservation equations – is intended to developing a theoretical model of the heat storage properties of phase change slurries capable of predicting the transient thermal response of a thermal energy storage system (TES). Most of the research work was focused on investigating the enthalpy–temperature curves resulting from a heating–cooling cycle around the melting point of the PCM. The influence of other parameters such as mico-particles diameter was assessed.

1. Introduction

Rational and effective energy usage combined with environmental requirements increased the interest for renewable energy sources such as solar energy or waste to energy technologies. The major disadvantage of such energy sources consists of the time shift between availability and demand. As a result, a thermal energy storage system which acts as a buffer between source and consumer should be implemented. The most common TES are sensible heat storage and latent heat storage (LHS). LHS with phase change have the advantage that they store and release heat at constant temperature.

One major disadvantage of LHS is the low thermal conductivity of the phase change materials, which results in long charging/discharging times and limits the heat flux the PCM is capable of taking over/supplying. Much work has been conducted for enhancing the conductivity of PCM by embedding structures of materials with high thermal conductivities [1,2], reducing the heat transport distances inside the PCM using extended surface heat exchangers with low distances between fins, or encapsulating the PCM into containers of various shapes with high ratio of surface area to volume [3,4]. The use of microencapsulated PCMs is another alternative of extending the surface to volume ratio and reducing dramatically the heat transport distances. Particles with a diameter of 2–20 μm are dispersed in a fluid (usually water) which acts as PCM carrier and heat transfer fluid.

The mixture of water and PCM particles (phase change slurry – PCS) can be used as energy transport and storage media. Microencapsulated paraffin is the most frequently used as phase change material with melanin–formaldehyde resinous shell [5]. Yamagishi et al. [6] studied the behaviour of such microcapsules exposed to melting–solidification cycles. No damage was observed after 5000 cycles. Gschwander et al. [5] tested PCSs developed by BASF consisting of a mixture of hexadecane and octadecane as phase change material. Long-term stability of the PCM capsules and the pressure drop and pumping characteristics were investigated. A conclusion was drawn that PCSs with paraffin microcapsules can be pumped for years without significant changes of the microcapsules. However, the mechanical stability was detrimental to the thermodynamical properties of the PCS since it was achieved by a thicker wall and a smaller diameter, which reduced the paraffin fraction.

The viscosity and shear rates of the two-phase binary water–PCM microcapsules mixtures were investigated by Pollerberg et al. [7]. The PCS investigated consisting of tetradecane–water emulsion exhibited a Newtonian behaviour in the PCM concentration range of 10–20 wt%. The encapsulated tetradecane suspension showed the behaviour of an Ostwald–de-Wale-fluid. The viscosity of the emulsion was 2–8 times higher than the viscosity of water depending on the concentration of tetradecane.

Thermodynamical properties of PCS are essential in any heat storage application. The most frequently used method for

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Nomenclature

c	specific heat capacity (J/(kg K))
d	PCM microcapsules diameter, m
G	water mass flow rate (kg/s)
h	heat transfer coefficient from water to PCM microcapsules (W/(m^2 °C))
i	specific enthalpy of the phase change slurry (kJ/kg)
I	storage capacity of the LHS system (kJ)
k	heat transfer coefficient from heating/cooling loop to water, W/(m^2 K)
m	mass (kg)
N	number of PCM microcapsules
Q	heat flux received or released by the PCS (W)
r	PCM latent heat of fusion/solidification (J/kg)
S	heat transfer surface area (m^2)
t	temperature (°C)
x	solid phase PCM mass fraction

Subscripts

0	initial
a	heating/cooling agent
f	fusion
in	inlet of the heating/cooling agent
L	heating/cooling loop
mc	PCM microcapsule
out	outlet of the heating/cooling agent
PCM	phase change material
ref	reference
w	water

Superscripts

l	liquid phase of the PCM
pc	phase change
s	solid phase of the PCM

Greek symbols

ρ	density (kg/m^3)
τ	time (s)

determining the dependence between specific enthalpy of PCS and temperature is the *T*-history method [8]. The *T*-history method is used for determining the phase change enthalpy and the phase change temperatures of the PCM. The method is based on comparing the temperature evolution of the investigated PCM and a reference material during the cooling to the ambient temperature. Identical heat transfer conditions for the sample and reference are ensured by placing them in containers with the same geometry. The *T*-history method has some advantages over other methods, such as: it can be used, due to large sample size, for inorganic and organic, encapsulated or composite PCM; the ranges of heating and cooling rates and temperatures are large enough to fit PCM for different applications. The major drawback of the *T*-history method is that no commercial instrument is available and every *T*-history installation must be set up individually. Older methods exist, such as differential scanning calorimetry (DSC), differential thermal analysis (DTA) and adiabatic calorimetry. *T*-history method was improved by Marìn et al. [9] by taking into account the temperature dependence of material properties. Good accuracy was obtained between *T*-history method and DSC method for liquid and solid phase specific heat capacity and heat of fusion. A lot of experimental data regarding thermodynamic properties of PCSs is available, such as Heinz and Steicher's [10] experimental investigation on a PCS heat storage tank. Heinz and Steicher determined experimentally the overall heat transfer coefficient for a flat plate heat exchanger and investigated the influence of PCM concentration on the overall heat transfer coefficient. Their measurements showed significant decrease of overall heat transfer coefficient as the concentration of PCM microcapsules increased. Lázaro et al. [11] employed the *T*-history method for gallium, water and hexadecane. Sub-cooling and hysteretic deviation of heating and cooling curves were observed for both pure PCM and phase change compounds. Saioth and Hirose [12] investigated theoretically and experimentally the energy storage in spherical PCM capsules. Transient thermal characteristics of a phase change energy storage system were developed and the effect of capsule diameter, flow rate, inlet–outlet temperature difference and PCM material was assessed.

2. Problem formulation

The objective of the present work was to develop a theoretical model of a LHS system based on energy conservation and heat exchange equations. A conventional PCS consisting of a mixture of water as heat transfer agent and various mass concentrations of PCM was selected as storage medium for the LHS system. The LHS system considered in the analysis consisted of a storage tank with two internal heat exchangers, one that charges the storage tank by releasing heat into the heat storage medium and the other discharges it by removing heat from the heat storage medium. An assumption essential to the reasoning developed in this paper is that the system has the characteristics of a lumped parameters model, i.e. uniform temperature throughout the whole volume of the phase change slurry. The heat exchange is assumed to occur from the heating/cooling surface to water and from water to PCM capsules. An implicit assumption was that no heat transfer occurs from the heat transfer surface to the PCM microcapsules. The phase change material microcapsules were assumed identical in shape (spherical) and diameter. Since microcapsules were identical, the same solid–liquid fraction was expected throughout the whole microcapsules mass during the phase change process.

Due to the limitations of the theoretical model caution should be exerted in applying the theoretical results developed in this study to a real system. The simplifications underlying the model developed were the lumped parameters model, PCM microcapsules spherical and identical, phase change process occurring at constant temperature, no supercooling effects, and negligible thermal resistance of the microcapsules shell.

3. Equations of the mathematical model

The basic principle underlying the model developed in this work is the virtual division of the bi-phase mixture of water and PCM into two sub-systems, water and PCM microcapsules. The heat storage system consists of a tank filled with phase change slurry warmed up and cooled down by two loops. The overall heat transfer mechanism from the heating/cooling loop to the phase change slurry is formally divided into two simultaneous phases: (1) convection from heating/cooling loop to water and (2) convection from water to PCM microcapsules.

Each phase of a heating–cooling cycle is investigated: heating starts with water and PCM microcapsules at the same temperature, lower than fusion temperature (PCM in solid phase); heating