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Simulation of the transient behaviour of encapsulated organic and inorganic phase change materials for low-temperature energy storage

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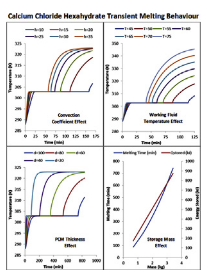
HIGHLIGHTS

- A numerical model for the transient behaviour of macro-encapsulated *PCM* is presented.
- Model simulation results are validated with published experimental data.
- $CaCl_2.6H_2O$ and paraffin C18 are studied and compared under various operational parameters.
- Paraffin C18 needs double the container volume of $CaCl_2.6H_2O$ to store same amount of energy.
- A storage mass-melting time and storage capacity relationship is established.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a detailed mathematical model was presented for the transient behaviour of rectangular macro-encapsulated phase change material (*PCM*) in both melting and freezing phases and was validated using published experimental data. A second order fully implicit finite difference scheme was employed to solve for the storage material solid–liquid moving boundary problem. Two *PCMs* of melting temperature in the range of 30 °C, calcium chloride hexahydrate and paraffin wax C18 have been studied and investigated under various operational parameters to compare their thermal performance and storage characteristics. Simulations have been carried out to assess the effect of working fluid temperature, convective heat transfer coefficient and storage material thickness employed on the transient variation of the *PCM* temperature, the thermal energy storage capacity and the material melting time. It was shown that a paraffin C18 storage mass needs double the container volume, about 3 times the melting time and has 1.2 times the thermal storage capacity of a similar mass of inorganic $CaCl_2.6H_2O$ salt hydrate. However, $CaCl_2.6H_2O$ *PCM* has higher volumetric storage capacity providing an opportunity to design compact energy storage systems. In addition, a relationship between the *PCM* storage mass and the corresponding melting time and storage capacity has been established.

1. Introduction

The continuous rise in the prices of conventional energy resources and the corresponding greenhouse gas emissions have urged the change in the energy generation and consumption patterns and the switch towards renewable energy resources. However, the majority of these resources are intermittent in nature with

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Nomenclature

cp	specific heat capacity at constant pressure (J/kg K)
d	storage material thickness (m)
E_s	total energy storage capacity (J)
h	enthalpy (J/kg)
h_c	heat convection coefficient (W/m^2 K)
h_f	latent heat of fusion (J/kg)
H	total enthalpy (J/kg)
i	node considered
k	thermal conductivity (W/m K)
L	storage material length (m)
L_f	storage material liquid fraction
m	mass (kg)
PCM	phase change material
t	time (s)
T	temperature (K)
TDMA	Tridiagonal Matrix Algorithm
W	storage material width (m)
z	storage material height (m)

Greek

ρ	density (kg/m^3)

Subscripts

0	initial
f	final
fluid	fluid
l	liquid
m	melting
s	solid

intensity variations based on different environmental and climatic conditions. Due to the discrepancy between energy supply and demand in many applications, investigating and developing thermal energy storage techniques are essential to bridge the gap between energy generation and consumption and to store excess energy produced which would otherwise be wasted [1]. This is achieved through designing an energy storage system for heat or coolth storage with the proper selection of the storage material and the storage technique used. Integrating such effective and economic thermal storage systems with low operational and investment costs, especially in the residential sector and low-temperature applications, will help in spreading the utilization of renewable energy-based systems on a large scale with an increase in the energy management capability and the overall efficiency of the renewable systems.

1.1. Thermal energy storage

There are three main types of thermal energy storage systems: sensible, latent and thermochemical storage systems. Although thermochemical storage systems provide promising advantages, the corresponding storage materials used are still too expansive with massive work remains to investigate the technical and economic feasibility of integrating such storage systems in the energy production sector [2,3]. On the other hand, the majority of studies up to date have been concentrated on sensible and latent storage materials as two successful candidates for thermal energy storage systems. Generally sensible energy storage is very simple and storage media are relatively cheap and easy to be utilized with water as a common sensible energy storage medium [4]. On the other hand, latent energy storage systems provide higher energy storage density allowing the design of more compact systems with less heat losses and higher overall efficiency. Such systems can store 5–14 times more heat per unit volume compared to sensible storage materials such as water or rock [5]. Different studies have shown that using *PCM*s could reduce the storage volume significantly where a rock-based medium requires 7 times the storage mass of paraffin 116 wax and eight times the storage mass of $Na_2SO_4.10H_2O$ to store the same amount of energy [6,7].

1.2. PCM energy storage system design

Thermal energy storage using phase change materials, for both heat and coolth storage, has attracted growing interest due to the high thermal storage density and massive potential over a wide range of applications from sub-zero to very high temperature systems. Generally, a latent thermal energy storage system is composed of a *PCM*, working fluid and an appropriate well-designed heat exchanger. The system operation is a complete thermodynamic cycle consisting of progressive charging (melting) and discharging (solidification) phases. Different studies have been carried out concentrating on *PCM* classification and selection, materials characteristics, system design and process optimization, *PCM* thermal storage applications and methods of heat exchange enhancement [1,8–13].

One of the most successful applications for *PCM* is thermal energy storage for air cooling and ventilation. Monodraught has provided a new air conditioning and ventilation system with a *PCM* energy store called Cool-Phase which can reduce energy consumption by 90% compared to conventional air conditioning systems [14]. As shown in Fig. 1, Cool-Phase system utilizes a thermal energy storage unit and an intelligently controlled air handling unit. The *PCM* is charged and discharged by passing air through the *PCM* heat exchanger allowing air to be cooled and providing thermal comfort for occupied spaces. In addition, *PCM*s are widely used in water and space heating applications. Wang et al. [15] have presented a high temperature phase change storage heater employing $AlSi_{12}$ as a *PCM* with a melting temperature up to 585 °C. The heater shown in Fig. 2 was designed to shift electricity from peak period to off-peak hours. Moreover, *PCM*s have been used in the recent years in various building applications as a part of building construction materials and *PCM* enhanced wallboards to maintain desirable thermal comfort. BASF has developed the Micronal *PCM* Smartboard to be integrated into innovative building construction concepts [16]. Micronal *PCM* is

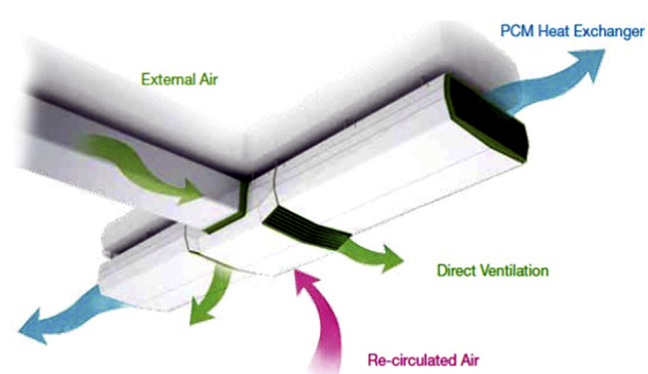

Fig. 1. Monodraught Cool-Phase cooling and ventilation system [14].