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Analysis of a laboratory scale thermal energy accumulator using two-phases heterogeneous paraffin wax-water mixtures

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To reduce the cost of materials in a thermal energy accumulator, the use of water as a substitute for a mass fraction of paraffin wax was considered in the present study which evaluates the thermal behavior of a combined sensible and latent heat storage system that used a beverage can containing paraffin wax and water in different proportions for experiences of thermal energy accumulation and discharge. Unlike other applications that consider the forming of emulsions, there will be two phases within the containers. In a second stage, energy discharge experiences were realized within a 12 cans laboratory scale energy accumulator to analyze its thermal behavior. Replacing 25% of paraffin wax decreases the accumulated energy by only 12%, retaining similar energy discharge times relative to a 100% paraffin wax configuration. Shorter energy loading times and higher heat removal were observed for configurations with a higher water content. No major differences in energy discharge efficiency were found for the same wax/water content, using air velocities of 1.3 m/s and 2.6 m/s. However, in the first 60 min differences up to 25% in the heat removal were observed. Heat transfer coefficients between 18.0 W/m^{2}K and 26.8 W/m^{2}K were determined experimentally.

1. Introduction

There is great concern worldwide about carbon dioxide concentration increase in the atmosphere, generated mainly by the industrial activity of mankind, since the energy required in the various industrial processes as well as domestic heating is obtained mainly using fossil fuels.

To reduce the carbon dioxide emissions the use of renewable energy sources should be maximized. One important energy source is the solar energy, although, due to its nature, it is available only during periods of radiation. This disadvantage can be minimized by storing the thermal energy during the radiation period in order to use it during periods of low or no solar radiation. The thermal energy can be stored with materials that increase its temperature (sensible heat) or by causing a phase change (latent heat) of the material used [1]. The accumulated energy as sensible heat uses a greater volume with respect to the use of phase change materials (PCM), even though the first one has the advantage of being of lower cost. One PCM suitable for storing energy at moderate temperatures is paraffin wax, although it presents as an important disadvantage a low thermal conductivity. To increase its thermal conductivity, the incorporation of metallic elements alongside the use of emulsions paraffin wax-water with the use of reagents to form and maintain the stability of the emulsion, has been evaluated [2–5].

Among the inorganic PCMs are the hydrated salts and metal compounds, which are characterized by their low cost, high heat storage capacity and high-energy storage density [6,7]. Within the organic PCM there are three groups of substances: paraffins, fatty acids, and organic mixtures. Organic PCMs are more chemically stable than inorganic substances, they are not corrosive and do not undergo subcooling or hysteresis. Selection of the most appropriate PCM should consider cost, thermal conductivity in both liquid and solid phases, storage capacity, and phase-change temperature [8].

Paraffin wax, a petroleum-derived (usually alkanes) with the chemical formula C_nH_{2n+2}, is mainly used as the PCM in applications regarding solar drying of agro-products. The melting temperatures and heats of fusion of alkanes increase with their number of carbon atoms [9].

Rehman et al. [10] made a review on improved thermal properties and enhanced heat transfer of PCMs by using metallic and carbon based porous materials/foams analyzing thermal charging

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Nomenclature

c	Specific heat capacity J/kgK
h	Heat transfer coefficient W/m^2 K
$\dot{m}$	Mass flow kg/s
m	Mass kg
$\dot{Q}$	Heat flow W
Q	Heat J
T	Temperature °C
t	Time s

Subscripts

0	Initial
f	Final
fus	Fusion
in	Inlet
L	Latent
liq	Liquid
lm	Logarithmic mean
out	Outlet
S	Sensible
sol	Solid
wall	wall

Greek

λ	Latent heat of fusion J/kg
ρ	Density kg/m^3
θ	Dimensionless temperature

Superscripts

a	Air
Al	Aluminum
c	Can
w	Water
wax	Paraffin wax

and discharging rates, melting temperature, latent and specific heat, density and foam porosity and appropriate PCMs in heat exchanger and solar applications. A disadvantage of paraffin waxes is that they have low thermal conductivity, which is why various techniques have been evaluated to increase the heat transfer rates, such as the use of metallic materials, PCM encapsulation, forming PCM-water emulsions among other options [11]. Qureshi et al. [12] presented a review about the enhancement of thermal conductivity by introducing highly thermally conductive metallic and carbon-based nanoparticles, metallic foams, expanded graphite and encapsulation of PCM, discussing the shape, size, and aspect ratio of particle in metal-based additives, the foam porosity, the packing density, aspect ratio, surface area and thickness of expanded graphite and thermo-mechanical properties of encapsulated PCMs. An additional alternative was the one developed by Reyes et al. [13], which doubled the thermal conductivity of the paraffin wax by adding 5% w/w aluminum stripes to the PCM and designed, built and evaluated a heat exchanger for solar energy accumulation, composed by 48 disposable soft drink cans filled with a total of 9.5 kg of paraffin wax and aluminum stripes. Another technique to improve the conductivity of paraffin wax was presented by Kabeel et al. [14], where they used a mixture of paraffin wax and graphite to improve the thermal properties of storage materials where the daily efficiency of solar energy increased from 51% to 65% for mass concentrations of graphite nanoparticles from 0% to 20%, respectively. Reyes et al. [15] evaluated the effect of adding aluminum foils obtained from waste materials to paraffin wax. Forming mixtures with 8% w/w of aluminum, the authors quantified the thermal conductivity and solidification time for different shapes and distributions of the aluminum foils. Also presented in this work are a mathematical model based on energy balances and its solution leading to simulation results for the PCM temperature profiles in the cooling process.

The dispersion of nanoparticles in PCM (also known as nano-PCM) is another method to improve the thermal conductivity of PCM. Al-Jethelah et al. [16] investigated a nano-PCM filled enclosure, which had a representative geometry of a thermal energy storage system, with up to 5% on volume fraction of CuO nanoparticles dispersed in coconut oil (PCM). The authors presented numerical and experimental results showing significant improvement of the melting process regarding the heat transfer rates.

Paraffin wax has been widely studied for the storage of thermal energy for the drying process. Akgun et al. [17] investigated the melting and solidification processes of paraffin as a PCM in a tube in shell heat exchanger system to evaluate the effect of increasing the inlet temperature and the mass flow rate of the heat transfer fluid both on the charging and discharging processes. Rabha and Muthukumar [18] studied a forced convection solar dryer integrated with a paraffin wax-based shell and tube latent heat storage unit. Knowledge of the latent heat storage material is of the utmost importance when designing the heat storage unit for any solar-thermal application. Agarwal and Sarviya [19] studied experimentally the thermophysical properties of commercial paraffin wax as a latent heat storage material for solar dryers. Bhagyalakshmi et al. [20] used a eutectic mixture as PCM in spherical shell storage system to store thermal solar energy.

Successful utilization of PCM for an enhanced heat transfer to the fluid is influenced by the means of containment. The PCM encapsulation with different geometries of capsules has its own advantages and disadvantages. Alva et al. [21] studied various thermal energy storage materials, focusing on reducing material and operation costs while improving the efficiency of the energy storage.

PCM microencapsulated in a polymeric material and dispersed in water is particularly difficult to maintain in a stable homogeneous flow state if the particles are not fabricated in a very small size, and with this the PCM capsule entails an extra cost. To overcome the above mentioned disadvantages of the so called Phase Change Material Slurry (PCSs), the phase change emulsion (PCE) as a novel PCS has received increased interests in recent years [22]. Both the mixture and paraffin wax-water mixtures as emulsions have been studied as an economical alternative compared to the storage of thermal energy using pure paraffin wax. PCE is a kind of two-phase heat transfer fluid with a PCM dispersed in carrier fluid. Water can be considered as an alternative to phase change materials for thermal energy storage due to its higher heat capacity than other coolants and capability of higher heat rates of charging and discharging. When a PCM is dispersed in liquid coolant through either surfactant encapsulation or microencapsulation, PCE are formed [23]. Huang et al. [24] presented an experimental study on the heat capacity and thermophysical properties of an emulsion containing 30% w/w paraffin, with a melting peak point of 9 °C, obtaining an emulsion with a heat of fusion two times higher than water, being an attractive alternative to chilled water for comfort