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Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water

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ABSTRACT

A theoretical model based on the energy equations was developed to predict the thermal behaviour and performance of a solar latent heat storage unit (LHSU) consisting of a series of identical tubes embedded in the phase change material (PCM). During charging mode, a heat transfer fluid (hot water) from the solar collector passes through the tubes and transfers the collecting heat of solar radiation to the PCM. The heat stored in the liquid PCM is next transferred to water during discharging mode to produce heating water. A simulation program based on the finite volume approach was also developed to numerically evaluate the thermal performance of the LHSU. The model was first validated by comparing the results of numerical simulations to the experimental data. A series of numerical simulations were conducted for three kinds of PCM (*n*-octadecane, Paraffin wax and Stearic acid) to find the optimum design for a given summer climatic conditions of Marrakech city: solar radiation and ambient temperature. Optimization of the LHSU involves determination of the mass of the PCM, the number of tubes, and the flow rate water in solar collector that maximise the thermal storage efficiency. Several simulations were also made to study the effect of the flow rate water on its outlet temperature, during the discharging mode.

1. Introduction

The storage of energy by latent heat during the melting process of phase change materials (PCMs) occurs in many applications: thermal comfort, electronic cooling, space craft, water heating, etc. Compared to sensible heat storage, latent heat storage is favourable due to the high energy storage density of PCMs and isothermal phase transition during melting. One of the important applications of latent heat storage is the solar water heating. In this application a solar collector is coupled with a latent heat storage unit (LHSU) filled with PCM, and a heat transfer fluid (HTF) which circulates through a solar collector, collects a fraction of the received solar energy and transfers it to PCM, during charging mode. The thermal energy which is collected during charging mode can be recovered next by cold water to produce hot water.

Solar water heating based on PCMs has been the subject of several investigations. A comparative study of two identical solar storage units, one of them contained paraffin wax (m.p. about 54 °C) and another unit simply contained the water in a tank, charged under the same conditions using the flat plate solar collectors having same absorbing area, has revealed that the LHSU yields more hot water on the next day morning as compared to sensible storage system [1]. A packed bed of combined sensible and latent heat thermal energy storage (TES) unit was experimentally investigated by Nallusamy et al. [2]. Charging experiments were carried out at constant and varying (solar energy) inlet fluid temperatures. Discharging experiments were carried out by both continuous and batchwise processes to recover the stored heat. It was found from the discharging experiments that the combined storage system employing batchwise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent. A new type of water-PCM solar collector which consisted of two adjoining sections one filled with water and the other with a PCM (Paraffin Wax, 45–50 °C) was developed and studied by Kurklu et al. [3]. The results of their study indicated that the water temperature exceeded 55 °C during a typical day of high solar radiation and it was kept over 30 °C during the whole night. The authors also showed that the proposed solar collector was much advantageous over the traditional solar hot water collectors. Hasan and Sayigh [4] has investigated some fatty acids as PCMs for domestic water heating. They recommended that myristic acid, palmitic acid and stearic acid, with melting temperatures between 50 °C and 70 °C are the promising phase change materials for water heating. Although the previous works has showed the feasibility of using LHSU for water heating, the heat transfer between water and PCM is poor due to the lower thermal conductivity of PCMs [1,5]. To get the hot water in the desirable temperature range more fins may be provided to increase the effectiveness of the LHSU [5].

The effect of climatic conditions on the thermal performance of a cylindrical LHSU in the closed loop with a flat plate solar collector was examined by Bansal and Buddhi [6]. In their work, an

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Nomenclature

A_c	area of absorber plate (m^2)
C	constant Eq. (1)
c	specific heat at constant pressure (J/kg K)
dt	time step (s)
f	liquid fraction
$\bar{f}$	liquid fraction at the end of the charging period
F	collector efficiency factor
h	volumetric enthalpy (J/m^3) or coefficient of convection (W/m^2 K)
k	effective thermal conductivity (W/m K)
k_l	thermal conductivity of the melt (W/m K)
L	length of the tube (m)
$\dot{m}$	mass flow rate of hot water during discharging period (kg/s)
$\dot{m}_f$	mass flow rate of water in solar collector (kg/s)
M	weight of PCM (kg)
NT	number of tubes
r	radial coordinate (m)
r_o	radius of tube (m)
P	incident solar radiation (W/m^2)
Q	latent heat stored by PCM (J)
R	radius of the repeating module (Fig. 2b) (m)
Ra	Rayleigh umber:$Ra = \frac{g\beta}{\alpha_1 \nu}(T_{r=r_o} - T_m)(R - r_o)^3$
S	solar radiation absorbed by absorber plate (W/m^2)
t	time (s)
t_c	time of the charge period (s)
T	temperature of PCM (K)
T_a	ambient temperature (K)
T_f	temperature of HTF (K)
T_m	melting temperature of PCM (K)
T_{out}	outlet temperature of hot water (K)
U	overall heat loss coefficient of plate collector (W/m^2 K)
x	axial coordinate (m)

Greek Symbols

α	thermal diffusivity of PCM (m^2/s)
β	coefficient of thermal expansion of liquid PCM (K^{-1})
δ	melt layer thickness (m)
ε_c	thermal storage efficiency
θ	difference of temperature: $T - T_m$ (K)
ν	viscosity of PCM (m^2/s)
ρ	density (kg/m^3)
ΔH	latent heat of fusion (J/kg)
Δx	axial space step (m)
Δr	radial space step (m)

Subscripts

c	charge
f	fluid
in	inlet
l	liquid phase of PCM
m	PCM or melting
o	previous time
out	outlet
s	solid
W, E, P, N, S	West, East, Center, North and South nodes
w, e, n, s	west, east, north and south faces of control volumes

analytical study has been developed for charging and discharging modes. Two kinds of PCM have been used for the calculations: a paraffin wax (P-116) and stearic acid for three representative months of climatic conditions in Delhi (January, May and August).

Others studies related to the numerical optimization of the thermal performance of LHSUs were conducted [7–10]. Font et al. [7] proposed an unidirectional model to study the heat transfer phenomenon in the PCM in order to optimize the design for domestic hot water using solid–solid PCM. Lee et al. [8] experimentally studied a LHSU in a two-phase thermosyphon solar water heater. Three PCMs were used as energy storage materials: tricosane, water, and sodium acetate. The results of a comparative study indicate that tricosane provides many advantages to be the energy storage material in LHSU. Other results show that the LHSU gives optimum charge and discharge performance under 40% alcohol fill ratio and with tricosane used as the energy storage material, and displays an optimum charge efficiency of 73% and optimum discharge efficiency of 81%. Tayeb [9] developed a system for domestic hot water using $Na_2SO_4 \cdot 10H_20$ as a PCM. The simulation model gives the optimum flow rate of the inlet water supply required to maintain the constant-temperature water at outlet. Esen and Durmu [10] numerically studied cylindrical latent heat storage tanks used for heating the water. Two different models describing the diurnal transient behaviour of the LHSU were used. The first is suited to tanks where the PCM is packed in cylinders and the HTF flows parallel to it. The second is suited to tanks where pipes containing the fluid are embedded in the PCM. A series of numerical tests are then undertaken to assess the effects of various PCMs, cylinder radii, pipe radii, total PCM volume in the tank, mass flow rates of fluid, and inlet temperatures of the HTF on the storing time. In addition, optimal geometric design of the store depending on these parameters and PCMs was presented.

Although the above optimization studies provide valuable guidance for engineering design, they are however restricted to the search of a limited number of optimum parameters. The present study, overcomes this limitation by looking at the search of the optimum values of the all key parameters, geometric and operating parameters, that maximize the thermal storage efficiency of the LHSU, during both charging and discharging modes. The first objective of the present study is to develop and validate a 2D mathematical model in order to study the transient thermal behaviour of a LHSU in the closed loop with a flat plate solar collector (the LHSU consists of a series of tubes, containing the HTF (water), embedded in a PCM). The second objective is to find the optimum values of geometric and operating parameters, for a given PCM, summer climatic conditions of Marrakech city, absorber surface, length and radius of the tubes. The optimization involves determination of the total PCM mass, the number of tubes, the mass flow rates of the HTF (water) circulating in the tubes during charging and discharging modes that maximise the thermal storage efficiency of a LHSU. Moreover, the proposed mathematical model takes into account the effect of natural convection during the melting process.

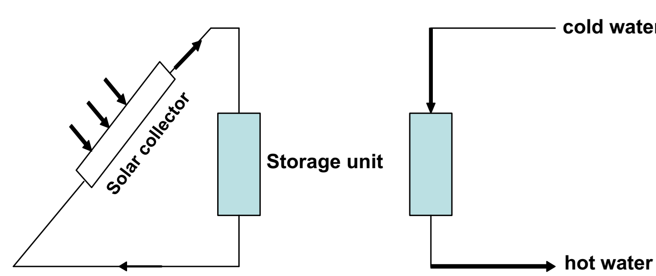

Fig. 1. Domestic hot water.