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Enhancement of latent heat storage in a rectangular cavity: Solar water heater case study

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ABSTRACT

The energy production provided by a heat excess or a discontinuous source (solar radiation, waste heat, etc.) involves the utilization of a thermal storage systems. In this work, an experimental study of a storage system using paraffin as phase change material (PCM) has been done. This system takes the form of two rectangular cavities incorporating behind the absorber of a flat plat solar collector. Measurements were performed during different weather conditions and illustrate that the PCM contributes to increase the performance of the solar collector at night. An analysis of the temperature stratification inside the PCM-filled cavities was also carried out. Theoretical solid–liquid of phase change material model is used to evaluate the PCM melted volume fraction, liquid–solid interfaces, PCM temperature and melting/solidification flow in the PCM-filled cavity used in the present experimental study.

1. Introduction

Sun is free energy, unlimited and environmentally benign. This immense resource will be able in the future to provide an important portion of energy needs. The solar water heater is one of the successful solar technologies. However, the intermittent characteristic of the solar radiations leads to the improvement of suitable collection and storage technologies. Thermal energy storage is simply the storage of high or low temperature energy for later use [1]. It can be stored as sensible, latent heat storage or a combination of these. Conventional water heating system stores the heat in the form of a sensible one. An integrated collector-storage solar water heater was designed, constructed and evaluated by Kalogirou [2]; the cost of the system is comparatively lower than the conventional solar water heater. The most attractive form of thermal storage energy is the latent heat storage in a phase change material (PCM). PCMs have the advantage to work within small temperature drop, low vapor pressure at the operational temperature. Some properties like cheapness, chemical stability, non-corrosiveness are required before choosing a PCM [3]. The phase change materials are used in several practical application areas, such as heating and cooling of buildings, cogeneration, electronics, automobile industry, and also solar heating water and air [4–7]. It is very important to provide the storage of solar energy during the day and then to use this stored energy for water-heating during the evening and night after the sunset. The number of PCMs applications in solar water heating collectors is very limited. Koca et al. [8] realized a latent heat storage flat-plate solar collector with phase change material ($CaCl_2 6H_2O$). The designed collector combines in a single unit solar energy collection and storage. PCMs are stored in a tank, which is located under the collector. They observed that the average net energy and exergy efficiencies are of 45% and 2.2%, respectively. Eman-Bellah et al. [9] investigated the performance of a compact solar collector with an absorber plate–container unit. Both absorbing and storing operations of solar heat in a paraffin wax were examined. Also a solar collector consisting of two adjoining sections, one filled with water and the other with paraffin wax as a PCM was developed and investigated in [10]. Canbazoglu et al. [11] tested the performance of solar thermal energy storage using sodium thiosulfate pentahydrate as PCM in a solar water-heating system. They founded that the storage time of hot water, the produced hot water mass and total heat accumulated in the system were approximately 2.59–3.45 times of that in the conventional water-heating system.

Many authors have reported a special attention to the numerical simulation on thermal latent heat storage during melting and solidification processes. The work of Lacroix [12], concerning a numerical and analytical study of a thermal energy storage system, where the elements for the energy accumulation are formed by cylindrical tubes. Laouadi [13], studied numerically a system based on a cyclic melting and solidification of phase change material, the system is capable of replacing the electric heaters during the peak

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Nomenclature

A	aspect ratio
A_c	surface area of the collector (m^2)
C_p	specific heat (J kg^{-1} °C^{-1})
f_l	melted volume fraction = melted volume/total volume
Fo	Fourier number (dimensionless time)
g	gravitational acceleration (m s^{-2})
H	height of the cavity (m)
h^C	convection heat transfer coefficient (W m^{-2} °C^{-1})
h^R	radiation heat transfer coefficient(W m^{-2} °C^{-1})
h_{los}	heat loss coefficient (W m^{-2} °C^{-1})
h_w	wind convection coefficient (W m^{-2} °C^{-1})
I_T	solar radiation (W m^{-2})
k	thermal conductivity (W m^{-1} °C^{-1})
L	width of the cavity (m)
L_1	collector length (m)
L_2	collector width (m)
L_3	collector depth (m)
L_H	latent heat of fusion (J kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (N m^{-2})
P	dimensionless pressure (N m^{-2})
Pr	Prandtl Number
q	heat flux (W m^{-2})
Q	dimensionless heat flux (W m^{-2})
Q_0	reference heat flux (W m^{-2})
Q_A	absorbed heat flux (W m^{-2})
Q_{los}	lost heat flux (W m^{-2})
Q_{st}	stored, heat flux (W m^{-2})
Q_u	useful heat flux (W m^{-2})
Ra	Rayleigh Number
Ste	Stefan number
t	time (s)
T	temperature (°C)
T_a	ambient temperature (°C)
T_A	absorber temperature (°C)
T_{in}	inlet temperature (°C)
T_m	melting temperature (°C)
T_{out}	outlet temperature (°C)
(u, v)	velocity compounds
(U, V)	dimensionless velocity compounds
(x, y)	Cartesian coordinates
(X, Y)	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (°C^{-1})
δ_b	bottom insulation thickness (m)
δ_e	bottom insulation thickness (m)
ϕ	inclination angle (rad)
η	energy efficiency (%)
η_0	optical yield (dimensionless)
λ_i	thermal conductivity of insulation (W m^{-1} °C^{-1})
ν	kinematic viscosity(m^2 s^{-1})
θ	dimensionless temperature
θ_m	dimensionless melting temperature
ρ	density (kg m^{-3})
τ	time step, $\tau = \text{Ste} \cdot \text{Fo}$

hours by restoring the thermal energy stored by the PCM. Other works connected to this topic exist in [14,15]. According to a recent study realized by Gong et al. [16], the capacity of charge in a cavity heated by a vertical side wall will be able to increase by 50% due to transfer by natural convection when the cavity undergoing a rotation of 180°.

In particular, the main disadvantages of the solar water heating systems are the greatest thermal losses during the night and cold season; and the overheating water during the hot season. The active research improved the latent storage materials in solar water heating applications. In the present study, Paraffin was selected as a PCM due to some advantages such as the low cost, the high latent heat storage capacity and the proper phase change temperature of 56 °C for solar heat storage applications. The primary objective of the present study is to investigate experimentally the thermal performance of an Integrated Solar Latent Storage Collector (ISLSC) with two PCM-filled cavities, by measuring the inlet, the outlet, the absorber and the PCM distribution temperatures of the ISLSC. An enhancement of solar thermal energy storage performance using Paraffin-PCM in the cavities integrated behind the absorber solar water heater during the month of March is carried out. The second objective is to examine theoretically the evolution of the PCM melted volume fraction, liquid–solid interfaces, PCM temperature and melting/solidification flow in the PCM-filled cavity used in the present experimental study.

2. Experimental study

In this study an experimental set-up was designed and built in order to investigate the melting process of an integrated solar latent storage collector with two PCM-filled cavities (Fig. 1). The set-up and the procedure are described below.

2.1. Experimental set-up

The solar collector is made up of galvanized steel sheets, with an area equal to 2 m^2. A transparent glass cover with 0.004 m of thickness (transmission and emissivity coefficients are respectively, 81% and 94%) was placed at a distance of 0.02 m from the absorber. A polyurethane insulation with 0.05 m of thickness, with thermal conductivity equal to 0.028 Wm^{-1}°C^{-1}, was placed behind the collector to decrease thermal losses through the backs. Copper pipe was used as a heat exchanger with outer diameter and thickness of 0.014 m and 0.002 m, respectively.

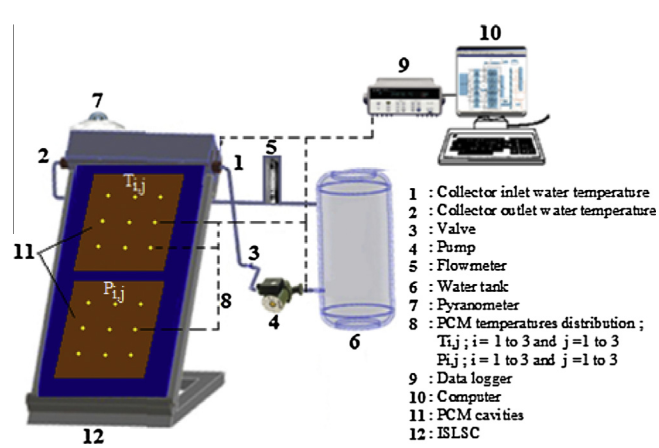

Fig. 1. Schematic view of the experimental set-up.