Energy Conversion and Management 177 (2018) 1–10

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An experimental investigation of the phase change process effects on the system performance for the evacuated tube solar collectors integrated with PCMs

Mohamed A. Essa*, Nabil H. Mostafa, Mostafa M. Ibrahim

Department of Mechanical Power Engineering, Faculty of Engineering, Zagazig University, 44519 Zagazig, Egypt

ARTICLE INFO

Keywords:
Evacuated tube collector
Phase change material
U-tube
Phase change process
Solar heating

ABSTRACT

This paper presents an experimental investigation of the performance of evacuated tube solar collectors integrated with Phase Change Materials systems. The performance of these systems depends on the thermal charging and discharging of the phase change materials. One of the important heat transfer parameters concerning these systems is the phase change process. Such a process depends on the flow rate of the heat transfer fluid and the environmental conditions. In the present study, a comparative study was carried out for two finned U-tube direct flow collectors. For the first collector paraffin wax was used as a phase change material. While for the second collector the control collector was left empty. Different flow rates were applied to study their effects on both the phase change process and the system performance. It was found that low flow rates allow a complete phase change and achieve the energy storage benefit of the phase change material. When the phase change process was complete, the system delivered its best efficiency. Under high flow rates, the system did not achieve the expected thermal energy storage benefits because the phase change material remained in the solid state. However, the solid phase provided a good insulator for the useful heat and enhanced the system's efficiency. At a flow rate that caused a partial phase change, the system's efficiency deteriorated, but the storage benefit of the phase change material was achieved. A novel correlation is proposed to estimate the hot water supply period according to a required discharge temperature. This correlation is valid for the direct flow finned and U-tube evacuated tube solar collectors integrated with paraffin wax as a phase change material.

1. Introduction

Solar energy is the mother source of all the renewable energies on earth. Because of its availability only during a certain period of the day, the need arose for energy storage for use at other times, for example at nighttime. There are two mechanisms used in thermal energy storage, which are the sensible and the latent heat. The sensible heat causes an increase in the material's temperature during heat addition, and a decrease during heat loss. This effect causes a variation in the temperature of the heat transfer fluid (HTF). Furthermore, it changes the rate of heat loss in the transient conditions because of the variations in the temperature difference. On the contrary, the latent heat mechanism has the ability of heat addition and removal at a fixed temperature range. This behavior provides a fixed temperature of the HTF during the discharge process, which signifies an advantage in the solar heating systems. The materials in which energy is stored in a form of latent heat are called phase change materials (PCMs), since the heat exchange takes place in the PCM through the phase change from solid to liquid to gas and vice versa. There are different types of PCMs concerning its organic or chemical base, melting temperature ranges, and reaction sensitivity with the other materials. Further information concerning PCMs can be found in Cunha and Eames [1]. Recently, some research works were performed on the use of the PCMs with solar heaters for their thermal energy storage advantages. PCMs are integrated with the solar systems in different configurations that will be described in the next paragraphs briefly.

Some studies were performed to investigate the effect of the PCM integration with the solar system's storage tank, or as a separate storage unit, on the system's performance. Kılıçkap et al. [2] investigated experimentally the performance of a flat plate collector (FPC) combined with a vertical tank filled with a PCM. The PCM used in this research was Calcium Chloride Hexahydrate. A hot water tank was placed Inside the PCM tank for the HTF circulation. This system achieved a maximum thermal efficiency of 58%, compared to 56% by the standard insulated

* Corresponding author.
E-mail address: maessa@eng.zu.edu.eg (M.A. Essa).

https://doi.org/10.1016/j.enconman.2018.09.045
Received 2 June 2018; Received in revised form 12 September 2018; Accepted 14 September 2018

Nomenclature

A_{ap}	collector aperture area (m^2)
Cp	specific heat (J/kg °C)
G	instantaneous solar radiation intensity on the collector (W/m^2)
h_{ls}	liquid to solid and solid to liquid latent heat (J/kg)
$\dot{m}$	working fluid mass flow rate (kg/s)
m	mass of the PCM (kg)
Q_{PCM}	energy stored in the PCM (MJ)
Q_{coll}	daily solar energy collected (MJ/day)
Q_{us}	useful heat from the collector (MJ/day)
$\dot{Q}_{us}$	rateoftheuseful heat collected (W)
$R_{\dot{Q}}$	useful heat rate ratio
R_Q	enhancement ratio of the overall useful heat ($=R_\eta$)
R_η	enhancement ratio of the collector efficiency
T_{nd}	non-dimensional temperature (–)
$\lvert T_{in}\rvert$	time averaged inlet temperature for the working fluid (°C)
T_{out}	temperature of the working fluid supplied from the collector (°C)
T_{in}	temperature of working fluid flowing to the collector (°C)
T_d	discharge temperature (°C)
t	time (s)

Subscripts

A	collector A
B	collector B
mean	the mean value of the variable over the day
Sun rise	Sun rise time
Sun set	Sun set time

Greek

η_s	daily system efficiency
Δt	time step of measurements (s)
ΔT	change in the temperature (°C)
τ_d	discharge time (s)
τ_{nd}	non-dimensional discharge time.

Abbreviations

ANN	Artificial Neural Network
CTM	capillary tubing mats
ETC	Evacuated tube collector
FPC	flat plate collector
HTF	heat transfer fluid
MPCM	microencapsulated PCM
PCM	phase change material
PVT	photovoltaic thermal
TSC	transpired solar collector

tank. They claimed that the higher performance of the PCM tank system was due to the good insulation properties of the PCM. H.M. In a numerical study, Teamah et al. [3] investigated the effect of inserting vertical cylinders of PCM inside the water tank. They developed a model based on the enthalpy-porosity method used in solving the phase change process. Their analysis showed that the required tank volume was undersized by using the PCM under the same demand. They also found that when the volume of the tank was increased, the benefit of the PCM as a thermal energy storage material vanished.

Poole et al. [4] investigated the performance of a transpired solar collector (TSC) using 80 kg of salt-hydrate as the PCM. They indicated that the system combined with the PCM provided 34% of the total useful heat during the nighttime for one-week period in April. They also indicated that the PCM thermal energy storage system stored between 76% and 107% of its theoretical thermal energy storage capacity using four different air flow rates of 0.033, 0.045, 0.053 and 0.063 m^3/s. Mehling et al. [5] investigated the effect of placing a proposed PCM-module in the upper part of the water tank. This PCM module had 1/16 vol% of the tank. They found that the energy density has been improved by 20–45% when using the proposed PCM-module. Cabeza et al. [6] investigated experimentally the effect of placing a PCM module of several cylinders (1.025 vol% of the tank) at the top of the water tank. The PCM was granular PCM–graphite compound of 90 vol% of sodium acetate and 10 vol% graphite. They found that the proposed PCM module granted a period of hot water supply (36–38 °C) of 45 min when using six PCM units. Tarhan et al. [7] proposed a trapezoidal built-in storage unit in the solar water heater as a reference heater to test two different configurations of PCM units. They found that using Lauric acid decreased the peak temperature by 15% relative to the reference heater. However, using myristic acid increased the temperature by 8.8% compared to the reference heater. Mohammad and Ali [8] studied experimentally the effect of using PCM-spherical capsules of paraffin wax as a storage media inside the solar tank of a jacketed shell type. The thermal storage density of the system found to increase by up to 39%. Additionally, the exergy efficiency was enhanced by16%. In that system, the time of the hot water supply from the tank increased by 25%.

Kanimozhi et al. [9] investigated experimentally the effect of using a proposed multitube PCM unit. They filled the PCM unit by both paraffin and honey waxes as storage materials. Artificial Neural Network (ANN) was used, in their research, to predict the system performance under different operating conditions. They found an improvement in the heat transfer through the charging and discharging processes by 40% when using honey and paraffin waxes. Wang et al. [10] investigated experimentally and numerically, the effect of both the HTF flow rate and the collector area on the system's performance. Their system used a separate heat exchanger filled with a PCM and combined with an FPC. They indicated that the mass flow rate has insignificant effect on the overall system's performance. Furthermore, they indicated that small solar collector areas were not sufficient for melting all the PCM. However, large areas led to an unsafe operation and lower efficiency concerning the heat storage and the exergy.

Some studies were performed to test the effect of the PCM integration with the solar collector itself as follows. Mettaweea and Assassa [11] investigated experimentally the performance of a solar water heater in which paraffin wax was employed as the PCM. Through this study, the PCM was located between the absorber plate and the insulator of an FPC. They found that the heat transfer coefficient increased with increasing the molten layer thickness of the PCM. They also found that the useful heat gain increased with increasing the mass flow rate. Additionally, they found that the natural convection is the principal heat transfer mechanism in the liquid phase. Khalifa et al. [12] investigated experimentally the effect of a PCM layer inside the FPC on the system's performance. In their work, the paraffin wax was applied as the PCM. They found that the use of PCM extended the hot water supply period. Furthermore, the system's efficiency found to vary smoothly by applying the PCM. Serale et al. [13] investigated experimentally the effect of using a microencapsulated PCM (MPCM) slurry with an FPC at low temperatures of order 40 °C. The used MPCM slurry was composed of microencapsulated PCM, water, and surfactants. In their study, the MPCM was used as an HTF in a part of the system. They indicated that the MPCM could overcome some of the limitations