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Experimental investigation of thermal performance of flat and v-corrugated plate solar air heaters with and without PCM as thermal energy storage

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ABSTRACT

The purpose of this research is to carry out an experimental investigation of flat and v-corrugated plate solar air heaters with built-in PCM as thermal energy storage material. The integrated solar air heater with paraffin wax as PCM was designed and tested under prevailing weather conditions of Tanta city (30° 43′N, 31°E), Egypt. The parameters affecting the thermal performance of the flat and v-corrugated plate solar air heater were presented with and without PCM. These parameters include solar radiation, the temperature difference of air across the heater, convective heat transfer coefficient between the absorber plate and the flowing air, instantaneous thermal efficiency, daily average efficiency and the PCM freezing time.

The thermal performance parameters were studied when the mass flow rates were 0.062, 0.028 and 0.009 kg/s. The effect of changing the thickness of PCM below the absorber plate was also studied. From the experimental results, it was found that when using the PCM, the outlet temperature of the v-corrugated plate solar air heater was higher than ambient temperature by 1.5–7.2 °C during 3.5 h after sunset compared with 1–5.5 °C during 2.5 h after sunset for flat plate solar air heater when the mass flow rate was 0.062 kg/s. It was also concluded that the daily efficiency of the v-corrugated solar heater using PCM was 12% higher than the corresponding ones without using the PCM and it was also 15% and 21.3% higher than the corresponding values when the flat plate was used with and without PCM when the mass flow rate was 0.062 kg/s, respectively.

1. Introduction

Egypt lays in the North African Sunbelt region with flat desert topography and perennially clear skies with high rates of solar intensity throughout the year which is favorable to thermal solar energy technologies [1]. The development of sustainable solar energy services for heating purposes like the supply of heating air using solar air collectors may face a great problem at the absence of solar radiation. The thermal energy storage has effective role in overcoming the periodic and diffused nature of the solar energy [2]. Energy storage techniques can eliminate the mismatch between energy supply and energy demand.

Among the most promising ideas for the storage of solar energy is the exploitation of latent heat of fusion by using some organic and inorganic materials known as phase change materials (PCM) [3]. These materials have the ability to store the excess of thermal energy throughout the day during its fusion and recover it after sunset during its solidification under constant temperature with high storage density, which makes it effective tool to enhance the thermal performance of solar heating systems.

Initially, many efforts had been performed to improve the thermal performance of solar air heaters without any storage medium by increasing the heat transfer area, besides improving the turbulence in the air duct with introducing fins [4–6] or corrugated surfaces with different designs [7–9]. Karim and Hawlader [10] investigated flat plate, finned and v-corrugated air heaters experimentally and theoretically. They indicated that the v-corrugated collector is 10–15% and 5–11% more efficient, compared to flat and finned plate collectors, respectively when $\dot{m} = 0.04$ kg/s. El-Sebaii et al. investigated double pass v-corrugated [11] and finned plate [12] solar heater experimentally and theoretically under forced convection mode, and compared their performances with the double pass flat heater. They found that the v-corrugated

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Nomenclature

A_p	projected cross section area of the plate (m^2)
A_s	total surface area of the plate (m^2)
C_p	specific heat of the flowing air (kJ/kg °C)
I	the total solar radiation on horizontal surface (W/m^2)
$\dot{m}$	mass flow rate of air (kg/s)
Q_u	useful thermal heat energy of the air across the heater (kJ)
t	time
t	thickness
ΔT_c	temperature difference of the air across the heater (°C)
T_{amb}	ambient temperature (°C)
$T_{a,out}$	outlet temperature of air from the heater (°C)
T_{am}	average temperature of air inside the heater (°C)
T_p	absorber plate temperature (°C)
T_{pm}	average value of the absorber plate temperatures (°C)
T_{pcm}	average value of the PCM temperatures (°C)
T_g	glass cover temperature (°C)
h	convective heat transfer coefficient between the air and the absorber plate

Greek letters

Δ	difference
η_{ins}	instantaneous thermal efficiency of the heater
η_{da}	daily average efficiency of the heater

Subscripts

av	average
am	mean
amb	ambient
p	absorber
da	daily
ins	instantaneous
i	inlet
o	outlet

Abbreviations

PCM	phase change material
TES	thermal energy storage
LHS	latent heat storage

plate is 9.3–11% and 11–14% more efficient than the finned and flat solar air collectors, respectively, when $\dot{m}$ = 0.02 kg/s.

So far, a few studies dealt with the effect of using PCM on the thermal performance of the solar air heater. The different designs and parameters affecting the solar air heaters performance by using PCMs as thermal energy storage material are tabulated in detailed reviews performed by Mohammed et al. [13], Tyagi et al. [14] and Farid et al. [15]. The specifications of different types of PCMs and its classifications are also reported [16,17]. Enibe [18] performed solar air collector with built-in PCM suitable for drying medicinal plant. Mettawee and Assassa [19] experimentally investigated integrated solar air heater implementing paraffin wax as latent heat storage material. They found that the discharging time and convective heat transfer coefficient increase as the PCM layer thickness below the absorber plate is increased. Fath [20] investigated solar air heater using a set of copper cylinders filled with storage material as an absorber using paraffin wax as a PCM. He found that the daily efficiency is 63.35% when air flow rate equals 0.02 kg/s, and the hot air outlet temperature (5 °C above ambient temperature) extended for about 4 h after sunset, compared with 38.7% and 1.5 h, respectively, for the conventional flat solar air heater. Tyagi et al. [21] studied the thermal performance of a solar air heater with and without PCM (Paraffin wax and hytherm oil). They noted that the outlet temperature with paraffin wax was slightly greater than that of hytherm oil. They also concluded that the thermal efficiency in the case of heat storage was 20–53% higher than that in the case without TES, besides the efficiency in the case of the paraffin wax was slightly higher compared with the hytherm oil. Shalaby and Bek [22] carried out experimentally the performance of solar dryer with and without using paraffin wax as PCM. They found that after using the PCM, the temperature of the drying air is higher than ambient temperature by 2.5–7.5 °C after sunset for seven hours at least. In addition, the solar heater provides a drying air temperature, after 2:00 pm, 3.5–6.5 °C more than the second case when it was free of PCM.

The low thermal conductivity of paraffin wax is considered the major problem of using it as energy storage material which causes a high decrement of the heat transfer process to/from the paraffin wax. In an attempt to improve the heat transfer process, Alkilani et al. [23] investigated indoor solar air collector integrated with paraffin wax as PCM genitive 0.5% aluminum powder. They concluded that the PCM freezing time inversely proportional to mass flow rate and reached longer time 8 h at 0.05 kg/s. So far, there is no trial to use extended or corrugated surface to increase the heat transfer area between the absorber and the PCM. In this work, for the first time as the authors know the flat and v-corrugated plate solar air heaters are tested with and without using PCM (paraffin wax) as energy storage medium. The flat and v-corrugated plate solar air heaters are also tested at a wide range of mass flow rates (0.009–0.062 kg/s) compared with (0.02–0.05 kg/s) as reported in the literature [11,12,20,23]. The factors influencing the thermal performance of both solar air heaters were investigated with and without PCM including the temperature difference of air across the heater, the instantaneous thermal efficiency, the daily average efficiency, the convective heat transfer coefficient, the PCM layer thickness and the PCM freezing time.

2. Thermal performance parameters

In this section, the governing equations of the thermal performance parameters of the solar air heater are evaluated as below.

The useful thermal heat energy of the air across the heater (Q_u) is given by;

$$Q_u = \dot{m} c_p \, \Delta T_C, \tag{1}$$

where $\dot{m}$ is the air mass flow rate through the heater (kg/s), C_p is the specific heat of the air (J/kg,°C) and ΔT_c is the temperature difference of air across the heater (°C).

The instantaneous thermal efficiency of the heater (η_{ins}) is given by [24];

$$\eta_{ins} = \frac{Q_u}{I \, A_p}, \tag{2}$$

where A_p is the heater projected area (m^2) and I is the total solar radiation incident on the heater (W/m^2).

The convective heat transfer coefficient between the air and the absorber plate is given by [25];

$$h = Q_u / A_p (T_{pm} - T_{am}), \tag{3}$$

where Q_u is the useful heat gain by the air (W), T_{pm} is the average value of absorber plate temperatures (°C) and T_{am} is the average air temperature in the heater (°C).