

Experimental investigation of a new solar air heater with packed-bed latent storage energy

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Abstract: An experimental study was conducted to present an experimental investigation of a solar air heater with a packed bed latent heat thermal energy storage system using PCM spherical capsules (SAHLSC) designed and realized in the Research and Technology Center of Energy (CRTE) in Tunisia. The experimentally obtained results are used to analyze the performance of the system, based on temperature distribution in different parts of the collectors, absorbed, instantaneous stored and used thermal energy. The net daily energy efficiency varied between 32% and 45%.

Keywords: Latent heat storage; packed bed solar air heaters; thermal efficiency.

1. Introduction

The thermal energy can be stored as sensible heat, latent heat, reaction heat or combination of those forms. Many thermal storage energy systems are cited in literature [1-5], with applications in cogeneration, building and solar heating of water or air. The use of Phase Change Material (PCM) storage in a solar air heater is less common, the majority of the studies were numerical. Hence, authors [6, 7] used numerical tools to determine the solar air heating systems performance using PCM energy storage, to examine the effect of the latent heat and the PCM melting temperature and to identify the optimum phase change materials physical properties. Ghoneim et al [8] evaluated the theoretical performance of solar heating collectors with PCM and sensible heat storage in water and in air. Fath [9] used a thermosyphon solar air heater with a series of packed tubes containing a PCM with different melting temperatures of 61, 51, 43 and 32 °C. The tubes were arranged parallel to each other in order to make a flat-plate-style configuration with air flowing over and under them simultaneously. This work will address packed beds of encapsulated PCM in the spherical capsules system which is one of the most effective and compact latent thermal energy systems [10-12]. In order to provide an amount of storage heat nocturnal use we will present an analytical and experimental investigation of a new Solar Air Heater with Latent Storage Collector (SAHLSC) using spherical capsules as a packed bed absorber. The SAHLSC designed and realized in the Research and Technology Center of Energy (CRTE) in Tunisia.

2. Description of the experimental set-up and measurement procedure

An experimental set-up of the solar air heater latent storage collector was designed and constructed to investigate the charging and discharging processes. The experiments were performed during March 2012 in CRTE.

A schematic arrangement of the solar air heater with phase change energy storage using spherical capsules is given in Figure 1. The experimental apparatus consists of a packed bed absorber formed of spherical capsules with a black coating and fixed with steel matrix. The PCM is confined inside spherical capsules. The packed bed absorber is the most important component of the solar air heater collector, which absorbs the sun radiations and stores the solar thermal energy as sensible heat and latent heat. The length, the width and the total volume of the collector are 2 m, 1 m and 0.28 m³, respectively. A 0.004 m thick transparent glass cover was placed 0.015 m apart from the absorber. A 0.05 m thick polyurethane insulation, with heat conductivity 0.028 W/m.K, is placed in the bottom of the collector to decrease thermal losses through the bottom.

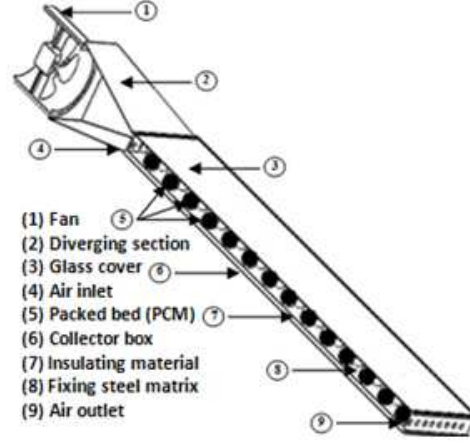


Figure 1: Schematic view of SAHLSC.

The charging process starts when the absorber is exposed to the solar radiation (from 9:00 to 16:00). It was measured by a Kipp and Zonen pyranometer placed facing to the south at the same inclination of the absorber. During this process, air inlet and outlet openings are closed. The discharging process starts from 16:00 to 9:00 (the next day). The inlet and outlet air openings are opened. A fan used to blow the air at a fixed speed equal to 1 ms^{-1} . The inlet and outlet air temperatures of the SAHLSC, respectively, were measured with K-type thermocouples. All the measuring instruments were connected to a multi-channel digital Agilent 34970A Data Acquisition. The experimental values are recorded every 5 min.

3. Energy analysis

The energy analysis presented in this section is mainly based on the first law of thermodynamics. The theoretical model employed for the study of the SAHLSC consists of using a thermal energy balance during both the charging and discharging phases:

$$Q_A = Q_u + Q_{st} + Q_{los} \quad (1)$$

Where Q_A , Q_u , Q_{st} , and Q_{los} are the absorbed, useful, stored and lost energy, respectively.

Based on Duffie et al. [13], the useful heat gain from the collector is:

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) \quad (2)$$

V_{av} are average air velocity and S are the sectional area of the duct at the inlet of the solar air heater.

The radiation absorbed flux of the absorber packed-bed is defined as:

$$Q_A = A_p (\alpha\tau) I_T \quad (3)$$

Where $(\alpha\tau)$ is the effective product transmittance-absorptance that is equal with the optical efficiency (η_0) .

The stored heat flux during the charging and discharging phases is given by:

$$Q_{ch} = [m_{PCM} C_{p,s} (T_m - \bar{T}_{ini_ch,PCM}) + m_{PCM} L + m_{PCM} C_{p,l} (\bar{T}_{fin_ch,PCM} - T_m)] / \Delta t_{ch} \quad (4)$$

$$Q_{dis} = [m_{PCM} C_{p,l} (T_m - \bar{T}_{fin_dis,PCM}) + m_{PCM} L + m_{PCM} C_{p,s} (\bar{T}_{in_dis,PCM} - T_m)] / \Delta t_{dis} \quad (5)$$

The lost heat flux is given by relation (7), U_{los} is the collector overall heat loss coefficient. The thermal energy lost from the collector to the surroundings by conduction, convection and infrared radiation. U_{los} is equal to the sum of energy loss through the top (U_t), bottom (U_b) and edges (U_e) of the collectors given below [13]:

$$Q_{los} = U_{los} A_c (\bar{T}_p - T_a) \quad (6)$$

$$U_{los} = U_t + U_b + U_e \quad (7)$$

The thermal efficiency based on the first law of thermodynamics is defined as the ratio between the useful energy and the solar radiation incident on the collector:

$$\eta = Q_u / A_c I_T \quad (8)$$

The daily average thermal efficiency (η) of the SAHLSC is the ratio of the desired energy output during the discharging process to the total energy input during the charging process.

$$\eta = \left(\int_{dis} Q_{dis} \right) / \left(\int_{ch} A_c I_T \right) \quad (9)$$

4. Results and discussion

Figure 2 and Figure 4 show the outlet SAHLSC temperature, wind velocity and ambient temperature as a function of day times. It is seen from Figure 2 that the temperature into the collector (closed cycle), under clear sky conditions, increases gradually at the beginning of the charging period and remains nearly constant around 35 °C to 42 °C, the PCM is completely charged. The 17 March 2012 is characterized by severely solar radiation fluctuation with ambient air temperatures from 16 °C, and wind velocity vary from 1 ms⁻¹ to 7 ms⁻¹. We noted that the temperature into the solar collector is ranging from 25 °C to 35 °C and the PCM is also charged during the closed cycle (Figure 4). In fact, during the discharging periods; after 16:00 (local time), the outlet temperature decrease progressively at the beginning of the opened cycle due to the coldness of the liquid PCM (sensible heat). After 2 hours, the temperature remains constant; nearly 18 °C, during the solidification process (latent heat) for two days.

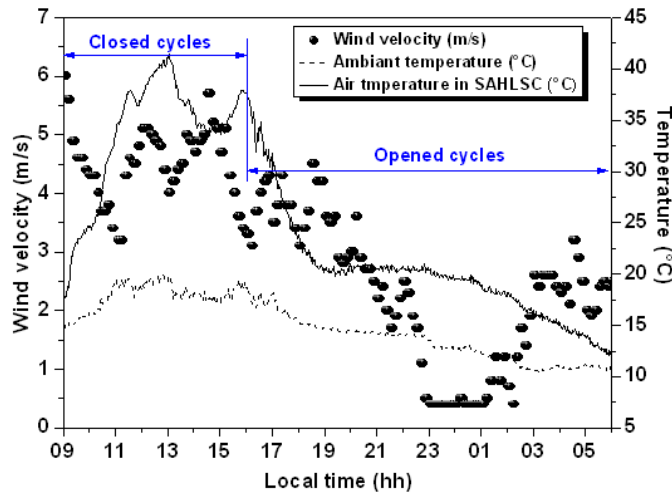


Figure 2: Ambient temperature, air temperature into SAHLSC and wind velocity as a function of times (26 March 2012).

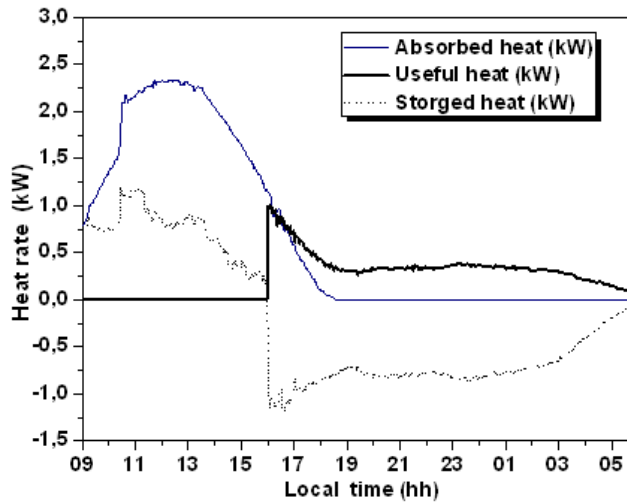


Figure 3: Absorbed, useful and stored heat rates as a function of times (26 March 2012).

Variations of absorbed, useful and stored energy are presented in Figure 3 and Figure 5 for different times during two days, 26 and 17 March 2012. Therefore, to evaluate the stored energy, the energy balance equation Eq. (1) has been used. A great part of the absorbed solar heat was stored inside the PCM. It is observed that during the initial period of charging, the instantaneous heat stored increases with insolation (Figure 3) and towards a maximum value of 1 kW at 13:00, we noted that at this time the absorbed heat is 2.2 kW, 45% of the solar energy is stored in the collector. During the charging process, Figure 5 shows the instantaneous stored heat fluctuate at the same time as insolation. As the discharging process proceeds, the PCM starts solidifying and the

used heat is uniform for a longer period. The uniform value of the used heat is about 200W/m^2 during 11 hours, we can also conclude that the useful heat was not affected by the solar radiations fluctuation during the day. This is the major advantage of a latent storage solar air heater, where a uniform discharging process is possible for a longer period, which will be useful for many applications of heating.

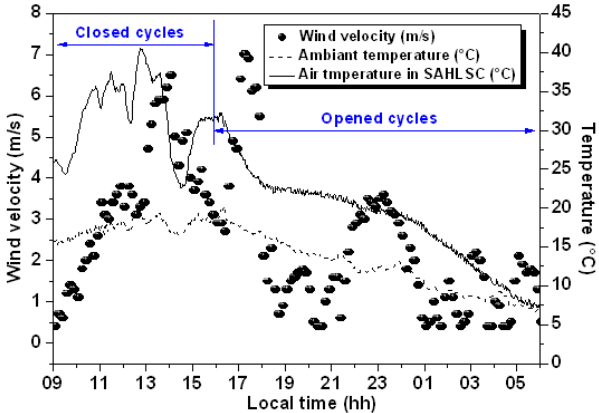


Figure 4: Ambient temperature, air temperature into SAHLSC and wind velocity as a function of times (17 March 2012).

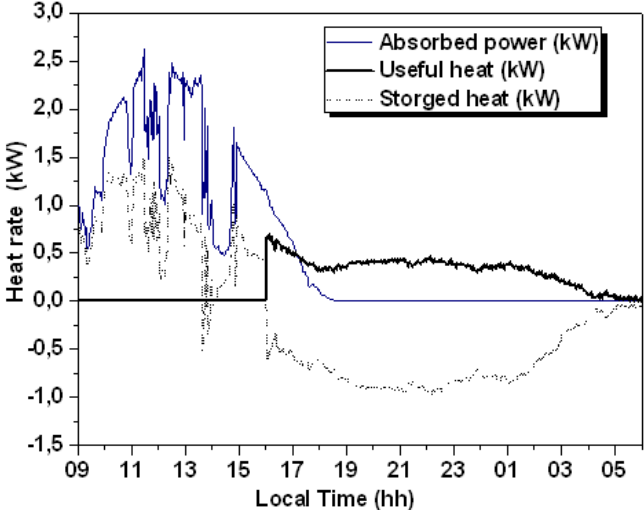


Figure 5: Absorbed, useful and stored heat rates as a function of times (17 March 2012).

The energy analysis of the SAHLSC was performed with data obtained from the experiments. Fig. 8 shows the values of the daily energy and exergy efficiency as function of days from 19 March 2012 to 30 March 2012 using Eq. (9). The daily average energy efficiency changed between 32% and 45%. The higher daily energy and exergy efficiencies are. The daily average value of energy efficiencies is about 40% obtained at 29 March 2012

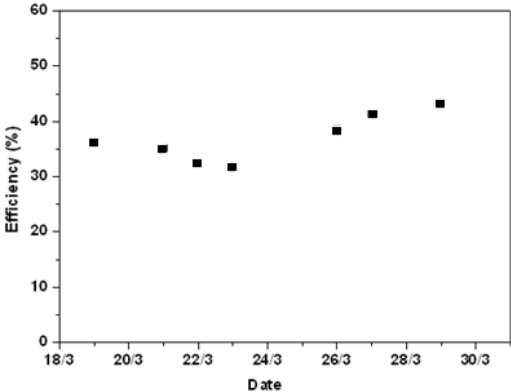


Figure 6: Daily energy efficiency as a function of days (19 March to 30 March 2012).

Conclusion

The solar air heater remains a uniform useful heat during the discharging process. The value of the heat was 200 W/m² during 11 hours at night. This useful heat was not affected by the severally global solar radiation fluctuation during the charging mode. In the Closed / Opened mode, the net daily energy efficiency of the SAHLSC varied between 32 % and 45 %.

Nomenclature

Symbole	Nom, unité	<i>a</i>	ambient
		<i>b</i>	bottom
A_c	surface area of the collector, m^2	<i>c</i>	cold
A_p	surface area of the absorber, m^2	<i>ch</i>	charging
C_p	specific heat, $J/kg^\circ C$	<i>dis</i>	discharging
I_T	solar radiation, W/m^2	<i>fin_ch</i>	final of the charging process
\dot{m}	mass flow rate, kg/s	<i>fin_dis</i>	final of the discharging process
\dot{Q}	heat rate, W	<i>ini_ch</i>	initial of the charging process
S	section area of the duct, m^2	<i>ini_dis</i>	initial of the discharging process
t	time, s	<i>l</i>	liquid phase
T	temperature, $^\circ C$	<i>los</i>	leakage, lost
\bar{T}	average temperature, $^\circ C$	<i>out</i>	outlet
T_m	melting temperature, $^\circ C$	<i>p</i>	absorber packed-bed
U	heat loss coefficient, $W/m^2^\circ C$	PCM	phase change material
Indices		<i>s</i>	solid phase
<i>A</i>	absorbed	<i>st</i>	storage

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