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Fabrication and Experimental Investigation of PCM Capsules Integrated in Solar Air Heater

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Abstract: Problem statement: Thermal Energy Storage (TES) process can reduce the time or rate mismatch between energy supply and energy demand. Organic latent heat materials are suitable to use as storage medium, however, the low thermal conductivity of these materials slow the thermal response during charging and discharging processes. **Approach:** A solar air heater integrated with (PCM) has been designed, fabricated and tested indoor. The system consists of top glazed isolated duct, air pump and array of PCM capsules plays to absorb the radiation and storing the thermal energy to discharge to demand when no radiation. Two cases were tested for storage medium used pure paraffin wax and paraffin wax-aluminum composite, the aluminum mass fraction was 0.5% and powder particulate size was 70 μm. Most of these experiments focused on discharge process. The outlet air temperature and thermal storage efficiency of the system has been studied. **Results:** Experimental results indicated that the charging time was reduced by approximately 70% when used the paraffin wax-aluminum composite. The thermal storage efficiency reached the maximum magnitudes 71.9 and 77.18% at mass flow rates 0.05 and 0.07 kg sec^{-1} for pure paraffin wax and the compound respectively. **Conclusion:** The discharging time was reduced by adding aluminum powder in the wax. The storage efficiency was increased after adding aluminum powder. The encapsulation procedure in this work was also explained.

Key words: Air heater, PCM, encapsulation, outlet temperature, discharge process

INTRODUCTION

Thermal energy storage becomes more important where the energy source intermittent such as solar. Energy storage process can reduce the interrupts in thermal energy supply to the demand. The thermal energy storage can be used in places where there is a variation in solar energy may by clouds like tropical areas or in areas where there is a high difference of temperature between day and night like desert areas.

In field of solar heating systems, water is still used as a heat storage material in liquid based systems, while a rock bed is used for air based system, but when you compare the volume requirements for the storage of heat energy between water and phase change material like Glauber's salt, you will see that the water heat storage requires almost five times amount of space as the Glauber's salt heat storage, this space savings would result in reduced costs for insulation and construction. Alkilani *et al*. (2009) and Solomon (1981), predicted the behavior of an array of PCM cylinders as a storage unit under some assumptions. The PCM used was a mix of sodium sulfate decahydrate and other salts with melting point of about 12.8°C, the results obtained from experiments agree fairly well with the predicted results.

Fatah (1995), developed a small and simple solar air heater integrated with thermal energy storage system. A set of copper tubes were filled with Different sensible and latent heat storage materials to study the difference between the materials in performance. Each capsule closed permanently using weld material then welded all the capsules in one row placed at the middle of the collector as an absorber. The results indicated that the heater filled with PCMs with 51 and 43°C melting temperatures gives the best performance, otherwise the system daily average efficiency varies between 27 and 63% depending on the PCM melting temperature, solar intensity and system air flow resistance.

Enibe (2002; 2003), constructed and studied a natural convection solar air heater with phase change

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material energy storage used the paraffin wax as a PCM, under natural environmental conditions involving ambient temperature variations in the range 19-41°C and daily global irradiation in the range 4.9-19.96 MJ m^{-2}. Peak temperature rise of the heated air was about 15°K, while peak cumulative useful efficiency was about 50%, the maximum predicted airflow rate was 0.01 kg sec^{-1}.

In this study, a solar air heater integrated with PCM unit has been designed and fabricated. Its outlet temperature and thermal storage efficiency during discharge process were studied experimentally. The experiments were carried out in indoor condition and parameters were measured by varying the mass flow rate of air.

MATERIALS AND METHODS

Experimental setup: This system consists of two essential parts which are: a single glazed thermal air collector and PCM storage unit, integrated together in one product. The physical dimensions of the tested thermal air collector are given in Table 1. The design takes into consideration many concerns such as, the integration with PCM storage unit, the simplicity of construction, dismantlement and handling the PCM unit, most of the collector dimensions were proposed in accordance with Choudhury (1995) studies on the design of solar air collectors. The dimensions were 300×128×15 cm (length × width × height), effective glazing area is 217×120 cm (length × width). Paraffin wax used as a PCM encapsulated in 53 aluminum cylindrical capsules fabricated in our laboratories. The insulation is glass wool 2.5 cm thickness. The aluminum capsules were coated with non-selective black paint then placed in the middle of collector arranged inline single row in the cross flow of pumped air as shown in Fig. 1. Spaces opened between the capsules to increase the heat exchanging to the pumped air.

Solar simulator: Thermal air collector integrated with PCM unit was tested under solar simulator which has 40 tungsten halogen lamps each has 500W and rated at 240 V and 11 A. The halogen lamps are arranged in 8 lines where each line contains 4 or 5 lamps for uniform distribution of irradiance. The dimensions of the simulator are 320×210 cm. the distance chosen is suitable with an average distance between the simulator lamps built by (Garg *et al*., 1985) for 35 cm. The distance between simulator and the collector surface is 120 cm. Intensity of the radiation simulator is controlled by 40 controllers.

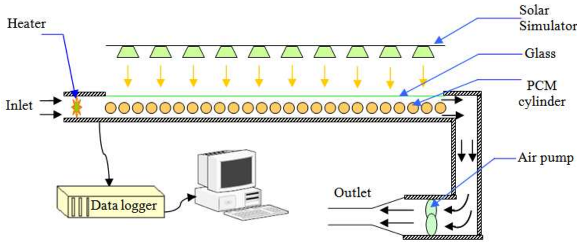


Fig. 1: Schematic diagram of the experimental system

Table 1: Thermo physical dimensions of the tested thermal air collector

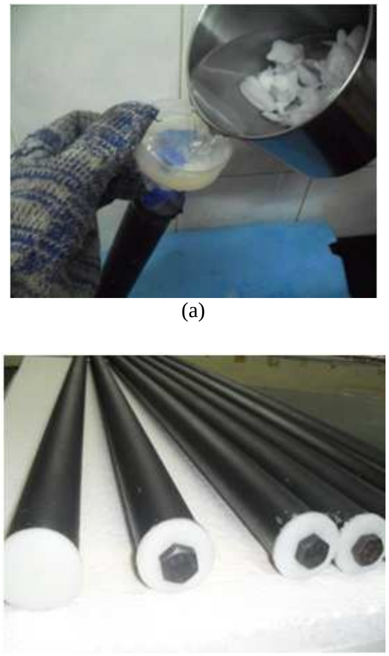
Parameter	Value
Collector length	300 cm
Collector width	128 cm
Collector height	15 cm
Channel depth	10 cm
Effective glazing area	217×120 cm
Glass thickness	0.4 cm
Insulation thickness (glass wool)	2.5 cm
Spacing between capsules	0.2 cm
Capsule surface emmittance	0.98
Capsule surface absorbance	0.98

Table 2: Thermophysical properties of paraffin wax phase change material

Property	Value
Latent heat of fusion	189 kJ/kg
Melting temperature	53°C
Thermal conductivity	0.2 W/m °K
Specific heat	2.5 kJ/kg °K
Liquid density	770 kg m^{-3}
Kinematic viscosity	3.3-3.6 mm^2/sec at 373°K

Fabrication of capsules: Microencapsulation means filling the PCM in a macroscopic containment that fit amounts from several ml up to several liters. These are often containers and bags made of metal or plastic (Mehling and Cabeza, 2008). The advantage of the microencapsulation is that the possibility to apply with both liquid and air as heat transfer fluids and easier to ship and handle (Lane, 1976; 1980; Baehr and Stephan, 2010).

In general, the storage unit should satisfy the following specifications: less volume, higher thermal storage efficiency, easier for installation (Dismantling and handling), cheaper, storage medium non hazardous and non interactive with the container. The thermophysical properties of the PCM are given in Table 2. While the physical dimensions of the capsules are given in Table 3. The storage unit consists of 53 kg paraffin wax encapsulated in a set of 3.77 cm diameter aluminum tubes. These capsules are work as a solar energy absorber and to store the thermal energy.


(a)

(b)

Fig. 2: Encapsulation process: (a) melting and pouring the paraffin wax (b) sealing the capsules

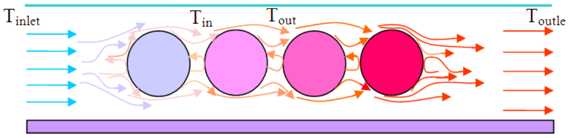


Fig. 3: Schematic diagram of freezing process in row of PCM cylinders in cross flow of pumped air

Table 3: Capsules physical dimensions

Parameter	Value
Number of capsules	53
Capsule length	120 cm
Capsule outer diameter	3.770 cm
Capsule thickness	0.15 cm
Total weight of PCM	50 kg

The capsule ends were sealed by nylon caps fixed by screws and epoxy has properties, waterproof, resistant to chemical and heat, available in the market, it commercial name is Araldite. The paraffin blocks were shredded into small pieces for easy melting then poured inside the tube via a big screwed hole made in order to re-use the capsule many times, such as if need to add some additives to enhance heat transfer or change the entire storage medium as shown in Fig. 2. The screw was closed when the tube was filled with paraffin wax in liquid phase, so as to reduce the PCM pressure during charging process. All these precautions were taken to prevent any leakage or expansion problems. The PCM melting point was tested experimentally in our laboratory using electro thermal melting point apparatus model 9100 refers that the melting point between 53-54°C.

Theoretical Background: During discharge process when no radiation and the PCM was initially at liquid phase. We consider a typical PCM cylinder in a row of N PCM cylinders in cross flow of pumped air has a constant inlet temperature T_i and a constant mass flow rate of $\dot{m}_a$, let T_{in}, T_{out} be the transfer fluid temperature before reaching a typical cylinder and after leaving it as shown in Fig. 3, conservation of energy Eq. 1 will be:

$$(T_{in}-T_{out})C_a\dot{m}_a = 2\pi R_o lh(T_{in}-T_{sfc})+\varepsilon A\sigma(T_{sfc}^4-T_{sur}^4) \quad (1)$$

Where:

T_{in} = Air temperature before the cylinder (°C)
T_{out} = Air temperature before the cylinder (°C)
C_a = Specific heat for air (kJ/kg °C)
$\dot{m}$ = Mass flow rate (kg/s)
R_o = Outside radius (m)
l = Capsule length (m)
h = Heat transfer coefficient (kJ/m^{2}s°C)
T_{sfc} = Capsule surface temperature (°C)
ε = Emissivity (-)
A = Capsule area (m^2)
σ = Stephan-Boltzman constant (kW/m^2 K^4)
T_{sur} = Surrounding temperature (°C)
T_m = Melting temperature (°C)

The heat transfer coefficient of flow normal to banks of tubes in line approximated (McAdams, 1954):

$$h = (K_a/D_o)\, b_2\, Re^n \quad (2)$$

Where:

K_a = Thermal conductivity of air (kW/m °C)
D_o = Outside diameter (m)
Re = Reynolds number (-)
b_2 and n = Constants equal to 0.3 and 0.6 respectively

Equation 2 used by (Solomon, 1981) to predict the behavior of a PCM cylinder array.

The cost of materials and fabrication of the TES unit and its efficiency are related to each other. The efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the thermal storage unit to the energy stored into it. The following Eq. 3 has been used to compute the efficiency of thermal energy storage:

$$\eta = \frac{Q_o}{Q_o + Q_L} \qquad (3)$$

Where:

η = TES efficiency

Q_o = Heat retrievable from TES (kw)

Q_L = Heat lost to the environment (kw)

RESULTS AND DISCUSSION

The experiments were carried out on this system during charge and discharge period to evaluate the outlet air temperature and to monitor the PCM temperature. The PCM unit has been charged using solar simulator by 700 W m^{-2} and inlet temperature was 35°C. The air temperature increased from 35°C and reached 51°C at the last capsule during discharge process when the mass flow rate at a constant value equal to 0.05 kg sec^{-1}.

Figure 4 indicates that for thermocouple fixed in the middle of a capsule, at the melting temperature (T_m) the melting time for pure wax was 70 min, while that for the composite was approximately 50 min, when the air mass flow rate and initial temperature of PCM were 0.05 kg sec^{-1} and 32°C respectively. The increase in the temperature of the composite is due to the high thermal conductivity of the aluminum powder. Variation of outlet temperature of air heater versus time during discharge process when used pure PCM is shown in Fig. 5, where mass flow rate was varied from 0.03-0.09 kg sec^{-1}. The stability for outlet air temperature is clarified in the curves during time intervals of around 45-50 min. The effect on PCM temperature by varying the mass flow rate during discharge process is shown in Fig. 6 when T_i = 35°C. Mass flow rate varies from 0.03, 0.05, 0.07 and 0.09 kg sec^{-1}. Figure 7 shows that the Variations of compound temperature versus time (the mass fraction was 0.5 Al powder) at various mass flow rate and T_i = 35°C. Comparison of temperature inside the PCM for both cases of pure paraffin and composite (discharge process) shown in Fig. 8 at $\dot{m}$ = 0.03 kg sec^{-1} and T_i = 35°C. From the figure, we can see that the heat transfer rate is increased for composite as compared to that for paraffin wax.

In Fig. 9 as the mass flow rate increases, thermal storage efficiency increases and approaches the stability condition in the flow rate over 0.05 kg sec^{-1}. The maximum value of the storage efficiency is equal to 71.13% for pure paraffin wax at mass flow rate while reaches 76.85% for the composite. The melting and freezing time decreases with increase in mass flow rate, also decreases when the aluminum powder percentage in the compound increased.

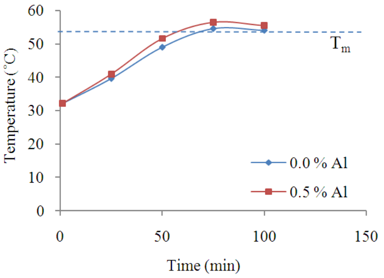


Fig. 4: Variation of PCM temperature inside the capsule for pure paraffin wax and composite (charging process)

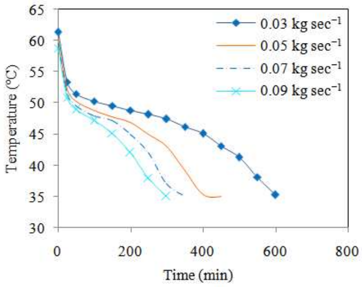


Fig. 5: Experimental variation of outlet temperature for pure wax at various mass flow rates and T_i = 35°C

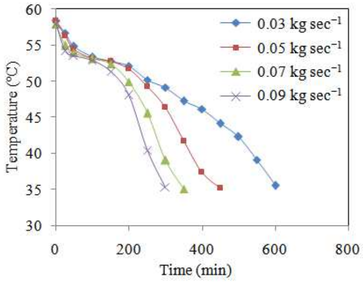


Fig. 6: Variations of pure PCM temperature versus time at various mass flow rates (discharging process)

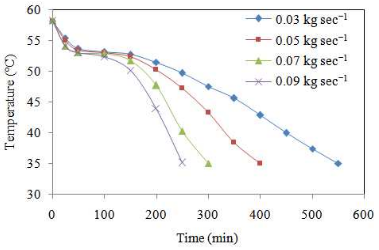


Fig. 7: Variations of compound temperature versus time at various mass flow rate and T_i = 35°C

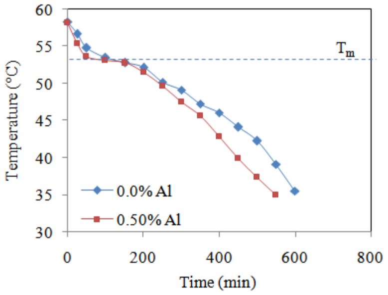


Fig. 8: Comparison of temperature inside the PCM (discharge process). For pure paraffin and composite at $\dot{m} = 0.03$ kg sec^{-1} and $T_i = 35$°C

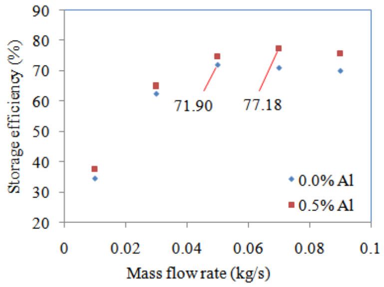


Fig. 9: Effect of mass flow rate on thermal storage efficiency for pure paraffin wax and the compound when $T_i = 35$°C

CONCLUSION

In this study, an indoor testing system consisting of solar heater integrated with PCM unit has been fabricated and studied. The charging time decreased by 70% for composite than pure paraffin wax due to the high thermal conductivity of the aluminum powder. Thermal storage efficiency of the solar heater obtained at indoor condition reached the maximum magnitudes which were 71.9% and 77.18% at mass flow rates 0.05 and 0.07 kg sec^{-1} for pure paraffin wax and the compound(paraffin wax with 0.5% mass aluminum powder)respectively. The capsules fabrication procedure can be used by manufacturers and researchers in laboratories.

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