Energy for Sustainable Development 29 (2015) 112–117

Contents lists available at ScienceDirect

Energy for Sustainable Development

Thermal performance of packed bed heat storage system for solar air heaters

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ARTICLE INFO

Article history:
Received 21 September 2014
Revised 23 October 2015
Accepted 27 October 2015
Available online xxxx

Keywords:
Packed bed
Rock pebble
Heat storage
Solar air heater
Solar collection efficiency
Heat retrieval

ABSTRACT

Thermal performance of the packed bed solar heat storage system was studied under varying solar and ambient conditions in different months. The insulated packed bed heat storage unit was filled with 8500 kg rock pebbles. The solar collection and heat retrieval efficiency of heat storage system ranged between 36–51% and 75–77%, respectively. Heat retrieval efficiency of the developed packed bed was found better as compared to the packed bed filled with phase change material (PCM). The experimental values were found in good conformity with predicted values of the packed bed temperature and hot air temperature retrieved from the bed.

Introduction

Solar energy is environment friendly and available most of the places. It can be harnessed for thermal applications. However, time dependent nature of solar energy is a major disadvantage (Duffie and Beckman, 2006). The unit operations, such as drying and heating, can be performed during the day time only. In order to overcome this, it is required to attach thermal energy storage devices with solar gadgets. The stored energy can be utilized during non-sunny hours or under peak load conditions. The packed bed is generally recommended for attaching with solar air heater in order to store thermal energy of hot air (Duffie and Beckman, 2006; Hseih, 1986). The packed bed is a large insulated container filled with loosely packed rock pebbles of a few centimetres in diameter (Hseih, 1986). The rock pebble size should be uniform enough to obtain large void fractions and to minimize pressure drop (Duffie and Beckman, 2006; Hseih, 1986). Circulation of the air through the void of the packed bed results in natural or forced convection between the air and rocks. Packed bed performs dual function of storing heat and acts as heat exchanger during heat retrieval (Hseih, 1986; Regin et al., 2008). The rocks has several characteristics that are desirable for solar energy applications—good heat transfer coefficient between the air and solids; lower cost of storage material and lower conductivity of the bed when air flow is not present (Dilip, 2005; Hadley and Heggs, 1969; Chandra et al., 1981; Garzoli, 1989; Tian and Zhao, 2013; Coutier and Farber, 1982).

Adeyanju and Manohar (2013) studied thermal behavior of a simultaneous charging and discharging of concrete bed during a heating cycle and developed model for design of flat plate solar collector. Thermal behavior of the packed bed heat storage system filled with phase change material capsules was analyzed numerically by Regin et al. (2009). A longer solidification time as compared to melting time was found due to very low heat transfer coefficient (Regin et al., 2009). Predominant role of system parameters on heat transfer characteristics of the packed bed was studied analytically by Singh et al. (2008). Maithani et al. (2013) investigated analytically the effect of stratification on thermal performance of large-sized packed bed elements for solar heat storage. The effective efficiency and frictional losses were strong function of geometrical parameters of the bed element (Maithani et al., 2013). In a theoretical study, Danok et al. (2011) found that the pressure drop decreased with increase in equivalent diameter of pebbles in the rock bed heat storage unit. However, it decreases the heat storage capacity. Therefore, in order to have increased heat storage capacity and reduced pressure drop, medium-sized rock pebbles (equivalent diameter 50 mm sizes) were filled in the packed bed under this study.

The present work presents a mathematical model to study packed bed heat storage system. Performance of the heat storage system filled with 8500 kg rock pebbles was also studied experimentally under charging and heat retrieval mode. Solar collection and heat retrieval efficiency of the developed system was compared with the underground rock filled and PCM (paraffin capsules) filled packed bed heat storage systems.

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http://dx.doi.org/10.1016/j.esd.2015.10.010

Nomenclature

A_c	area of solar collector, m^2
A_r	cross-sectional area of the packed bed, m^2
C_{pa}	specific heat of air, kJ/kg °C
C_{pb}	specific heat of rock pebble, kJ/kg °C
dt	period of data taken, s
D_e	equivalent spherical diameter, m
h_v	volumetric heat transfer coefficient, W/m^3 °C
I	solar intensity, W/m^2,
m_a	mass of air flow per unit time, kg/s
n_t	total numbers of rock pebble
PCM	phase change material
Q_c	heat energy collected in the packed bed, kW
Q_{rc}	heat energy retrieved from the packed bed, kW
t	time, s
T_{pb}	temperature of the pebble bed, °C
T_{in}	inlet fluid (air) temperature, °C
T_{out}	outlet fluid (air) temperature, °C
T_a	ambient temperature, °C
V_t	total volume of the rock pebbles, m^3
dT/dt	temperature gradient of node, °C/s
Δx	thickness of the nodal elements, m
ρ_a	density of air, kg/m^3
ρ_{pb}	density of the pebbled bed including voids, kg/m^3
ε	void ratio
η_c	packed bed collector efficiency, %
η_{rc}	heat retrieval efficiency of the bed, %

Added subscripts/superscript

s	any pebble bed segment
P	time step

Experimental

Packed bed solar heat storage system

The schematic diagram of the packed bed solar heat storage system is shown in Fig. 1. It consisted of the solar collector, packed bed heat storage unit, blower and control valves. The packed bed heat storage unit was a rectangular box filled with 8500 kg rock pebbles (equivalent diameter 50 mm size). Cross-sectional area of the bed (A_r) was 4.5 m^2. Overall size of the packed bed box was 1.5 m × 3.0 m × 1.4 m. Thickness of the stone pebble bed was 1.17 m. The solar air heating collectors (collector area: 12 m^2) were attached with the heat storage unit to add heat into rock pebbles. The heat storage box was insulated at all sides to reduce heat loss. Under heat charging mode, hot air from the solar collector was passed through packed bed heat storage unit. In discharging mode, hot air was retrieved from the packed bed by allowing fresh air through the heat storage unit. A centrifugal blower was provided for air circulation through the bed. During heat charging, the circulating air flow rate between solar air heaters and packed bed was maintained at 0.147 m^3/s. The exit hot air flow rate during heat retrieval mode was maintained at 0.0833 m^3/s.

Measurements

Performance of the packed bed heat storage system was studied under varying solar insolation and ambient conditions in March, April and May months. Temperature gain in the packed bed during charging mode, and exit hot air temperature retrieved from packed bed during discharging mode were measured. Packed bed temperature was measured at five points during charging mode and average was worked out. The pre-calibrated thermocouples were used for temperatures measurement. The air temperature at inlet and outlet of packed bed heat storage box was measured during heat retrieval mode. Ambient temperature, relative humidity and wind speed were also measured during the test. Under steady state condition, variation in the temperatures was within ±0.1 °C. Solar irradiation was measured by pyranometer (National Instrument Company, India make) kept on the adjustable base plate at the slope of solar collector. The dry bulb and wet bulb thermometers and psychometric chart were used for relative humidity measurement. The air speed in the duct was measured with help of digital hot wire anemometer for obtaining air flow rate. Wind speed was measured using digital anemometer.

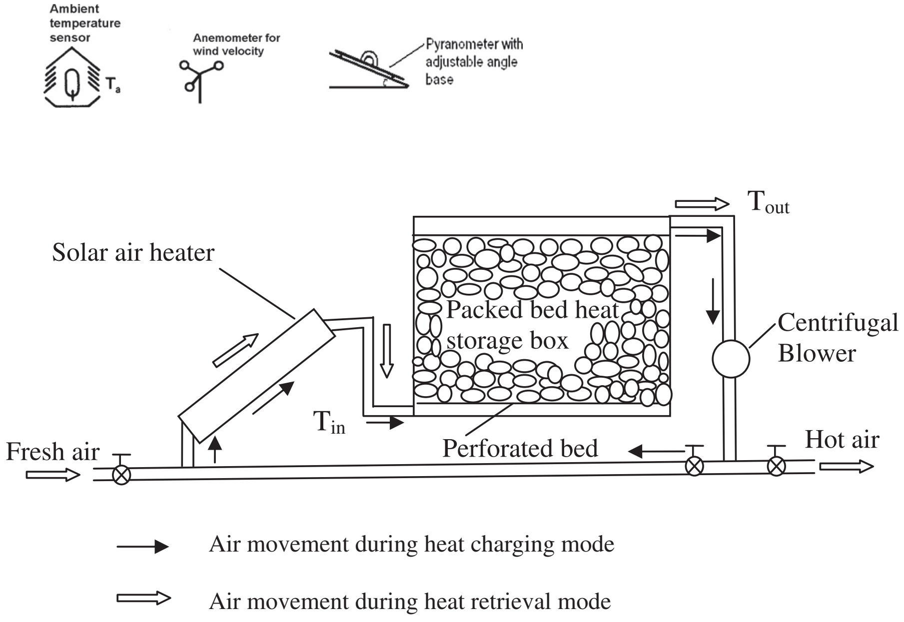

Fig. 1. Schematic diagram of operations of packed bed heat storage system.

Table 1
Physical properties of the rock pebble packed bed.

Parameters	Values
Specific heat of the rock pebbles (C_{pb}), kJ/kg °C (Hseih, 1986)	0.88
Porosity (void ratio), %	47 (measured)
Specific heat of air (C_a) (for range 30–50 °C), kJ/kg °C (Hseih, 1986)	1.0
Density of air (for range 30–50 °C), kg/m^3 (Hseih, 1986)	1.1
Equivalent diameter (D_e) of rock pebbles, mm	50 [calculated from Eq. (1)]
Volumetric heat transfer coefficient of bed, W/m^3 °C	347 [calculated from Eq. (6)]

Determination of equivalent rock pebble diameter, porosity, and pebble density

The porosity was determined by measuring volume of a container with rock pebbles and volume of water in the same container. Division of the former to the latter one gave the porosity of rock pebble bed (Kürklü et al., 2003). Equivalent diameter (D_e) of the rock pebbles was calculated by using the equation given below (Chandra et al., 1981):

$$D_e = \left[\frac{6V_t(1-\varepsilon)}{\pi . n_t}\right]^{1/3}. \tag{1}$$

Density of the rock pebbles was determined by net weight of the pebbles in the container divided by volume of the container. Taking the container volume into consideration, the density was then expressed as kg/m^3. The thermo-physical properties of the used rock pebbles bed are given in Table 1.

Solar energy collection and heat retrieval efficiencies

Solar collection efficiency of the heat storage system is the indicator of system efficiency to trap and store solar energy into it. Similarly, heat retrieval efficiency of the heat storage system is the ability to discharge heat energy out of the stored energy. Eqs. (2) and (3) were used for calculation of the solar energy collected and heat retrieval, respectively (Duffie and Beckman, 2006; Hseih, 1986):

$$Q_c = mC_{pa}(T_{in} - T_{out}) \tag{2}$$

$$Q_{rc} = mC_{pa}(T_{out} - T_{in}). \tag{3}$$

The solar collection and heat retrieval efficiencies were determined with help of Eqs. (4) and (5), respectively (Kürklü et al., 2003). The heat loss from the packed bed to the surrounding was not taken in to account during calculation.

$$\eta_c = \frac{\int_{t1}^{t2} Q_c dt}{\int_{t1}^{t2} IA_c dt} \tag{4}$$

$$\eta_{rc} = \frac{\int_{t1}^{t2} Q_{rc} dt}{\int_{t1}^{t2} Q_c dt}. \tag{5}$$

The solar collection and heat retrieval efficiencies of the developed packed bed heat storage system have been compared with other kind of the packed bed heat storage systems, such as the underground rock filled packed bed; and the paraffin capsules (as PCM) filled packed bed heat storage systems.

Modeling of the packed bed

Energy equations that govern heat transfer in the system are based on the following assumptions: the bed is uniformly packed having the same apparent density and uniform apparent thermal capacity throughout; thermal gradient within the solid particles are negligible; and the heat transfer in the rocks in the radial direction were neglected. The numerical finite difference approximation was applied for modeling the pebble-bed. The pebble-bed was divided into equal thickness segments/nodes in the opposite direction of the air flow. Fluid (air) temperature at the centre of each segment was calculated using the developed model. The volumetric heat transfer coefficient (h_v) was calculated as given below (Löf and Hawley, 1948):

$$h_v = 652\left[\frac{m_a}{A_r D_e}\right]^{0.7}. \tag{6}$$

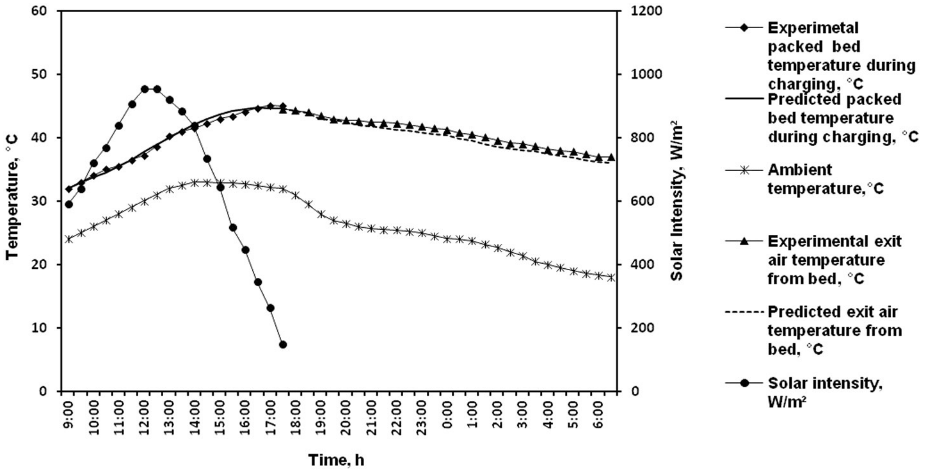

Fig. 2. Packed bed temperature during heat charging, exit hot air temperature during heat retrieval, solar insolation and ambient temperature in March. The bed temperature rose slowly during heat charging mode and continue to increase up to evening, though solar intensity started decreasing during afternoon.

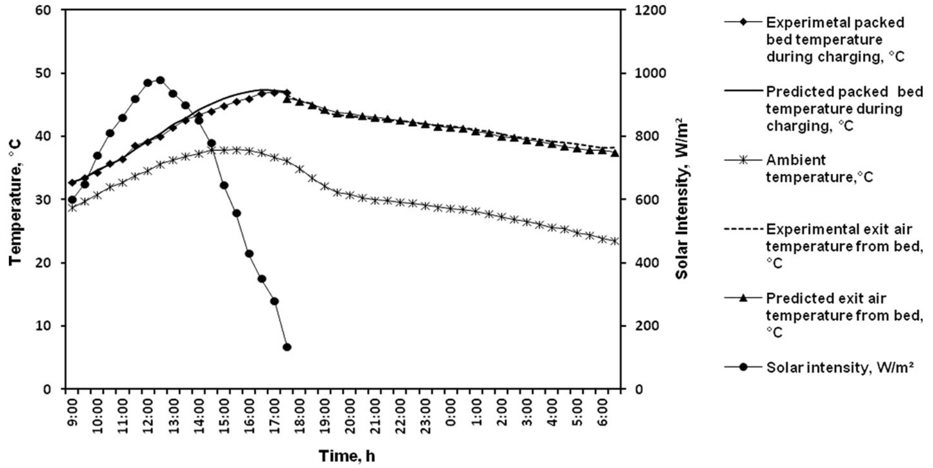

Fig. 3. Packed bed temperature during heat charging, exit hot air temperature during heat retrieval, solar insolation and ambient temperature in April. The packed bed temperature during charging mode rose from 32.7 °C to 47 °C as compared to 32 °C to 45 °C in March.

Air temperature and rock pebble temperatures were considered to be equal in any segment because the calculated value of the h_v was found quite higher (Table 1). The following rule was used for stability of numerical equations (Garzoli, 1989):

$$\frac{h_v A_r \Delta x}{m_a C_{pa}} < 1. \tag{7}$$

The whole bed was divided in to 30 nodes/segment and thickness of each segment was 0.039 m. The energy balance of any node was as given below:

$$\rho_b C_{pb} A_r \Delta x \left(dT_{pb,s}/dt\right) = h_v A_r \Delta x \left(T_{a,s-1} - T_{a,s}\right). \tag{8}$$

Considering air and rock pebble temperatures equal, $T_{\mathrm{a,s}} = T_{\mathrm{pb,s}}$ the Eq. (8) can be re-written as:

$$\rho_b C_{pb} A_r \Delta x \left(dT_{pb,s}/dt\right) = h_v A_r \Delta x \left(T_{a,s-1} - T_{pb,s}\right). \tag{9}$$

Considering any step 'P' and next step 'P + 1', Eq. (9) can be expressed as:

$$\rho_b C_{pb} A_r \Delta x \left(T^{P+1}_{pb,s} - T^{P}_{pb,s}\right) = h_v A_r \Delta x \left(T^{P+1}_{a,s-1} - T^{P+1}_{pb,s}\right) dt. \tag{10}$$

By keeping the period interval (dt) for data as one minute (60 s, expecting slow increase/decrease in the bed temperature), the value of $T^{P+1}_{pb,s}$ can be obtained from Eq. (10) and written as:

$$T^{P+1}_{pb,s} = \frac{60 m_a C_{pa} T^{P+1}_{a,s-1} + \rho_r C_{pb} A_r \Delta x T^{P}_{pb,s}}{60 m_a C_{pa} + \rho_r C_{pb} A_r \Delta x}. \tag{11}$$

To calculate in the next time step, $T^{P}_{pb,s}$ was taken equal to $T^{P+1}_{pb,s}$ and the calculations continued till the required final time.

Results and discussion

Performance of the packed bed heat storage system under charging and heat retrieval mode

Fig. 2 shows the experimental and predicted values of the average packed bed temperature during charging mode and exit hot air temperature during heat retrieval mode on a day in March. The packed bed temperature increased slowly from 32 °C to 45 °C during the day (9:00 h to 17.30 h). Solar intensity during the day was between 400 and 900 W/m^2. The average ambient temperature and relative humidity were 29 °C and 43%, respectively. The temperature rise of the pebble bed was attributed to accumulation of solar energy by solar collectors into pebble bed. Similar results were also obtained by other authors

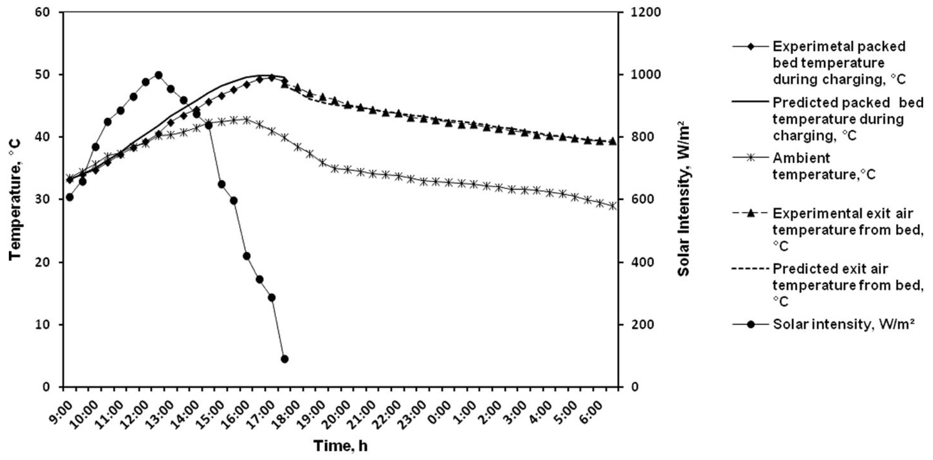

Fig. 4. Packed bed temperature during heat charging, exit hot air temperature during heat retrieval, solar insolation and ambient temperature in May. The packed bed temperature during charging mode rose from 33.2 °C to 49 °C as compared to 32 °C to 45 °C in March.

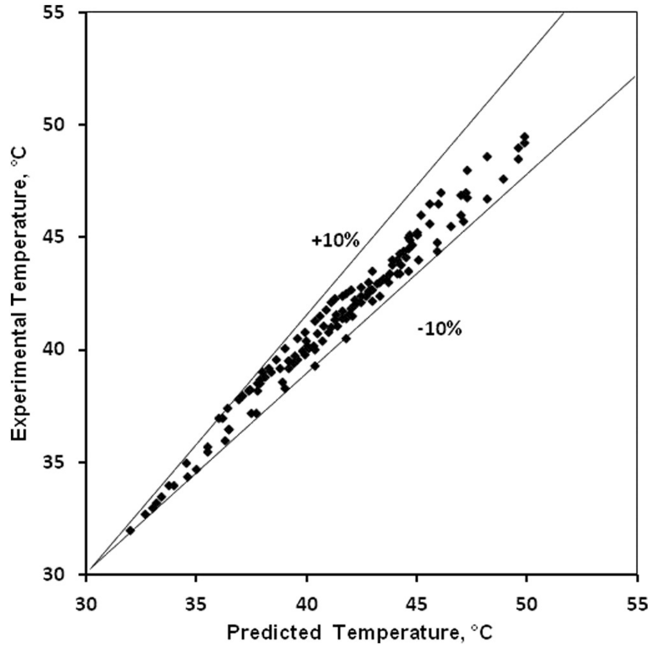

Fig. 5. Predicted versus experimental values of the packed bed and exit hot air temperature.

(Harmeet et al., 2010; Valan Arasu and Sornakumar, 2006; Nallusamy et al., 2006). During 13 h of operation after sunset, the average exit hot air temperature from the bed was 41.5 °C. It varied from 37 °C to 44.5 °C (Fig. 2). The ambient temperature and relative humidity during the heat discharging test were 18–32 °C and 35–50%, respectively. Wind speed during the test was varied between 0.1 and 1.4 m/s. The exit hot air temperature was slowly reduced during the heat retrieval. This may be attributed to reduction in ambient temperature and stored heat reserve in the bed. The predicted values of the packed bed temperature and exit hot air temperatures were within ±2 °C of the actual values.

Similar results were also obtained during other months. The packed bed temperature was raised from 32.7 °C to 47 °C and 33.2 °C to 49 °C from morning to evening during April and May, respectively (Figs. 3 and 4). The average exit hot air temperature during heat retrieval mode was 42.8 °C (from 38.3 to 46.5 °C) and 44 °C (from 39.5 to 48.6 °C) in April and May, respectively. The higher temperature as compared to March may be attributed to higher solar intensity and ambient temperature in April and May. The ambient temperature during heat retrieval test in April and May was 23.5–36.1 °C and 29–40 °C, respectively. The relative humidity during the test was 40–52% and 35–47% in April and May, respectively. Wind speed during the test varied between 0.1 and 1.5 m/s in April and May.

Table 2
Comparative solar collection and heat retrieval efficiencies of the packed bed heat storage systems.

Type of the packed bed heat storage system	Solar collection efficiency	Heat retrieval efficiency
The packed bed solar heat storage system with stone pebbles under this study.	43.5%	76%
Underground packed bed heat storage filled with rock pebbles coupled with green house by Kürklü et al. (2003).	34%	80%
Solar thermal energy storage unit containing spherical capsules of paraffin as PCM with different heat transfer fluid flow rate by Nallusamy et al. (2006).	50-70%	72%
Solar heat storage system with spherical capsules packed bed filled with Paraffin as PCM by Wu et al. (2011).	Not available	66.4%

Fig. 5 shows the comparison between experimental and predicted values of the packed bed temperature and exit hot air temperature from the bed. The experimental results match with the predicted ones with 10% accuracy.

Comparative solar collection and heat retrieval efficiencies of the packed bed heat storage systems

Table 2 shows the comparison of efficiencies of the developed system and other types of packed bed heat storage systems, such as the underground rock filled packed bed heat storage system built within the green house structure, and packed bed heat storage system filled with paraffin capsules as PCM. The average solar collection efficiency of the developed packed bed heat storage was 43.5%. It varied from 36% to 51%. The increase in collection efficiency was observed with increase in the temperature difference between inlet hot air and bed temperature. The average heat retrieval efficiency of the packed bed heat storage system was 76% (from 75 to 77%). Kürklü et al. (2003) found 34% solar collection efficiency and 80% heat retrieval efficiency of the heat storage system for heating of the green house. Lower collection efficiency of the heat storage unit may be attributed to weak insulation characteristics of the plastic cover over green house collector. In the case of PCM (paraffin) filled heat storage system studied by Nallusamy et al. (2006), the solar collection efficiency was found in the range of 50–70% with different fluid flow rate used for heat transfer. The higher collection efficiency may be attributed to the better heat transfer characteristic in case of PCM as compared to the rock pebbles. The higher specific heat of the paraffin (1.85 kJ/kg/°C) as compared to the rock bed (0.88 kJ/kg/°C) might also have contributed to the better collection efficiency. The heat retrieval efficiency of the PCM based heat storage system was found in the range of 66.4–72% by Nallusamy et al. (2006) and Wu et al. (2011) as compared to 76–80% in case of rock pebble packed bed (Table 2). The higher retrieval efficiency in case of rock filled packed bed may due to better heat exchange properties of the rock pebble bed.

Conclusions

The study indicated that packed bed solar heat storage system was found suitable for storing heat from solar air heaters. Temperature gain in the packed bed was significantly affected with the input solar insolation. Temperature of the packed bed was raised up to 49 °C from 34 °C during charging mode. The average exit hot air temperature was ranged between 41.5 and 44 °C during 13 h of operation after sunset. The experimental values were found in good conformity with predicted values of the packed bed temperature and hot air temperature retrieved from the bed. The average solar collection efficiency of the heat storage system was 43.5%. Heat retrieval efficiency of the packed bed (75–77%) was found slightly better as compared to the same in PCM based heat storage system (66.4–72%) (Nallusamy et al., 2006; Wu et al., 2011).

Acknowledgement

The authors are very thankful to Director, CIAE, Bhopal for providing research facilities and valuable guidance.

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