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

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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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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.

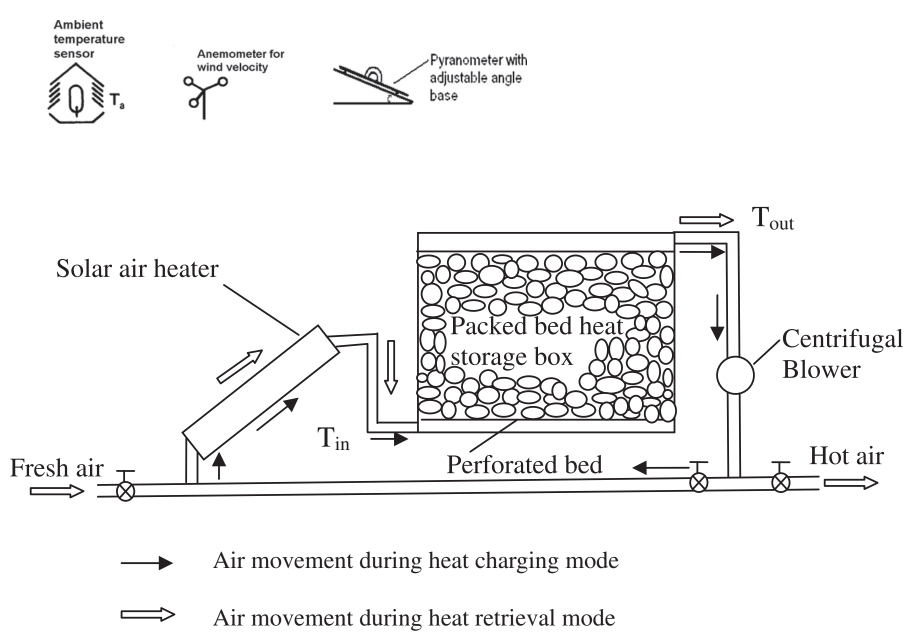

Fig. 1. Schematic diagram of operations of packed bed heat storage system.