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Simulated Performance of Packed Bed Solar Energy Storage System having Storage Material Elements of Large Size - Part I

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Abstract: Packed bed or rock bed is very commonly known thermal energy storage component for solar air heaters. The major concern for design of packed bed energy storage system is to maximize the heat transfer with minimum pressure drop or pumping power. Under the given operating conditions, system parameters could affect heat transfer and pressure drop in the bed considerably. An attempt has been made to report the simulated performance of a packed bed solar energy storage system. Large size storage material elements of five different shapes have been used to carry out the present simulation study. Nusselt number and friction factor correlations reported by the authors under previous experimental study have been utilized to analyze the packed bed energy storage system for a range of system and operating parameters. Performance of the system has been evaluated based on temperature distribution, thermal energy stored and available energy stored in the bed, energy consumption by fan to propel air through the bed and thermal efficiency of the collector as a function of system and operating parameters. In present part of the paper, various component models of packed bed solar energy storage system and development of computer program have been reported. Results of simulated system performance have been reported and discussed in Part-II and III of this paper.

Keywords: Packed bed, solar air heater, thermal energy storage.

1. INTRODUCTION

Solar energy is most important among renewable energy sources due to its quantitative abundance. In order to face the problem of energy crisis and environmental threat as a result of continuous use of fossil fuels, scientists and researchers are putting efforts to develop technologies for an effective use of solar energy. People may use energy for many purposes, but a few general tasks like heating, cooling, electricity generation, transport and industry consume most of the energy. Solar energy can be applied to all these tasks with different levels of success. However, intermittent nature of solar energy demands an integration of energy storage system with the solar collectors in order to make solar energy source more reliable. Packed bed or rock bed system is well known for various engineering applications. It can also be used with solar air heating system for storing thermal energy of hot air. Thermal energy stored in the packed bed may be useful to have uninterrupted supply of energy in the absence of solar radiation and also to fulfill the peak load energy demands even in the presence of solar radiation.

Packed bed consists of energy storage material elements packed in a container. Hot air from solar collector/s flows from top to bottom of the bed in order to transfer heat energy to the storage material elements during charging phase. Energy stored in the bed can be extracted by making flow of air through the bed from bottom to top during discharging phase. Heat transfer to and from a flowing fluid in a packed bed has been the subject of many theoretical and experimental investigations for various engineering applications. Schmidt and Willmott [1] mentioned that the distinct disadvantage of packed bed is the large pressure drop, which causes a large amount of energy consumption by fan to propel hot air through the bed.

The literature reveals that system design must be based on the methods to reduce pressure drop in the bed in order to enhance the effective use of solar energy storage system. Sagara and Nakahara [2] reported that large size material elements can be used for reducing pressure drop in the bed. Singh *et al.* [3] carried out an extensive experimental study to analyze the effect of shape of large sized material elements and void fraction of the bed under set of operating conditions. In order to predict the performance of the packed bed system Nusselt number and friction factor correlations as a function of Reynolds number, sphericity and void fraction of the bed have been developed by the authors. Authors reported that the system parameters play a predominant role to influence heat transfer and fluid flow characteristics of packed bed energy storage system. Therefore, it is necessary to investigate the effect of these parameters on thermal and hydrodynamic performance of packed bed energy storage system. The present part of the paper deals with development of a computer program by using the component models in order to predict performance of the system based on temperature distribution in the bed, thermal energy stored in the bed, energy consumption by fan to propel the air through

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the bed and thermal efficiency of the collector as a function of system and operating parameters. Nusselt number and friction factor correlations reported by Singh *et al*. [3] have been used in the present simulation study. Results of simulated system performance have been reported and discussed in Part-II and III of this paper.

2. MODELING AND ANALYSIS OF PACKED BED SOLAR ENERGY STORAGE SYSTEM

The schematic of a conventional packed bed solar energy storage system operating in a closed cycle is shown in Fig. (**1**). For carrying out the present simulation study, it is assumed that during charging phase, temperature of air at the outlet of collector will become an inlet temperature to the bed and temperature of air at outlet of the bed will become an inlet temperature to the collector. It has also been assumed that system has no heat loss to the surroundings. The range of system and operating parameters and values of other parameters used in the present simulation study are given in Table **1**. The charging time (t_{ch}) for the bed has been taken as eight hours by considering average sunshine hours during a sunny day. Development of computer program for carrying out the present simulation study involves sizing of the packed bed and mathematical models of solar air heater and packed bed.

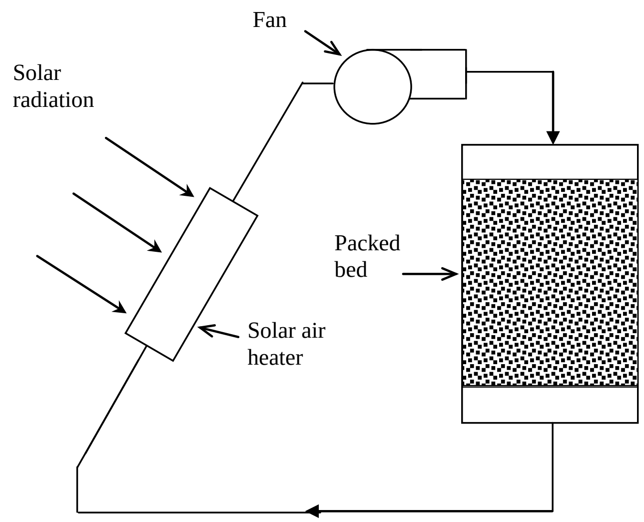

Fig. (1). Schematic of packed bed solar energy storage system.

2.1. Sizing of Packed Bed

It is generally required to size the bed corresponding to the amount of energy to be stored at the required temperature. The size of the bed should be fixed in such a way that the bed absorbs maximum amount of energy delivered by the flowing air during charging phase and mean temperature of the bed at the end of the charging should

Table 1. Value/Range of System and Operating Parameters

S. No.	Parameter	Value/Range
1.	Volume of packed bed (V_b)	15 m^3
2.	Length of packed bed (L)	6 m
3.	Number of bed elements (N)	60
4.	Initial bed temperature (T_{bi})	25°C
5.	Equivalent diameter of material element (D_e)	Corresponding to the material element under consideration
6.	Sphericity of material element (ψ)	Corresponding to the material element under consideration (0.55-1.00)
7.	Void fraction (ε)	Corresponding to the value under consideration (0.31- 0.63)
8.	Density of storage material (ρ_s)	1920 kgm^{-3}
9.	Density of air (ρ_a)	1.1 kgm^{-3}
10.	Specific heat of storage material (C_s)	835 $Jkg^{-1}K^{-1}$
11.	Specific heat of air (C_{pa})	1008 $Jkg^{-1}K^{-1}$
12.	Dynamic viscosity of air (μ_a)	$18.5x10^{-6}$ $kgs^{-1}m^{-1}$
13.	Ambient temperature (T_{amb})	25°C
14.	Inlet air temperature to bed (T_{ai} or T_{ib})	40°C
15.	Insolation (I)	500 Wm^{-2}
16.	Collector area (A_c)	20 m^2
17.	$F_R\left(\tau\alpha\right)_e$ (for collector)	0.62
18.	F_RU_l (for collector)	3.38
19.	Initial inlet air temperature to the collector (T_i)	25°C
20.	Time interval (Δt)	15 minute

become nearly equal to inlet air temperature. Therefore, to evaluate the bed size, following energy balance equation has been used.

$$\left(\dot{m}C_p\right)_a \left(T_{ai} - T_{bi}\right) t_{ch} = \left(\rho C\right)_s \left(1-\varepsilon\right) V_b \left(T_{bm} - T_{bi}\right) \quad (1)$$

In the present simulation study, storage material elements of different shapes have been assumed to be made from an easily and economically available masonry brick material. Thermo-physical properties of masonry brick material are listed in Table **2**. Inlet air temperature to the bed (T_{ai}) and initial temperature of the bed (T_{bi}) are assumed to be 40°C and 25°C respectively. While sizing the bed, it is assumed that the temperature of the air leaving the bed during charging phase is equal to initial temperature of the bed (T_{bi}) and inlet air temperature to the bed (T_{ai}) is equal to temperature of air at outlet of the collector (T_o).

Table 2. Thermo-Physical Properties of Masonry Brick Material

S. No.	Property	Value
1.	Specific heat	835 $Jkg^{-1}K^{-1}$
2.	Thermal conductivity	0.70 $Wm^{-1}K^{-1}$
3.	Density	1920 kgm^{-3}

2.2. Solar Air Heater Model

The amount of energy to be delivered by the collector depends upon the collector area, insolation, flow rate of air and ambient conditions. A model of conventional solar air heater has been adopted to carry out the present study. The change in collector outlet temperature can be expected with change of collector inlet temperature under the condition of constant insolation and constant ambient temperature. However, temperature at the outlet of the collector can be kept constant by changing the flow rate of air. The flow rate of air was calculated from the following Hottel-Williar-Bliss equation reported by Duffie and Beckman [4] for useful energy gain in the collector:

$$Q_u = A_c\left[IF_R\left(\tau\alpha\right) - F_R U_l\left(T_i - T_{amb}\right)\right] \quad (2)$$

Useful energy gain Q_u is also given by;

$$Q_u = \left(\dot{m}C_p\right)_a \left(T_o - T_i\right) \quad (3)$$

Therefore $$\dot{m}_a = \frac{A_c\left[F_R\left(\tau\alpha\right)_e I - F_R U_l\left(T_i - T_{amb}\right)\right]}{C_{pa}\left(T_o - T_i\right)} \quad (4)$$

where T_i is inlet air temperature to the collector, which is assumed to be equal to the initial temperature of the bed i.e. T_{bi}. T_o is air temperature at outlet of the collector, required to be kept equal to 40°C i.e. the temperature of air at inlet to bed T_{ai}.

2.3. Packed Bed Model

In closed cycle of a packed bed solar energy storage system, hot air leaving the collector enters into the bed. Therefore temperature of air at collector outlet and bed inlet will be same. During charging phase, temperature of lower portion of the bed starts to rise, which may change the temperature of air at the outlet of the collector. Abbud *et al*. [5] recommended that for preserving the stratification in the bed, the hot air from collector to the bed should be supplied at a constant temperature by varying flow rate of air. Therefore, in the present simulation study, flow rate of air during charging of the bed has been allowed to vary, in order to maintain a constant inlet air temperature to the bed.

For predicting thermal performance of a packed bed, many mathematical models have been reported in the literature. However, most of the investigators have used Mumma and Marvin model reported by Howell *et al*. [6]. This model has been adopted to carry out the present simulation study.

In the present study, bed is assumed to be consisting of 'N' number of elements of equal axial thickness 'Δx' as shown in Figs. (**2a**) and (**2b**). The following governing equations of Mumma and Marvin model are used to evaluate the temperature distribution for air and solid in the bed;

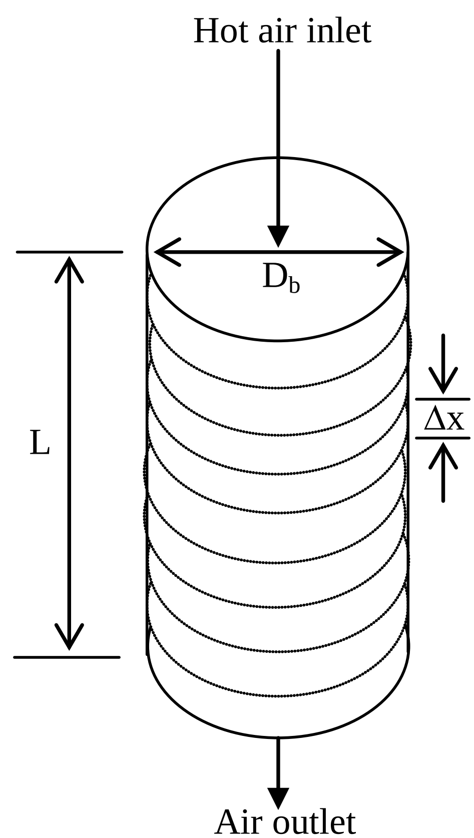

Fig. (2a). Packed bed (voids are not shown).

$$T_{a,m+1} = T_{b,m} + \left(T_{a,m} - T_{b,m}\right)\exp\left(-\phi_1\right) \quad (5)$$

where $$\phi_1 = \frac{h_v AL}{N\left(\dot{m}c_p\right)_a} = \frac{NTU}{N} \text{ and } N = L/\Delta x \quad (6)$$

$$T_{b,m\,(t+\Delta t)} = T_{b,m\,(t)} + \left[\begin{matrix} \phi_2 \left(T_{a,m} - T_{a,m+1}\right) \\ -\,\phi_3 \left(T_{b,m} - T_{amb}\right) \end{matrix}\right] \Delta t \qquad (7)$$

where $\phi_2 = \dfrac{\left(\dot{m} C_p\right)_a N}{\rho_s\, AL \left(1-\varepsilon\right) C_s}$ and

$$\phi_3 = \frac{\left(U\ \Delta A\right)_m}{\left(\dot{m} C_p\right)_a} \phi_2 \qquad (8)$$

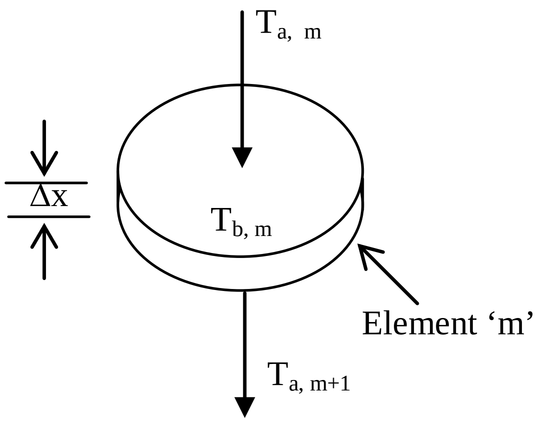

Fig. (2b). Element 'm' of packed bed.

The following Nusselt number correlation reported by Singh *et al*. [3] is used to evaluate the volumetric heat transfer coefficient.

$$Nu = 0.437 \left(\mathrm{Re}\right)^{0.75} \left(\psi\right)^{3.35} \left(\varepsilon\right)^{-1.62} \left[\exp\left\{29.03 \left(\log \psi\right)^2\right\}\right] \qquad (9)$$

where $Nu = \dfrac{h_v D_e^2}{K}$ and $R_e = \dfrac{G\ D_e}{\mu_a}$ (10)

Thermal energy stored in the bed is calculated by using the following general equation;

$$Q = \int_o^L \left(\rho C\right)_s \left(1-\varepsilon\right) A \left(T_{mm} - T_{im}\right) dx \qquad (11)$$

Initially bed is assumed at uniform temperature of T_{bi} and has been divided into 'N' number of elements of equal thickness. The above governing equation for thermal energy stored 'Q' can be written in finite difference form as;

$$Q = \left(\rho C\right)_s \left(1-\varepsilon\right) A \frac{L}{N} \left(\sum_{n=1}^{N} T_{nm} - N\, T_{bi} \right) \qquad (12)$$

or $Q = \left(\rho C\right)_s \left(1-\varepsilon\right) V_b \left(T_{bm} - T_{bi}\right)$ (13)

Available energy stored in the bed (Q_a) is calculated by using the following equation given by Torab and Beasley [7];

$$Q_a = \int_o^L \left(\rho C\right)_s \left(1-\varepsilon\right) A \left[\left(T_{mm} - T_{mi}\right) - T_{mi} \ln\left(\frac{T_{mm}}{T_{mi}}\right) \right] dx \qquad (14)$$

The above equation for available energy stored in the bed can be transformed to finite difference form as;

$$Q_a = \left(\rho C\right)_s \left(1-\varepsilon\right) A \frac{L}{N} \left[\left(\sum_{n=1}^{N} T_{mm} - N\, T_{bi} \right) - T_{bi} \ln\left(\frac{T_{1\,m}\, T_{2\,m}\, T_{3\,m}\ \ldots\ldots\ldots\, T_{Nm}}{T_{bi}^{N}} \right) \right] \qquad (15)$$

or $$Q_a = \left(\rho\, C\right)_s \left(1-\varepsilon\right) V_b \left[\left(T_{bm} - T_{bi}\right) - \frac{T_{bi}}{N} \ln \left(\frac{T_{1\,m}\, T_{2\,m}\, T_{3\,m}\ \ldots\ldots\ldots\, T_{Nm}}{T_{bi}^{N}} \right) \right] \qquad (16)$$

The following friction factor correlation reported by the Singh *et al*. [3] is used to calculate pressure drop $\left(\Delta P\right)$ in the bed.

$$f = 4.466 \left(\mathrm{Re}\right)^{-0.2} \left(\psi\right)^{0.696} \left(\varepsilon\right)^{-2.945} \left[\exp\left\{11.85 \left(\log \psi\right)^2\right\}\right] \qquad (17)$$

where $f = \dfrac{\Delta P \rho_a D_e}{G^2}$, $\psi = \dfrac{a_s}{a_e}$ and $\varepsilon = \dfrac{V_b - V_s}{V_b}$ (18)

Energy consumption by the fan (W) to propel air through the bed is calculated by using the following equation;

$$W = \frac{\dot{m}_a\, \Delta P\ t_{ch}}{\rho_a} \qquad (19)$$

Thermal efficiency of the collector is evaluated by using the following equation;

$$\eta_{th} = \frac{Q_u}{A_c\, I} 100 \qquad (20)$$

In the present simulation study, following values of sphericity and void fraction parameters, similar to an experimental study reported by Singh *et al*. [3] have been used along with values of system and operating parameters listed in Table 1;

Sphericity (ψ): 0.55, 0.63, 0.72, 0.80 and 1.00

Void fraction (ε): 0.31, 0.40, 0.45, 0.54 and 0.63

It may be noted that although non-spherical elements can yield different values of void fractions, randomly packed spheres can have void fraction of 0.40 only. The bed elements get charged in the given time interval of 15 minutes corresponding to the calculated flow rate of air. Hence 32 result sets have been obtained with charging of the bed for eight hours in each case.

3. DEVELOPMENT OF COMPUTER PROGRAM

The performance of packed bed solar energy storage system has been predicted with the help of a computer program developed in C++ language by using the above discussed component models. The objective of developing the computer program was to obtain values of various parameters like mass flow rate of air, temperature of air at the outlet of each element of the bed, mean temperature of each element of the bed, mean temperature of the bed, thermal energy stored in the bed, available energy stored in the bed, energy consumption by fan and thermal efficiency of the collector. The required data were generated for time intervals of 15 minutes. The temperature variation in the bed at the end of each time interval was considered an initial condition for next time interval of 15 minutes. This process was repeated for eight hours. For charging of the bed in next time interval of 15 minutes, the inlet temperature to the collector was kept equal to the air temperature at the outlet of the bottom most bed element, which was noted from the data of previous temperature distribution.

4. CONCLUSIONS

In the present part of this paper an attempt has been made to describe the component models of a packed bed solar energy storage system, in order to develop a computer program for predicting simulated performance. The results of simulated performance w.r.t. temperature distribution in the bed, thermal and available energy stored in the bed, energy consumption by fan to propel air through the bed and thermal efficiency of the collector have been reported and discussed in Part-II and III of this paper.

NOMENCLATURE

A	=	Cross sectional area of packed bed (m^2)
A_c	=	Collector area (m^2)
ΔA	=	Surface area of packed bed for thickness or height of Δx (m^2)
a_s	=	Surface area of a sphere having volume equal to volume of material element (m^2)
a_e	=	Surface area of material element (m^2)
C_{pa}	=	Specific heat of air at constant pressure (Jkg^{-1}K^{-1})
C_s	=	Specific heat of storage material (Jkg^{-1}K^{-1})
D_e	=	Equivalent diameter of material element (m)
D_b	=	Diameter of packed bed (m)
F_R	=	Heat removal factor (dimensionless)
f	=	Friction factor (dimensionless)
G	=	Mass velocity of air (kg s^{-1}m^{-2})
h_v	=	Volumetric heat transfer coefficient (Wm^{-3} K^{-1})
I	=	Insolation (Wm^{-2})
K	=	Thermal conductivity of air (Wm^{-1}K^{-1})
L	=	Length or height of the bed (m)
$\dot{m}_a$	=	Mass flow rate of air (kgs^{-1})
N	=	Number of bed elements (dimensionless)
Nu	=	Nusselt number (dimensionless)
NTU	=	Number of transfer units (dimensionless)
ΔP	=	Pressure drop in bed (N m^{-2})
Q_u	=	Useful energy gain in collector (W)
Re	=	Reynolds number (dimensionless)
T_{ai}, T_{ib}	=	Temperature of air at inlet to bed (°C, K)
T_{bi}	=	Initial temperature of the bed (°C, K)
$T_{a,m}$, T_{im}	=	Air temperature at inlet to bed element 'm' (°C, K)
$T_{a,m+1}$	=	Air temperature at outlet of bed element 'm' (°C, K)
T_{bm}	=	Mean temperature of bed (°C, K)
T_i	=	Air temperature at inlet of collector (°C, K)
T_o	=	Air temperature at outlet of collector (°C, K)
T_{mi}	=	Initial temperature of bed element 'm' (K)
T_{mm}	=	Mean temperature of bed element 'm' (°C, K)
T_{nm}	=	Mean temperature of nth element of the bed (°C, K)
$T_{b,m(t)}$	=	Mean temperature of bed element 'm' at time t (°C, K)
$T_{b,m(t+\Delta t)}$	=	Mean temperature of bed element 'm' after time interval Δt (°C, K)
T_{amb}	=	Ambient temperature (°C, K)
t_{ch}	=	Charging time (s)
Δt	=	Time interval (s)
U, U_l	=	Overall heat loss coefficient (Wm^{-2} °C^{-1}, Wm^{-2} K^{-1})
V_b	=	Volume of packed bed (m^3)
V_s	=	Volume of storage material packed in the bed (m^3)
Δx	=	Thickness or height of bed element (m)
ρ_a	=	Density of air (kgm^{-3})
ρ_s	=	Density of storage material (kgm^{-3})
ψ	=	Sphericity (dimensionless)
ε	=	Void fraction of bed (dimensionless)
μ_a	=	Dynamic viscosity of air (kgs^{-1}m^{-1})
η_{th}	=	Thermal efficiency of collector (%)
$(\tau\alpha)_e$	=	Effective transmittance-absorptance product (dimensionless)

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