International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Sensible heat energy storage technology using low cost locally available thermal energy storage packed bed materials for space heating and crop drying

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Abstract

Thermal energy storage in packed beds is increasing attention due to necessary component for efficient utilization of solar energy. A one dimensional thermal model for the behavior of a packed bed is presented for low cost thermal energy sensible heat energy storage materials (i.e. stone, glass, rocks, bricks, and granite) and air as the heat transfer fluid. This model predicts successfully during storage are presented for brick and rock in a cylindrical packed bed storage unit. Explicit expression for time variation of storage material temperature and air flowing in the system have been developed and performance parameters have been computed for five storage materials.

Keywords: Packed beds, Thermal energy storage, Sensible heat storage, System Performance Parameters

1. Introduction

Research in sustainable energy sources continues in order for addressing concerns over climate change, pollution, and non-renewable energy sources. Therefore solar energy thermal storage systems are emerging as one such sustainable energy option for rural and remote areas. However, solar energy availability is also variable, such as from day to night or summer to winter, and the levelized cost of electricity is high. Thermal energy storage can offset variability and reduce costs [1]. However, storage and recovery of thermal energy must be done efficiently to achieve high thermal energy capacity as described in the review of Mishra et al. [5], Solar Thermal Energy Storage (STES) technologies must meet several requirements (i.e. high energy density, good heat transfer between the heat transfer fluid , solid storage media, mechanical and chemical stabilities of the storage medium, low thermal losses, low cost, and reversibility through many charging and discharging cycles [2]. A comparison of thermal energy storage designs is given by Lof , et al. [3]. STES can be done with sensible heat storage systems (heating a solid materials). The present study explores sensible thermal energy storage; [4] . The solid storage arrangement studied here is to store the heat in a packed bed [4] , which is considered an emerging technology to boost total system efficiency. Charging the bed is achieved by flowing fluid, heated by solar radiation, through the packed bed to heat the storage material. To recover the thermal energy stored from the packed bed in the flow direction is reversed and low temperature air enters in the heated bed. In packed bed systems like these, experimental and modelling studies have examined the effects of performance parameters such as void fraction, flow rate variations, particle size, packing material, and fluid inlet temperature [5] . For packed beds to be efficient in thermal cycling, they must maintain a high degree of thermal stratification [2], which is affected by the aforementioned system parameters. A low void fraction in the bed will lead to a smaller storage vessel for a given amount of energy to be stored, but the pressure drop is increased. Similarly, smaller bead sizes minimize intra-particle temperature gradients (assuming sufficiently high thermal conductivity of the storage media), but also lead to a higher pressure drop. Four energy balance models typically exist in packed bed systems as reviewed by Mishra et al. [4]. The continuous solid-phase model, which treats the solid as a continuum (no individual particles) includes equations for the full energy balance of the solid and fluid phases. This approach takes into account the enthalpy changes, heat conduction in the bed, convective

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heat transfer between the fluid and solid, and the heat loss from the vessel. Schumann's model [6] is similar to the continuous solid-phase model, but assumes no radial (perpendicular to the flow axis) heat conduction, nor conduction in the fluid or solids. The single-phase/one-equation model assumes thermal equilibrium between the solid and fluid, and the properties are written as equivalent parameters (e.g., an equivalent thermal conductivity *k*eq). Lastly, one could solve a model with energy equations for the fluid and solid phases that allows for thermal gradients within the particles themselves. Depending on the solid and fluid materials and on what information is desired, one of these general modelling approaches can be chosen or modified. Previous work explored the air and alumina system with an energy balance for both fluid and solid with coupling via the heat transfer coefficient. This approach is needed when thermal equilibrium may not exist between the fluid and solid; however, the temperatures in were quite similar for solid and fluid. Based on that, thermal equilibrium is a reasonable approximation and the one-equation model can be used in such cases. In this work, packed bed thermal energy storage is considered with air as the heat transfer fluid, such as could occur with solar collector is utilizing an air heat transfer fluid. The solid storage materials in the sphere pieces of irregular shapes, which is considered a good storage material for thermal energy storage due to its (thermal/mechanical and chemical stabilities.

This paper presents a simplified, one dimensional equation energy model coupled to a Navier–Stokes solution of the flow to calculate the transient temperature profiles in a packed bed during storage. In calculating the thermal behavior, the model incorporates temperature-dependent thermo-physical properties. This model is successfully validated against experimental data for bed materials with air as heat transfer fluid. To further highlight the importance of temperature-dependent thermo-physical properties, storage materials and flowing air is presented.

Limitations to the assumption of thermal equilibrium between the fluid and solid phases are presented along with an analysis of the particle Biot number at various conditions. Importance of this work shows that this one-dimensional equation thermal model approach is sufficiently accurate for future thermal design studies.

2. General modeling approach: one dimensional equation thermal model and coupled Navier–Stokes solution

The one-equation approach to the energy balance is presented here. This modeling approach is also referred to as a 'one-phase' model where the bed is reasonably approximated as a quasi-homogeneous medium [24]. This approach assumes thermal equilibrium between the fluid and solid phases, which is reasonable for the materials and conditions considered here. The model also assumes no intra-particle temperature gradients, which is important in energy storage applications. Based on previous results with stones and air, estimates for the heat transfer coefficient show the Biot number ($Bi = hLc/k$) satisfies $Bi < 0.1$. Limitations to this approach and a more detailed analysis of thermal equilibrium and the Biot number are discussed in a later section. The overall thermal model considers heat transfer in a porous media/packed bed domain and in the solid domains of the vessel and insulation. The velocities and pressure drop in the packed bed are also solved. The generalized Navier–Stokes equations are considered with a velocity-dependent body force accounting for viscous and inertial losses within the porous medium. The viscous and inertial coefficients are constants calculated by Ergun [9] and then applied before the simulation is run. The one-equation thermal model is coupled to the Navier–Stokes solution of the domain through the porous region. The velocity and pressure results are not presented here as no experimental data was collected for these. They studied the pressure drop across the packed beds. Mishra [5-6] deals with the time dependent thermal model of open and close loop solar energy systems using rock beds. Solar collector cum storage system is more expensive due to cost of collector and cost of thermal energy storage unit. In this paper we considered solar matrix air heating absorber cum storage units of easily available thermal energy storage material in the rural/remote areas for crops drying applications and developed a time dependent thermal model to study its performance**.** The developed model is the modification of Schumann [7] model by considering the effect of conduction in the thermal energy storage materials. The analytical expressions for various parameters have been obtained explicitly. Former work of Dunkle RV [2] in this direction was done by numerically solving Schumann model with finite difference technique. The model dev eloped in this paper has been tested corresponding to a data available for solar intensity and ambient temperature for a critical day of New Delhi (India) types climates. The effect of various parameters such as particle size porosity etc. on the thermal performance (in terms of time variation of efficiency, useful energy flux have been carried out for different energy storage materials).

3. Thermal analysis of a packed bed collector cum storage systems using low cost absorber materials.

The analysis of packed bed energy storage systems have been performed under following mode of operation.

3.1 Different matrix & fluid temperatures

In the configuration of the storage system, packed bed has been connected into a porous air heater, in which the performance of the system depends upon collector parameters and storage parameters. The energy balance equation for the bed temperature over the packed bed segment of thickness dX can be written as

$$h_v\left(\mathrm{T}_f\,(X,t)-T_m(X,t)\right)+K_e\left(\frac{d^2\mathrm{T}_m\,(X,t)}{dX^2}\right)-\frac{dQ}{dX}=\rho_m C_{pm}\left(\frac{dT_m(X,t)}{dt}\right) \qquad (1)$$

Where T (x,t) is the local air temperature & dI/dx is the heat energy attained by the surfaces. The first term in the equation represents the heat retained in the bed while second term is for the heat transfer from the hot air to the rocks. The third term represents the energy stored by the packed bed. The rock temperature is however related to air temperature by the following expression

$$-\beta \dot{m}_c c_{pf}\left(\frac{d\mathrm{T}_f(X,t)}{dX}\right) = h_v\left(\mathrm{T}_f(X,t) - T_{mi}(X,t)\right) \qquad (2)$$

The (-) sign in equation (2) is due to the fact that hot air loses heat to the packed bed. Correlations relating volumetric heat transfer coefficient to the bed characteristics into the fluid flow conditions are given by G.O.G.L of [3], Farber & Courtier [9] as follow.

$$h = 700\left[\frac{\frac{m}{A_c}}{d}\right]^{0.70} (W/m^3K)) \qquad (3)$$

Eliminating bed temperature from eqs. (2) - (1), one obtains a third order differential eqs. In terms of air temperature.

$$d^3T_{fo}(x)/dx^3 + a_1d^2T_{fo}(x)/dx^2 + a_2dT_{fo}(x)/dx + a_3T_{fo}(x) = -a_3I_{to} \qquad (4)$$

$$y_2(-a_3I_{tn}(n)\mu)/(-\mu^3 + a_1\mu^2 - a_2\mu + a_4$$

$$a_4 = in\omega\rho_m C_{pm} a_3$$

$$a_5 = \exp((-A_c U_l F')/(\dot{m}_c\ C_{pf}))$$

$$a_6 = a_1$$

$$a_7(n) = -(a_2) + (in\omega\rho_m C_{pm})/K_e)$$

$$a_8(n) = in\omega\rho_m C_{pm} a_3$$

$$a_9(n) = T_{an}(n) + ((\tau\alpha\ I_{tn}(n)/U_L)$$

Rearranging and separating the eqs. Into time dependent & time independent parts one can get solution of differential eqs.

$$\begin{aligned} T_f &= (C_1\exp(\beta_1 X) + C_2\exp(\beta_2 X + C_3\exp(\beta_3 X) + y_1\exp(-\mu X) + \\ &\mathrm{Re}\,al\sum_{n=1}^{6}\ (C_4\exp(\beta_4 X) + C_5\exp(\beta_5 X + C_6\exp(\beta_6 X) + y_2\exp(-\mu X)\exp(in\omega t) \end{aligned} \qquad (5)$$

The following boundary conditions are used

$$\begin{aligned} &-K_m dT_m(d,t)/dX = h_f(T_f(d,t) - T_a(t)) \\ &\dot{m}C_{pf}(T_{co}(t) - T_f(0,t)) = h_f(T_{co}(t) - T_m(0,t)) \\ &-K_m dT_m(0,t)/dX = h_f(T_f(0,t) - T_m(0,t)) \end{aligned} \qquad (6)$$

Application of boundary conditions in eqs. (5-6) yield the following, 3 X 3 matrix for time independent part & time dependent parts. The packed bed material temperature & fluid temperature can be obtained by substituting x=d in eqn. (6) and eqn. (6) in eqn. (2)

4. Results and Discussion

Values of parameter have been used for numerical computation to validate proposed thermal model taken from Mishra (1992, 96). The values of collector outlet temperature have been calculated because it depends upon the efficiency of collector cum storage unit and incidents of the radiation on the collector. The outlet temperature variation of the storage units with mass flow rate of air have been calculated along with corresponding variation of thermal efficiency and useful energy flux. It was observed that the effect of increasing the particle size on the volumetric heat transfer co-efficient between the particle and air along with temperature of particles, the heat transfer decreases with the increasing storage size particle effecting the bed temperature also. Similarly increasing the value of porosity effect the cooling effect of medium i.e. the temperature of air coming out the storage keeps on increasing porosity. The temperature distribution of the storage material up to a thickness of 50 cm, it was observed that bed temperature remain constant which it drops suddenly due to size of particle and the spacing between the particles. The effects of porosity of the storage media effect the thermal performance of a thermal energy systems considerably. It is therefore observed that the particle size and the porosity of the particle is kept to a minimum possible. One has to however balance it against increasing pressure losses and hence the fan power requirements. Table (1) shows the variation of particle temperature corresponding to hourly variation of the solar flux and ambient for a typical day. It was observed that particle can be heated more than twenty two degree centigrade than above ambient temperature. The time variation of thermal energy storage material with flowing air temperature with time along with solar flux shown in the tables (1-4) respectively. The time variation of useful energy flux and thermal efficiency with time for different thermal energy storage material are shown in the tables (1-4) respectively. It was observed that fire brick is a best material foe thermal sensible energy storage packed bed.

Table 1(a): Variation of temperature ($T_m(t)$) of thermal energy storage materials, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar flux W/m^2	Stone Bed (°C)
7 AM	21.9	50	24.3
8	25.6	150	30.6
9	23.9	375	38.9
10	22.4	550	45.2
11	27.1	650	54.1
12	31.4	750	59.9
13	28.8	700	56.9
14	23.0	675	48.9
15	23.9	575	42.4
16	26.2	475	37.4
17	22.9	150	35.1
18	19.1	50.0	32.4

Table 1(b): Variation of temperature ($T_m(t)$) of thermal energy storage materials, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Glass Bed (°C)
7 AM	21.9	50	24.4
8	25.6	150	31.9
9	23.9	375	36.3
10	22.4	550	44.4
11	27.1	650	54.0
12	31.4	750	58.6
13	28.8	700	56.8
14	23.0	675	47.7
15	23.9	575	39.3
16	26.2	475	37.2
17	22.9	150	34.8
18	19.1	50.0	32.0

Table 1(c): Variation of temperature ($T_m(t)$) of thermal energy storage materials, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Rock Bed (°C)
7 AM	21.9	50	24.6
8	25.6	150	30.1
9	23.9	375	37.4
10	22.4	550	45.2
11	27.1	650	53.9
12	31.4	750	58.5
13	28.8	700	56.0
14	23.0	675	54.8
15	23.9	575	45.7
16	26.2	475	42.7
17	22.9	150	37.5
18	19.1	50.0	32.7

Table 1(d): Variation of temperature ($T_m(t)$) of thermal energy storage materials, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Brick Bed (°C)
7 AM	21.9	50	24.7
8	25.6	150	32.6
9	23.9	375	40.2
10	22.4	550	47.0
11	27.1	650	53.5
12	31.4	750	58.2
13	28.8	700	55.7
14	23.0	675	55.1
15	23.9	575	48.1
16	26.2	475	44.5
17	22.9	150	40.8
18	19.1	50.0	32.9

Table 1(e): Variation of temperature ($T_m(t)$) of thermal energy storage materials, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar lux W/m^2	Granite Bed (°C)
7 AM	21.9	50	24.5
8	25.6	150	32.1
9	23.9	375	37.6
10	22.4	550	46.6
11	27.1	650	53.5
12	31.4	750	58.3
13	28.8	700	55.5
14	23.0	675	48.7
15	23.9	575	42.4
16	26.2	475	40.0
17	22.9	150	32.0
18	19.1	50.0	32.9

Table 2(a): Variation of fluid temperature ($T_f(t)$) using thermal energy storage materials , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Stone Bed (°C)
7 AM	21.9	50	24.2
8	25.6	150	30.5
9	23.9	375	38.9
10	22.4	550	45.2
11	27.1	650	54.0
12	31.4	750	59.9
13	28.8	700	56.9
14	23.0	675	48.8
15	23.9	575	42.3
16	26.2	475	37.0
17	22.9	150	32.1
18	19.1	50.0	32.4

Table 2(b): Variation of fluid temperature ($T_f(t)$) using thermal energy storage materials , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Glass Piece Bed (°C)
7 AM	21.9	50	24.4
8	25.6	150	31.9
9	23.9	375	36.2
10	22.4	550	44.3
11	27.1	650	54.0
12	31.4	750	58.5
13	28.8	700	56.8
14	23.0	675	47.6
15	23.9	575	39.2
16	26.2	475	36.9
17	22.9	150	32.0
18	19.1	50.0	32.0

Table 2(c): Variation of fluid temperature ($T_f(t)$) using thermal energy storage materials , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp(°C)	Solar Flux W/m^2	Rock Bed (°C)
7 AM	21.9	50	24.6
8	25.6	150	30.0
9	23.9	375	37.3
10	22.4	550	45.0
11	27.1	650	53.9
12	31.4	750	58.5
13	28.8	700	56.0
14	23.0	675	54.8
15	23.9	575	45.7
16	26.2	475	42.5
17	22.9	150	32.6
18	19.1	50.0	32.7

Table 2(d) : Variation of fluid temperature ($T_f(t)$) using thermal energy storage materials , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp (°C)	Solar Flux W/m^2	Brick Bed (°C)
7 AM	21.9	50	24.4
8	25.6	150	32.5
9	23.9	375	40.2
10	22.4	550	46.1
11	27.1	650	53.5
12	31.4	750	57.6
13	28.8	700	55.6
14	23.0	675	55.0
15	23.9	575	48.0
16	26.2	475	44.4
17	22.9	150	32.9
18	19.1	50.0	32.7

Table 2(e): Variation of fluid temperature ($T_f(t)$) using thermal energy storage materials , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp (°C)	Solar Flux W/m^2	Granite Bed (°C)
7 AM	21.9	50	24.5
8	25.6	150	32.1
9	23.9	375	37.6
10	22.4	550	46.6
11	27.1	650	53.5
12	31.4	750	58.3
13	28.8	700	55.5
14	23.0	675	48.7
15	23.9	575	42.4
16	26.2	475	40.0
17	22.9	150	32.0
18	19.1	50.0	32.9

Table 3(a): Variation of ($\Delta T_f/I_t$) and Thermal efficiency of thermal energy storage material using stone in the packed bed thermal energy storage system, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp/Inlet of Fluid Temp (°C)	Solar Flux (W/m^2)	$\Delta T_{Stone}/I_t(t)$ (°C/W/m^2)	Eff.$_{stone}$ (%)
7 AM	21.9	50	0.048	16.26
8	25.6	150	0.0333	13.5
9	23.9	375	0.04	18.15
10	22.4	550	0.04145	20.053
11	27.1	650	0.04355	18.11
12	31.4	750	0.038	17.04
13	28.8	700	0.04837	19.12
14	23.0	675	0.040	22.03
15	23.9	575	0.0322	21.42
16	26.2	475	0.02358	28.7
17	22.9	150	0.08133	23.945
18	19.1	50	0.266	18.0

Table 3(b): Variation of ($\Delta T_f/I_t$) and Thermal efficiency of thermal energy storage material using stone in the packed bed thermal energy storage system , solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp/Inlet of Fluid Temp (°C)	Solar Flux (W/m^2)	$\Delta T_{glass}/I_t(t)$ (°C/W/m^2)	Eff $_{glass}$ (%)
7 AM	21.9	50	0.05	21.1
8	25.6	150	0.042	18.5
9	23.9	375	0.0331	23.24
10	22.4	550	0.04	25.13
11	27.1	650	0.0434	23.16
12	31.4	750	0.03667	22.02
13	28.8	700	0.04837	19.12
14	23.0	675	0.040	22.03
15	23.9	575	0.0322	21.42
16	26.2	475	0.02358	28.7
17	22.9	150	0.08133	23.945
18	19.1	50	0.266	18.0

Table 3(c): Variation of ($\Delta T_f/I_t$) and Thermal efficiency of thermal energy storage material using stone in the packed bed thermal energy storage system, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp/Inlet of Fluid Temp (°C)	Solar Flux (W/m^2)	$\Delta T_{Rock}/I_t(t)$ (^{o}C/W/m^2)	Eff $_{Rock}$. (%)
7 AM	21.9	50	0.054	16.23
8	25.6	150	0.03	13.2
9	23.9	375	0.036	17.77
10	22.4	550	0.04145	19.5
11	27.1	650	0.04322	17.45
12	31.4	750	0.036	16.21
13	28.8	700	0.039	18.118
14	23.0	675	0.047	20.8
15	23.9	575	0.038	19.94
16	26.2	475	0.0347	26.85
17	22.9	150	0.097	21.29
18	19.1	50	0.272	20

Table 3(d): Variation of ($\Delta T_f/I_t$) and Thermal efficiency of thermal energy storage material using stone in the packed bed thermal energy storage system, solar flux and ambient temperature with time

Time Hr.	Ambient Temp/Inlet of Fluid Temp (°C)	Solar Flux (W/m^2)	$\Delta T_{Brick}/I_t(t)$ (^{o}C/W/m^2)	Eff.$_{Brick}$ (%)
7 AM	21.9	50	0.056	17.26
8	25.6	150	0.0467	16.12
9	23.9	375	0.0435	20.7
10	22.4	550	0.04473	22.6
11	27.1	650	0.0426	20.6
12	31.4	750	0.0357	19.57
13	28.8	700	0.03843	21.7
14	23.0	675	0.0476	24.68
15	23.9	575	0.0421	24.2
16	26.2	475	0.0385	21.7
17	22.9	150	0.0112	17.35
18	19.1	50	0.276	20.0

Table 3(e): Variation of ($\Delta T_f/I_t$) and Thermal efficiency of thermal energy storage material using stone in the packed bed thermal energy storage system, solar flux and ambient temperature with time

Time (Hr.)	Ambient Temp/Inlet of Fluid Temp (°C)	Solar Flux (W/m^2)	$\Delta T_{Granite}/I_t(t)$ (^{o}C/W/m^2)	Eff$_{Granite}$ (%)
7 AM	21.9	50	0.06	18.17
8	25.6	150	0.0433	20.4
9	23.9	375	0.0365	17.7
10	22.4	550	0.044	15.55
11	27.1	650	0.0427	14.53
12	31.4	750	0.036	14.7
13	28.8	700	0.0381	15.5
14	23.0	675	0.0382	16.28
15	23.9	575	0.0325	17.5
16	26.2	475	0.029	21.1
17	22.9	150	0.076	20.4
18	19.1	50	0.26	21.76

Table-4(a): Performance parameters of packed bed solar energy thermal storage systems using low cost thermal energy storage materials for space heating and crop drying applications

Materials	Collector Efficiency Parameters $F'(\tau\alpha)_{effective}$	System heat Loss parameters $F'U_{L\_system}$
Stone	0.225	1.8
Glass	0.210	2.15
Rocks	0.310	2.385
Bricks	0.340	3.40
Granite	0.255	2.5

Table-4(a): Performance parameters of packed bed solar energy thermal storage systems using low cost thermal energy storage materials for space heating and crop drying applications

Materials	Collector Efficiency Parameters $F_R(\tau\alpha)_{effective}$	System heat Loss parameters $F_RU_{Lsystem}$
Stone	0.201	2.67
Glass	0.207	2.05
Rocks	0.280	2.33
Bricks	0.320	2.57
Granite	0.248	1.82

5. Conclusions

This thermal modelling of packed bed thermal energy storage with air as heat transfer fluid using low cost five thermal energy storage materials have been presented.

This modelling approach assumes thermal equilibrium between the fluid and solid phases, which is valid on the high heat energy storage capacity and thermal conductivity of the solid compared to the fluid. This model solves the axial temperature profiles in the packed bed,

The model matches experimental data well for a given conditions. For accuracy, temperature-dependent thermo-physical properties of the air and storage materials are used this approach Biot number remains less than 0.1.

The performance parameters in terms of system efficiency factor (F(τα)effective), system heat loss coefficient ($FU_{Lsystem}$) system heat removal efficiency factor ($FR(\tau\alpha)_{effective}$) and system heat loss ($F_RU_{Lsystem}$) of packed bed thermal energy storage with air as working fluid and low cost locally available thermal energy storage materials (i.e. stone, glass, rock, brick and granite as storage material) have been computed. It was observed that brick and rocks based packed bed system perform in efficient manner as compared to other used low cost thermal energy storage material in the rural and remote areas.

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