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Sensible heat energy storage packed bed systems from waste materials for space heating and crop drying

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Abstract

This paper mainly deals with one dimensional to thermal energy storage model used for a packed bed of black painted scratch /waste chips materials available from machine shop used as absorber in the solar air heating collector, along with air as heat transfer fluid. This modelling approach assumes thermal equilibrium between the air and solid phases, which is valid here based on the high heat capacity and as will as high& low thermal conductivity of the thermal energy storage solids compared to the air. This model solves the axial temperature profile in the packed bed. The model also predicts variation of thermal efficiency, temperature dependent with time which is nearly similar behavior of air and thermal energy storage materials. The performance parameters of the system have been obtained for different thermal storage materials used for low temperature applications.

Keywords: Packed beds; Thermal energy storage; Sensible heat; Performance parameters

1. Introduction

Research in sustainable energy sources continues in order to address concerns over climate change, pollution, and non-renewable sources. Solar energy storage systems are emerging as one such sustainable energy option that can convert thermal energy from solar energy. Systems such as solar rock bed air heating collectors, parabolic trough collectors, converts solar energy into thermal energy which may be used for space heating and crop drying application in rural remote areas. Due to intermittent solar energy availability the thermal energy storage systems can be used in the rural remote areas. Modelling of Packed bed thermal energy storage with air as heat transfer fluid and thermal energy storage materials have been carried out by considering energy balances equation for thermal energy storage material and for air . This thermal model matches the experimental results well. The thermal model includes heat losses from the packed bed storage unit. As described by several investigators [1], Thermal energy storage technologies must meet several requirements: high energy density, good heat transfer between the heat transfer fluid and solid storage media because volumetric heat transfer is taking place in the system and also function of bed depth and storage material size. Several expression of volumetric heat transfer coefficient (W/m3K), and pressure drop in the packed bed have been developed and relationship between surface heat transfer coefficient (W/m2K) and porosity of thermal energy storage are available in the literature for charging and discharging cycles and comparison of thermal energy storage designs is given by choi et al [2-3]. The thermal energy storage can be done with sensible heat storage systems (heating a solid material) study explores sensible thermal energy storage; using different sensible heat based systems are provided in [3].

2. Packed bed thermal energy storage systems

The solid storage arrangement studied here is to store the heat in a packed bed, which is considered an emerging technology to boost total system efficiency. Charging the bed is achieved by flowing fluid, heated by solar

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radiation, through the packed bed to heat the storage material. To recover the stored energy from the bed (discharge), the flow direction is reversed and low temperature fluid enters the already heated bed [4].

In packed bed systems the effects of input parameters such as void fraction , flow rate variations , wall thermal losses , particle size , packing material and fluid inlet temperature is nearly as ambient temperature) on the thermal performance have been analyzed [5] because packed beds to be more efficient in thermal cycling and also maintaining a high degree of thermal stratification , which is affected by system parameters. A low void fraction in the bed will lead to a smaller storage size of vessel for a given amount of thermal energy to be stored, but the pressure drop in the system is increased due to functional relationship of mass flow rate. Similarly, smaller bed sizes minimize intra-particle temperature gradients (assuming sufficiently high thermal conductivity of the storage media), but also lead to a higher pressure drop. The energy balance models typically exist in packed bed systems as reviewed by Ahmed et al. [6, 12, 14, 15, 16,]. 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 heat transfer between the fluid and solid, and the heat loss from the vessel. (ii) Schumann's model [7] 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. (iii) The one dimensional model assumes thermal equilibrium between the solid and air , and the properties of thermal energy storage materials are functional dependency of as equivalent parameters [8] (e.g. equivalent thermal conductivity of packed bed material which is a function of several parameters such as porosity of material [20]). This model can determine the spatial distribution throughout the packed bed and (iv) to solve a model using energy equations for the fluid and solid phases which allowing a thermal gradients within the particles, depending on the solid and fluid materials., one of these general modeling approaches can be chosen or modified for the air and packed bed system with an energy balance for both fluid and solid through coupling via the heat transfer coefficient [21-23]. This approach is needed when thermal equilibrium may not exist between the fluid and solid; however, the temperatures of solid and fluid were similar. Based on that, thermal equilibrium is a reasonable approximation and the one dimensional time model can be used in such cases. Therefore modelling approach is used in this study. In this work, packed bed thermal energy storage is considered with air as the heat transfer fluid [10], such as could occur with solar receivers utilizing a gaseous heat transfer fluid. The solid storage material of irregular shape in terms of equivalent spheres, high heat storage capacity, and low thermal conductivity. This paper presents a simplified, one-equation energy model coupled to a Navier–Stokes solution of the flow to calculate the transient temperature profiles in a packed bed during storage. The model is successfully validated against experimental data for an alumina bed with air as heat transfer fluid at constant flow rate. The importance of temperature-dependent thermo-physical properties, storage materials results and flowing air are presented for allow temperature operation [10] and shows that this one-equation thermal model approach is sufficiently accurate for future design studies of high temperature rock bed systems for space heating applications.

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

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. 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 [13]. Based on predicted results with storage matrix material packed bed and air, estimates for the heat transfer coefficient. The overall thermal model considers heat transfer in a porous media/packed bed domain and in the solid domains. The generalized Navier–Stokes equations are considered with a velocity-dependent body force accounting for viscous and inertial losses within the porous medium.

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

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

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

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

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:

$$h_v = 700\left(\frac{\dot{m}/A_c}{d}\right)^{0.70} (W/(m^3K)) ------(3)$$

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

$$d^3T_{fo}(x)/dx^3 + a_1 d^2T_{fo}(x)/dx^2 + a_2 dT_{fo}(x)/dx + a_3 T_{fo}(x) = -a_3 I_{to} -----(4)$$

Where

$$a_1 = (h_v/(m_c/A_c)C_{pf}\beta),$$
$$a_2 = (h_v/K_e)$$
$$a_3 = -h_v/((m_c/A_c)C_{pf}\beta\, K_e)$$
$$y_1 = (-a_3\mu\, I_{to})/(\mu^3 - a_1\mu^2 + a_2\mu + a_3)$$

$$y_2(-a_3 I_{tn}(n)\mu)/(-\mu^3 + a_1\mu^2 - a_2\mu + a_4$$
$$a_4 = in\omega\rho_m C_{pm} a_3$$
$$a_5 = \exp((-A_c U_l F')/(\dot{m}_c\, C_{pf}))$$
$$a_6 = a_1$$
$$a_7(n) = -(a_2) + (in\omega\rho_m C_{pm})/K_e)$$
$$a_8(n) = in\omega\rho_m C_{pm} a_3$$
$$a_9(n) = T_{an}(n) + ((\tau\alpha\, I_{tn}(n)/U_L)$$

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

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

The following boundary conditions are used

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

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 eq. (6) and eq. (6) in eq. (2)

4. Result and Discussion

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 behaviour of a packed bed is presented here. The thermal performances of different units of thermal energy storage packed bed made of sketched /waste chips of aluminum/mild steel/wrought iron materials has been compared with different units of other thermal energy storage units using small pieces of stone /rocks/bricks as solid storage materials and air as the heat transfer fluid [13]. The viscous and inertial coefficients are constants calculated by Ergun [24] have been used here The one-equation thermal model is coupled to the Navier–Stokes solution of the domain through the porous region and the velocity of fluid flow (air) in the packed bed and pressure results are function of mass flow rate as experimental data was collected for these materials as 0.005 (Kg/sec), Depth of packed bed =0.1(m) to 0.2 (m) , with the particle size ranging between 0.005 (m) to 0.03 (m)

This model predicts successfully time dependent behaviour of thermal efficiency and heat flux over time for different waste chips of materials used in the cylindrical packed bed for crop drying and space heating applications as shown in Table-1. Similarly using other thermal energy storage materials are shown in table-2 respectively.

Table 1: Variation of temperature Tm (t) of packed bed thermal energy storage materials and ambient temperature with time

Time (Hr.)	Ambient Temp/Inlet of Fluid temp (°C)	Al-chips Bed (°C)	ΔT/It (^{0}C/W/m^2)	M.S Chips Bed (°C)	ΔT/It (^{0}C/W/m^2)	Wrought iron chips in Bed (°C)	ΔT/It (^{0}C/W/m^2)	Cast Steel chips of bed (°C)	ΔT/It (^{0}C/W/m^2)	Solar Flux W/m^2
7 AM	21.9	24.0	0.042	23.8	0.038	24.0	0.042	24.0	0.042	50
8	22.6	30.0	0.0493	29.9	0.04867	30.0	0.0493	30.1	0.05	150
9	23.9	38.9	0.040	36.3	0.0331	36.1	0.0325	36.2	0.0328	375
10	25.4	45.2	0.036	44.4	0.0345	44.0	0.03382	44.1	0.034	550
11	27.1	54.1	0.04154	54.0	0.0412	53.6	0.04077	53.7	0.04092	650
12	31.4	59.9	0.038	58.6	0.03627	58.5	0.0361	58.6	0.0363	750
13	31.8	56.9	0.03586	56.8	0.0357	56.0	0.03457	56.7	0.03557	700
14	30.0	48.9	0.028	47.7	0.0262	47.8	0.02637	47.9	0.02652	675
15	27.9	32.4	0.00783	32.3	0.00765	31.7	0.0066	32.8	0.00852	575
16	26.2	27.4	0.00253	27.2	0.0021	27.0	0.0017	27.3	0.00232	475
17	22.9	23.1	0.00133	23.1	0.00133	22.9	0.0	22.9	0.0	150
18	19.1	19.0	0.0	19.0	0.0	19.1	0.0	19.1	0.0	50

Table 2: Variation of various thermal energy storage materials efficiency with time

Time	Stone	Stone	Glass Pieces	Glass Pieces	Rock	Rock	Brick	Brick	Granite	Granite	Solar Flux
(Hr.)	Useful Flux (W/m^2)	Eff. (%)	Useful Flux (W/m^2)	Eff. (%)	Useful Flux (W/m^2)	Eff. (%)	Useful Flux (W/m^2)	Eff. (%)	Useful Flux (W/m^2)	Eff. (%)	(W/m^2)
7AM	32.6	16.26	26.2	21.1	20.1	16.23	26.3	17.26	22.5	18.17	124.1
8	59.9	13.5	47.2	18.5	43.67	13.2	66.65	16.12	56.52	20.4	255.2
9	103.35	18.15	93.6	23.24	101.54	17.77	103.6	20.7	110.9	17.7	402.6
10	171.86	20.053	143.7	25.13	181.74	19.5	186.2	22.6	170.7	15.55	571.9
11	204.02	18.11	168.5	23.16	226.7	17.45	222.2	20.6	202.8	14.53	725.6
12	215.37	17.04	175.4	22.02	229.18	16.21	235.53	19.57	210.9	14.7	796.5
13	217.92	19.12	179.7	24.01	235.6	18.118	237.22	21.7	214.4	15.5	748.3
14	195.25	22.03	163.4	26.8	226.85	20.8	211.44	24.68	188.3	16.28	609.64
15	139.91	21.42	115.9	26.02	158.79	19.94	152.3	24.2	133.4	17.5	445.3
16	84.87	28.7	68.2	23.06	99.8	26.85	93.6	21.7	82.6	21.1	295.7
17	54.167	23.945	42.0	17.72	63.98	21.29	59.6	17.35	52.6	20.4	159.6

From table (1)–(2) the performance parameters were obtained for different thermal energy storage systems are presented in Table -3 and Table-4 respectively.

Table-3 Performance Parameters of packed bed using waste chips of different materials

Material	F'(τ_α effective)	F'ULc
Al. Chips	0.28901	2.3627
M.S. Chips	0.27105	2.2083
Wrought Iron	27.683	2.295
Cast Steel	0.27827	2.2851

Table-4 Performance Parameters of low cost locally available waste materials of irregular shapes

Material	F'(τ_α effective)	F'ULc
Stone	0.225	1.80
Glass	0.320	2.15
Rocks	0.310	2.385
Granite	0.255	0.25
Brick	0.340	3.40

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5. Conclusion

The one-equation approach to thermal energy storage in a packed bed of scratch /waste chips materials with air as heat transfer fluid. The modelling approach assumes thermal equilibrium between the fluid and solid phases, which is valid here based on the high heat capacity and thermal conductivity of the solid compared to the fluid. The model solves the axial in the packed bed, insulation, and vessel. The model matches experimental data well for two flow-rate conditions. For accuracy, temperature-dependent thermo-physical properties of the air and storage materials must be used to validate model**.** It was observed that using waste chips of different materials gives good performance as porous absorber but not have much storage effect as compared to brick/stone/marvel/ quartz and broken glass pieced used in the packed bed.

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