Energy Storage Characteristics in Fixed Beds - Part 1. Charging Mode

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ABSTRACT

In the present work, the numerical model was refined to predict the thermal analysis of energy storage in a fixed beds during charging mode. The governing energy equations of both fluid and the solid particles along with their initial and boundary conditions are derived using a two-phase, one dimensional model. The refined model is carried out by taking into account change of (air density , air specific heat) with air temperature and also by taking into considerations heat losses from bed to surrounding. Finite difference method was used to obtain solution of two governing energy equations of both fluid and solid particles through a computer program especially constructed for this purpose. The temperature field for the air and the solid are obtained, also energy stored inside the bed is computed. A comparison between refined model and non refined model is done. Finally using refined model the effect of bed material (Glass, Fine clay ,and aluminum), and air flow rate per unit area Ga (0.3, 0.4, and 0.5 kg/m^2-s) on energy storage characteristics was studied.

Key Words : Thermal energy storage, Fixed bed, Thermal properties, Numerical model

기 호 설 명

Alphabets

A	cross sectional area of the bed (m^2)
Cp	specific heat (kJ/kg-°C)
D	diameter of the fixed bed (m)
D_p	diameter of solid particle (m)
E	energy stored in the fixed bed (kJ)
G	mass flow rate of air per unit area (kg/m^2-s)
hv	volumetric heat transfer coefficient (kJ/m^3-s-°C)
i	space index
k	thermal conductivity (KJ/m-°C-s)
K	time index
L	length of the fixed bed (m)
t	time (s)
T	temperature (°C)
Z	distance at axial direction
ε	void fraction
ρ	density (kg/m^3)
U	heat loss coefficient (W/m^2-K)
η	charging efficiency
P	atmosphere pressure (kPa)
V	air velocity (m/s)
R	gas constant for air (kJ/kg-K)

Subscripts

a	air
h	hot
s	solid
o	ambient condition

1. Introduction

Thermal energy storage (TES) have been recognized for a long time as a means to extend the use of solar energy in many thermal applications to times where solar energy are not available. Also thermal storage is well known concept in the field of waste heat recovery from waste hot streams emerging from various industries processes or

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exhaust gases of combustion power generation unit. Thermal energy storage is necessary because there is always a gap between the power source and the power demand. There is therefore a need for energy storage and a very wide range of techniques is used for this purpose including electrical storage, as in a battery for example, the compression of air and the pumped storage of water, all such methods involve a high capital investment and hence the cheaper alternative must be get. Existing methods using different physical and chemical processes and materials range from sensible to latent heat storage forms. The storage of energy as sensible heat in either a solid or a liquid. The problem with a liquid storage medium is that if, say, energy is to be received from an air stream, then a liquid to gas exchange must be incorporated into the cycle thus adding to the cost. This is not the case with a solid, where the bed of material acts as both the store and the heat exchanger. The use of the packed bed heat storage units for thermal energy storage has become an attractive design option in terms of constructive cost and storage efficiency. Packed beds serve satisfactorily for thermal energy storage because of their relatively fast response and large surface area to volume ratio. Several investigators [1-5] have studied the performance and efficient design of packed bed thermal energy storage system, and other [6] have considered the numerical approach by solving the governing equations using finite difference techniques. The objective of the present study are to develop a mathematical model for a cylinder fixed bed storage system by taking into account change of air properties with air temperature. The model is used to predict the transient one-dimensional temperature distribution inside the bed, the variation of temperature distribution with time, the variation of energy stored, storage rate in the storing media with time, and the charging storage efficiency.

2. Mathematical Model and Prediction Procedure

2.1 Model Description

The physical model of fixed bed thermal storage considered here is shown in Fig. 1. The model is a cylindrical bed of internal diameter of 15 cm and total bed length is 45 cm . The bed is insulated at its cylindrical walls. The bed is charged with flowing hot air where thermal interaction occurs between the air and the solid. The hot air has a constant inlet temperature of 700℃ and the ambient temperature as 25, and the air mass flow rate $G = 0.3\ \mathrm{kg/m^2\text{-}s}$

2.2 Governing Differential Equation

The considered model permits the appropriate conservation equation to be applied for the air flowing into the bed and to the solid phase separately, taking into consideration the thermal interaction between them, where heat is transfer from hot air to solid during charging process.

The energy equation that governs the thermal behavior of the air considering that air flows axially and neglecting heat transfer by conduction is as in Eq. 1

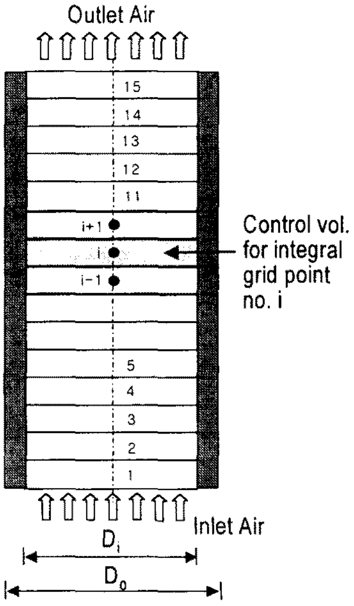

Fig. 1. Physical model of fixed bed thermal storage

$$\varepsilon\rho_a c_{pa}\frac{\partial T_a}{\partial t}+Gc_{pa}\frac{\partial T_a}{\partial Z}+(\frac{\pi DU}{A_h})(T_a-T_0)=h_v(T_a-T_s)$$

$$\text{where}\quad h_v=0.7\left(G/d_s\right)^{0.75} \tag{1}$$

Energy equation for a solid is written as,

$$(1-\varepsilon)\rho_s c_{ps}\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial Z}\left(k\frac{\partial T_s}{\partial Z}\right)+S_s \tag{2}$$

3. Initial and Boundary Conditions for Air and Solid

The initial and boundary conditions applicable to the air express the physical situation in which the air temperature equals the ambient temperature (To) through the field except at the upstream boundary , the inlet, where its temperature is T h . Then at Z=0

$T_a=T_h$ for all time

And at t = 0, $T_a=T_h$ Z=0

$T_a=T_0$ $Z\neq0$

Also the initial condition of the solid temperature field is described as

At t = 0, $T_s=T_0$ for all Z

4. Solution Procedure

The two partial differential equations Eqs (1) and (2), that govern the thermal behavior of a fixed bed thermal storage system are first reduced to finite difference equations along with their boundary and initial conditions. The grid points shown in Fig. 1 is considered we take 15 grid nodes in the axial. The solution is obtained by marching in time from the given initial distribution of temperature of both air and solid. Denoting the space index by i and time index by K, the air energy equation is discretized as:

$$\varepsilon\rho_a c_{pa}\frac{T_{a_{i,K+1}}-T_{a_{i,K}}}{\Delta t}+Gc_{pa}\frac{T_{a_{i,K+1}}-T_{a_{i-1,K+1}}}{\Delta Z}$$
$$+(\frac{\pi DU}{A_h})(T_{a_{i,K+1}}-T_0)\qquad=-h_v(T_{a_{i,K+1}}-T_{a_{i,K}}) \tag{3}$$

$$(\frac{\varepsilon\rho_a c_{pa}}{\Delta t}+\frac{Gc_{pa}}{\Delta Z}+h_v+\pi DU/A_h)T_{a_{i,K+1}}$$
$$=\frac{Gc_{pa}}{\Delta Z}T_{ai-1,K+1}+\frac{\varepsilon\rho_a c_{pa}}{\Delta t}T_{a_{i,K}}+h_vT_{s_{i,K}}+\pi DUT_o/A_h \tag{4}$$

Where Δt and ΔZ are the time step and space mesh size respectively.
Also Energy equation for solid is discretized as:

$$(1-\varepsilon)\rho_s c_{ps}\frac{T_{s_{i,K+1}}-T_{s_{i,K}}}{\Delta t}$$
$$=\frac{k_s(T_{s_{i+1,K+1}}-2T_{s_{i,K+1}}+T_{s_{i-1,K+1}})}{(\Delta Z)^2}+h_v(T_{a_{i,K+1}}-T_{s_{i,K+1}}) \tag{5}$$

$$(\frac{-K_s}{\Delta Z^2})T_{s_{i+1,K+1}}+(\frac{(1-\varepsilon)\rho_s c_{ps}}{\Delta t}+\frac{2k_s}{(\Delta Z)^2}+h_v)T_{s_{i,K+1}}$$
$$+(\frac{-k_s}{\Delta Z^2})T_{s_{i-1,K+1}}\qquad=\frac{(1-\varepsilon)\rho_s c_{ps}}{\Delta t}T_{s_{i,K}}+h_vT_{a_{i,K+1}} \tag{6}$$

The set of equations for I = 1 to 15 is solved directly using a tri-diagonal matrix solver to obtain the temperature field through the solid in the bed at k+1 time step.

The energy stored in solids at each time step can be obtained by numerically integrating the following equation,

$$E_s=(1-\varepsilon)A\rho_s c_{ps}\int_0^L(T_s-T_0)dZ \tag{7}$$

Also charging efficiency is calculated at each time step as,

$$\eta=\frac{E_s}{m_{airt}c_{pa}(T_h-T_o)} \tag{8}$$

During running program c_{pa} is taken as a + b T_a + c T_a^2 + d T_a^3 where a, b, c, and d are constant for air [8] also air density is taken as,

$$\rho=\frac{\mathrm{P}}{RT_a} \tag{9}$$

where p atmospheric pressure in kPa and R is gas constant for air. For well thermally insulated bed we take U=0.1 W/m^2-K.

5. Results and Discussion

A numerical model of the fixed bed thermal energy storage has been modified and presented in this work. A computer program has run which include physical properties (density, specific heat, and thermal conductivity) of bed material [9] to give indication about thermal behavior and performance of the bed. The thermal behavior of the bed is generally described by the temperature distribution in the bed for the fluid (air) and the solid and the energy stored inside the bed and charging efficiency at any instant time.

5.1 Temperature

Air temperature

Variation of air temperature with time at different axial locations (x/L= 0.066, 0.533,and 1) for glass at air mass flow rate of 0.3 kg/m^2-s is shown in Fig. 2 It can be seen that air temperature versus time has the same trend at all values of x/L. Also it can be seen that air temperature at any value of x/L decrease with time firstly and increase with time after that, and the increase rate is higher for lower values of of x/L which mean that downstream air temperature take a long time to reach a maximum temperature than upstream air in bed. Fig.3 shows variation of air temperature with x/L at different time (t =1, 50, and 100 minute) for a glass, at air mass flow rate of 0.3 kg/m^2-s. it can be seen from figure that air temperature decrease with increasing x/L and this decrease was clear at a lower time t=1 min and this decrease was obvious in upstream at lower time t=1 and at downstream for medium time t=50 min as shown in the figure.

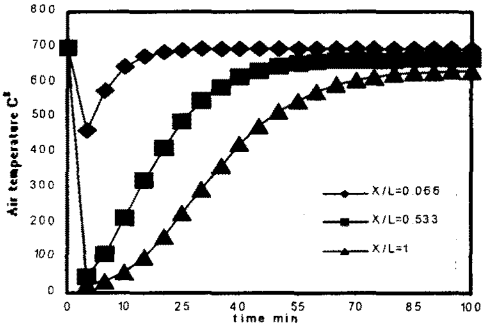

Fig. 2 Variation of air temperature with time at different axial locations for glass at air mass flow rate = 0.3 kg/m^2-s.

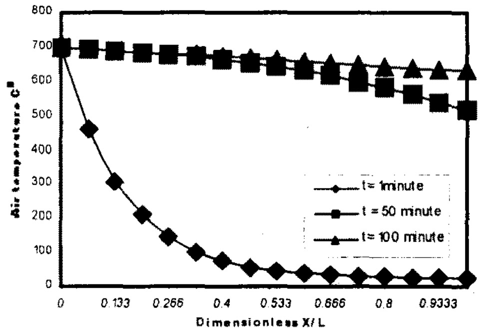

Fig. 3 Variation of air temperature along the bed at different times for glass at air mass flow rate=0.3 kg/m^2-s.

Solid temperature

Fig.4 shows variation of solid temperature with time at different axial locations (x/L= 0.066, 0.533 ,and 1) for glass at air mass flow rate =0.3 kg/m^2-sec. It can be seen from the figure that solid temperature versus time has the same trend at all values of x/L also it can be seen that solid temperature increase with time until it reach to a maximum steady state temperature, and this rate of increase was higher at lower values of x/L than higher values of x/L which mean that solid temperature at downstream take a long time than at upstream to reach maximum temperature. The general trend of solid temperature versus time is parabolic, and the passe of solid temperature with time (especially at downstream position) can be characteristics by three zones firstly threshold zone where the temperature is a little bit change with time, and secondly the transient zone where temperature change with time and finally the steady state zone where temperature will be steady with time. Fig. 5 shows variation of solid temperature with x/L at different time (t =1, 50, and 100 minute) for a glass, at air mass flow rate of 0.3 kg/m^2-s. It can be seen from the figure that solid temperature decrease with increasing x/L and this decrease was clear at a lower time t=1 min and this decrease was obvious in upstream at lower time t=1 and at downstream for medium time t=50 min as shown in the figure, and this can be attributed to at lower time change in temperature will be obviously occurs in upstream and at higher time the change will be occurs in downstream where upstream temperature will be reached to maximum temperature.

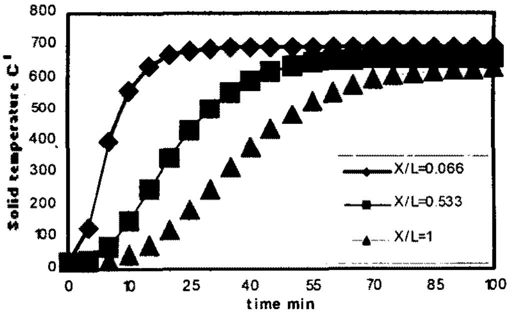

Fig. 4 Variation of solid temperature with time at different axial locations for glass at air mass flow rate = 0.3 kg/m^2-s.

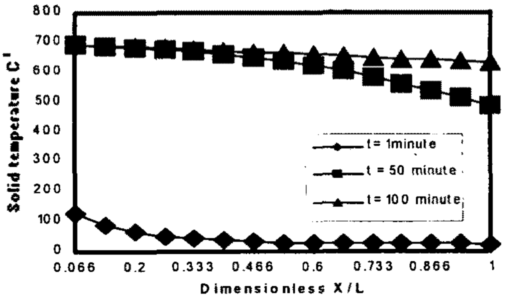

Fig. 5 Variation of solid temperature along the bed at different times for glass at air mass flow rate = 0.3 kg/m^2-s.

5.2 Comparison between Modified and Non-modified Model

The variation of (solid temperature at x/l=0.533, stored energy, and charging efficiency) with time for a glass at air mass flow rate =0.3 kg/m^2-s are shown in figures 6, 7, and 8 respectively. It can be seen from these figures that modified model has the same trend as non modified model. Also modified model has a lower considerable values of (solid temperature, stored energy, and charging efficiency) than non-modified model. And this difference is obviously at a higher time where temperature will be higher, and this difference can be attributed to taking into account effect of physical properties of air with temperature in modified model.. Finally it can be seen that the stored energy increase with time and charging efficiency decrease with time.

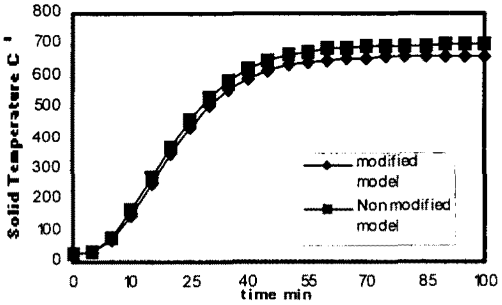

Fig. 6 Variation of solid temperature with time for modified and non modified model for glass at x/L=0.533 and air mass flow rate = 0.3 kg/m^2-s.

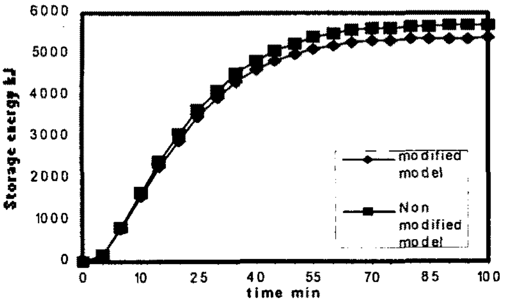

Fig. 7 Variation of stored energy with time for modified and non modified model for glass at air mass flow rate = 0.3 kg/m^2-s.

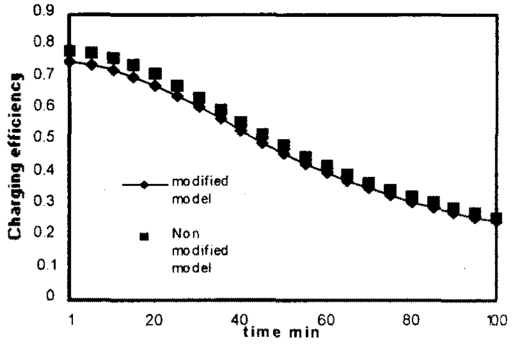

Fig. 8 Variation of charging efficiency with time for modified and nonmodified model for glass air mass flow rate = 0.3 kg/m^2-s.

5.3 Effect of Bed Material

The variation of (solid temperature at x/l=0.533, stored energy, and charging efficiency) with time for different bed materials at air mass flow rate =0.3 kg/m^2-s are shown in Fig. 9, 10, and 11 respectively. It can be seen from these figures that all bed materials (glass, fine clay, and aluminum) has the same trend as shown in the three figures. Also it can be seen that a bed materials that has a higher value of (ρ cp) will be have a lower values of solid temperature and a higher values of both stored energy and charging efficiency where (ρ cp) are 2430, 1968, and 1675 kJ/m3.0C for (glass, fine clay, and aluminum) respectively.

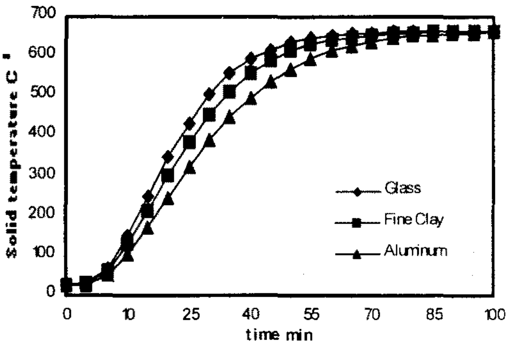

Fig. 9 Variation of solid temperature at x/L=0.533 with time for different bed material at air mass flow rate =0.3 kg/m2.S

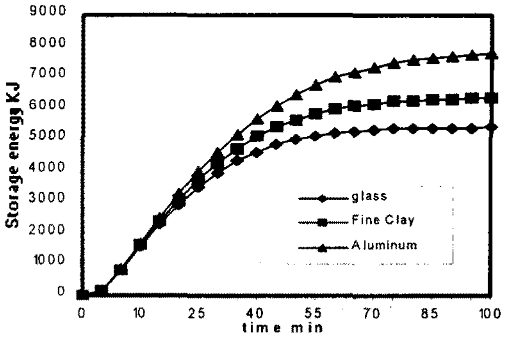

Fig. 10 Variation of stored energy with time for different bed material at air mass flow rate = 0.3 kg/m^2-s.

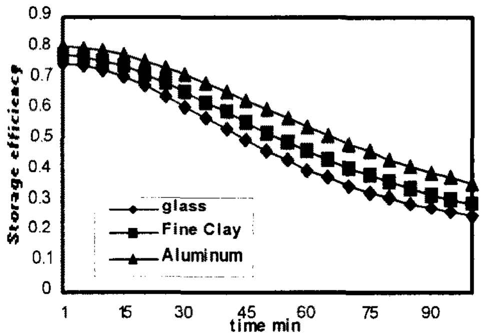

Fig. 11 Variation of charging efficiency with time for different bed material at air mass flow rate = 0.3 kg/m^2-s.

5.4 Effect of Air Mass Flow Rate

The variation of (solid temperature at x/l=0.533, stored energy, and charging efficiency) with time for a glass at different air mass flow rate (0.3, 0.4, and 0.5 kg/m^2-s) are shown in Fig. 12, 13, and 14 respectively. It can be seen from these figures that the higher value of air mass flow rate produce higher values of both solid temperature and stored energy but produce a lower values of charging efficiency.

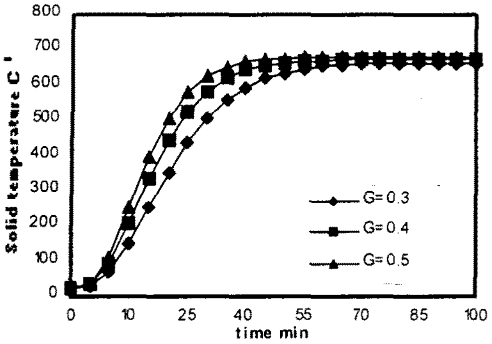

Fig. 12 Variation of solid temperature at x/L=0.533 with time for glass at different air mass flow rate

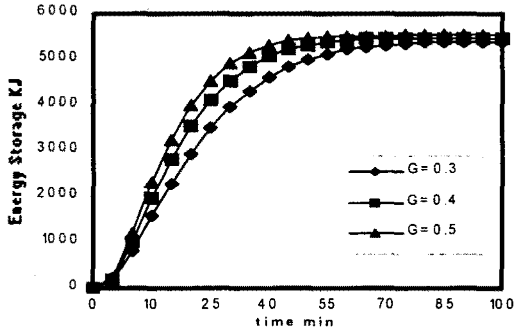

Fig. 13 Variation of stored energy with time for glass at different air mass flow rate

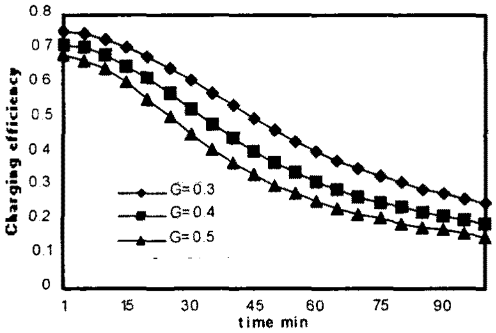

Fig. 14 Variation of charging efficiency with time for glass at different air mass flow rate

6. Conclusion

A mathematical model was refined to study the basic design parameters affecting the air and solid temperature at any instant along the fixed bed as well as the energy stored, and charging efficiency. It can be concluded that energy storage characteristics in fixed bed are affected by (bed material, and air mass flow rate). Also it can be concluded that a modified model produced a lower considerable values for (solid temperature, stored energy, and charging efficiency) than non-modified model. Finally it could be concluded that a bed material of a higher values of ρ cp has a lower values of solid temperature but at the same time it has a higher values of (a stored energy and charging efficiency), also the higher air mass flow rate values the higher will be the solid temperature and stored energy and the lower will be the charging efficiency.

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