Energy Storage Characteristics In Fixed Beds (Charging, Storing, Discharging)

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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 ,storing, discharging) 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 efficiency of energy stored inside the bed is computed. Finally using refined model the effect of air flow rate per unit area Ga (0.2, 0.3, and 0.4 kg/m^2-s), and inlet air temperature (200, 250, 300 °C) on energy storage characteristics was studied in three mode (charging ,storing, discharging). The rock particles of diameter 1 cm is used as bed material in this research.

Key Words : Energy storage, Fixed bed, Numerical model, Charging, Storing, Discharging

1. Introduction

There are many situations where available energy is wasted because it is in the wrong place at the wrong time. One example of this is solar energy, where, when the sun is shining , energy is not required and when energy is required, the solar source rarely puts in an appearance. Whenever a gap exists between availability and requirement of energy, temporary storage of energy is needed to maintain the continuity of the thermal process. Fixed beds serve satisfactorily for thermal energy storage in solar air systems because of their relatively fast response and large surface area to volume ratio. The optimization and control of such systems depends on having an accurate and not overly complex mathematical model for the transient temperature profile. Rock bed energy storage is generally preferred for the air based thermal energy storage system. The performance of the rock bed storage system is influenced by various design and operational parameters such as size of rock, size of bed, air mass flow rate, void fraction within the rock bed, thermal and physical properties of rock, and inlet temperature of air. 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. Thermal energy storage (TES) system is very important concept in various thermal applications as solar heating, solar cooling, solar power generation, and many industrial operations where waste heat recovery from waste hot streams emerging from various industries processes or exhaust

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기 호 설 명

A	cross sectional area of the bed (m2)	T_s	solid temperature (℃)
C_{pa}	specific heat of air (kJ/ Kg oC)	Z	distance at axial direction
C_{ps}	specific heat of solid (kJ/ Kg oC)	Δ	increment of variable
D	diameter of the fixed bed (m)	ε	void fraction
Dp	diameter of solid particle (m)	ρ	density (kg/m^3)
E	energy stored in the fixed bed (KJ)	U	heat loss coefficient, W/m^2-K
G	mass flow rate of air per unit area (Kg/m^2-s)	η	charging efficiency
		P	atmosphere pressure kPa
hv	volumetric heat transfer coefficient (KJ/m^3-s-℃)	V	air velocity m/s
		R	gas constant for air kJ/kg-K
i	space index		
k	thermal conductivity (kJ/m-℃-s)	**Subscripts**	
K	time index	a	air
L	length of the fixed bed (m)	h	hot
t	time (s)	s	solid
T_a	air temperature (℃)	o	ambient condition
T_h	hot air temperature (℃)		

gases of combustion power generation . A very wide range of techniques is used for (TES) system including electrical storage, as in a battery, 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. . Several investigators [1- 8] 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 efficiency of energy stored, in the storing media with time.

2. Mathematical Model and Prediction Procedure

2.1 Model Description

The physical model of fixed bed thermal storage considered here is shown in figure 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. In charging mode 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 (200, 250, 300°C) and the ambient temperature as 25°C, and the air mass flow rate (G =0.2, 0.3 , and 0.4 kg/m^2-s). In storing mode the air flow is stopped, and the initial temperatures of both air and solid in storing mode are the finial temperatures of air and solid in charging mode. In discharging mode the bed is discharged with flowing atmospheric air where thermal interaction occurs between the air and the solid. The air has a constant inlet temperature of 25°C and the ambient temperature as 25°C, and the air mass flow rate G =0.2, 0.3, and 0.4 kg/m^2-s.

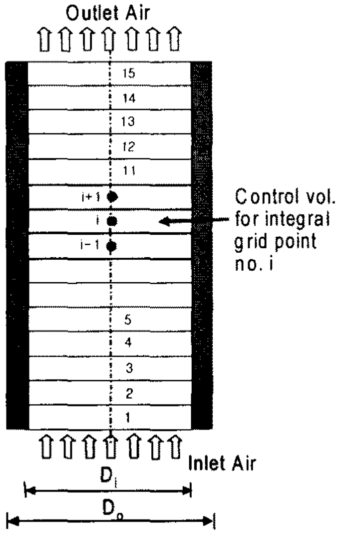

Fig. 1 Physical model of fixed bed thermal storage

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 , and from hot particle to air during both storing and discharging .

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

$$\varepsilon \rho_a c_{pa} \frac{\partial T_a}{\partial t} + G c_{pa} \frac{\partial T_a}{\partial Z} + (\pi D U / A_b)(T_a - T_0) = h_v (T_a - T_s)$$

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

The energy equation that governs the thermal behavior of the air considering that there is no flow of air during storing mode and neglecting heat transfer by conduction is as in Eq. 2.

$$\varepsilon \rho_a c_{pa} \frac{\partial T_a}{\partial t} + (\frac{\pi D U}{A_b})(T_a - T_0) = \frac{6h(1-\varepsilon)}{d_p}(T_a - T_s) \tag{2}$$

Taking h = 300W/m^2-K as this value give losses of 5% during storing mode [8].

Energy equation for a solid is written for charging and discharging mode as

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

$$\text{where } S_s = h_v (T_a - T_S) \tag{3}$$

Energy equation for a solid is written for storing mode as

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

$$\text{where } S_s = \frac{6h(1-\mu)}{d_p}(T_a - T_s) \tag{4}$$

3. Initial and boundary conditions for air and solid

The initial and boundary conditions applicable to the air express the physical situation

Charging mode

The air temperature equals the ambient temperature (T_o) through the field except at the upstream boundary , the inlet, where its temperature is T_h. Then at Z=0

$T_a = T_h$

(where in this research it taken as (200,250,300°C)) for all time

And at t = 0,

$T_a = T_h$ Z=0

$T_a = T_o$ $Z \neq 0$

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

At t=0 $T_s = T_o$ for all Z

Storing mode

The following initial and boundary conditions could be applied

And at t = 0

$T_a = T_{a,initial}$ for all Z

Also the initial condition of the solid

temperature field is described as

At $t = 0$,

$T_s = T_{s,initial}$ for all Z

Where $T_{a,initial}$ and $T_{s,initial}$ is the finial temperature of air ,and solid respectively in charging mode.

Discharging mode

The following initial and boundary conditions could be applied

the air temperature equals the initial temperature (T_{ida}) through the field except at the upstream boundary , the inlet, where its temperature is T_o.

Then

And at $t = 0$,

$Ta=To$ (taken here as 25°C) $Z=0$

$Ta=T_{ida}$ $Z\neq0$

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

At $t=0$, $T_s = T_{ids}$ for all Z

Where T_{ida} and T_{ids} is the finial temperature of air, and solid respectively in storing mode.

4. Solution Procedure

The two partial differential equations of both air and solid phase, 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 in each mode (charging, storing, and discharging) Denoting the space index by i and time index by K,

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. Following is the method of calculation

Energy stored

The energy stored in solids in (charging, storing, and discharging) at each time step can be obtained by numerically integrating the following equation

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

Charging efficiency

Charging efficiency is calculated at each time step as $\eta = \dfrac{E_s}{m'_{air} t c_{pa}(T_h - T_o)}$, in charging mode.

Storing efficiency

Storing efficiency is calculated at each time step as $\eta = \dfrac{E_s}{A\rho_s cp_s(1-\varepsilon)L(T_{initial} - T_o)}$, in storing mode. where $T_{initial}$ is the final temperature of solid at the end of charging mode.

Discharging efficiency

Discharging efficiency is calculated at each time step as $\eta = \dfrac{m'_{air} t c_{pa}\sum(Ta_{exit} - T_o)}{(1-\varepsilon)A\rho_s cp_s L(T_{initial} - T_o)}$, in discharging mode, where $T_{initial}$ is the final temperature of solid at the end of storing mode.

During running program C_{pa} is taken as $C_{pa} = a + b\,T_a + c\,T_a^2 + d\,T_a^3$ Where a, b, c, and d are constant for air [8] also air density is taken as $\rho = \dfrac{P}{RT_a}$ where p is 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 for (charging, storing, and discharging) modes 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 charging, storing, and discharging) efficiency at any instant time. Also study the effect of air mass flow rate Ga (=0.2, 0.3, and 0.4 kg/m^2-s), and air inlet temperature (200, 250, 300 °C) on thermal behavior and performance of the bed.

5.1 Temperature

Variation of air temperature with time at different axial locations (x/L= 0.533) for rock at air mass flow rate of 0.3 kg/m^2-s is shown in Fig. 2. It can be seen in the charging mode that the air temperature decrease with time firstly and increase with time after that. Also in storing mode it can be seen that the air temperature is a little bit decrease with time and this can be attributed to that in storing mode there is no air flow and losses in energy is low. Finally in discharging mode it can be seen that air temperature decrease with time.

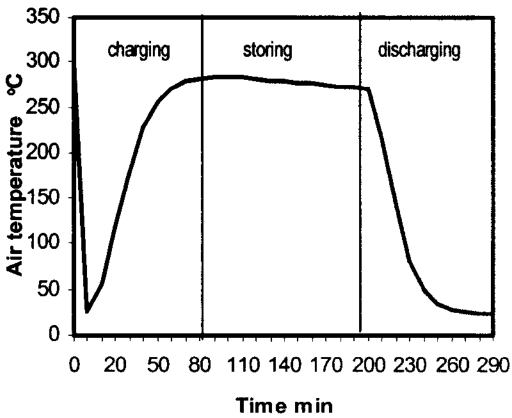

Fig. 2 Variation of air temperature with time during (charging, storing, discharging) at axial locations of x/l= 0.533 for rock at air mass flow rate = 0.3 kg/m^2-s, and at air inlet temperature of 300 °C

Fig. 3 shows variation of solid temperature with time at different axial locations (x/L= 0.533) for rock at air mass flow rate =0.3 kg/m^2-s. It can be seen from the figure that solid temperature increase with time until it reach to a maximum steady state temperature. The general trend of solid temperature versus time is parabolic, and the pass 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. Also in storing mode it can be seen that the solid temperature is a little bit decrease with time and this can be attributed to that in storing mode there is no air flow and losses in energy is low. Finally in discharging mode it can be seen that the solid temperature decrease with time. Fig. 4 shows variation of solid temperature with x/L at time (t =50 minute from beginning of each charging, storing, discharging) for a rock, at air mass flow rate of 0.3 kg/m^2-s. In charging mode it can be seen from figure that solid temperature decrease with increasing x/L. Also in storing mode it can be seen from the figure that solid temperature do not change with x/L. Finally in discharging mode it can be seen that solid temperature increase with x/L.

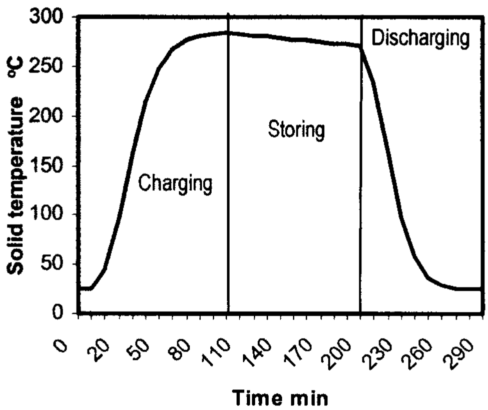

Fig. 3 Variation of solid temperature with time during (charging, storing, discharging) at axial locations of x/L= 0.533 for rock at air mass flow rate = 0.3 kg/m^2-s, and at air inlet temperature of 300°C

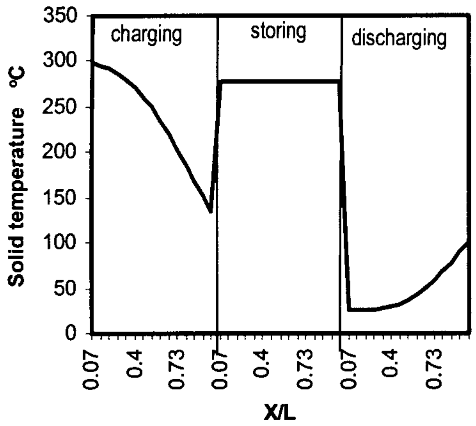

Fig. 4 Variation of solid temperature along the bed at time of 50 minute from beginning of each (charging, storing, discharging) for rock at air mass flow rate = 0.3 kg/m^2-s, and at air inlet temperature of 300°C

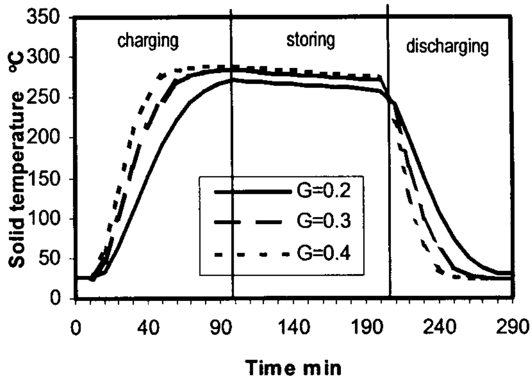

Fig. 5 Variation of solid temperature at x/L=0.533 with time for rock at different air mass flow rate and at air inlet temperature of 300°C

5.2 Effect of air mass flow rate

The variation of (solid temperature at x/l=0.533, and (charging, storing, discharging) efficiency) with time for a rock at different air mass flow rate (0.2, 0.3, and 0.4 kg/m^2-s) are shown in Fig. 5 and Fig. 6 respectively. It can be seen from Fig. 5 that the higher value of air mass flow rate produce higher values of solid temperature in both of charging and storing mode, and produce lower values of solid temperature in discharging mode. It can be seen from Fig. 6 that the higher values of air mass flow rate produce lower values of charging efficiency, and storing efficiency do not affect by change of air mass flow rate. Finally it can be seen from Fig. 6 in discharging mode that the higher values of air mass flow rate give higher values of discharging efficiency.

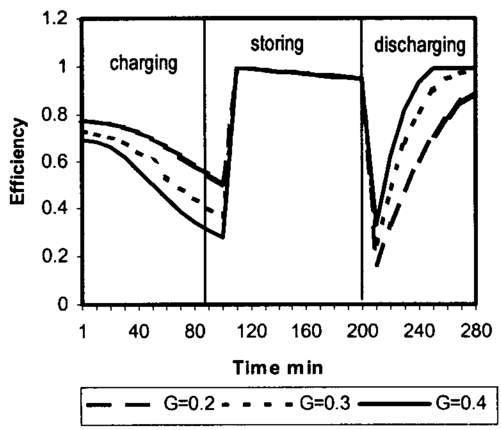

Fig. 6 Variation of (charging, storing, discharging) efficiency with time for rock at different air mass flow rate for air inlet temperature of 300°C

5.3 Effect of air inlet temperature

The variation of (charging, storing, and discharging) efficiency with time at different inlet air temperature of (200, 250, 300°C) is shown in Fig. 7 it can be seen from the figure that the inlet air temperature has no effect on efficiency of (charging, storing, and discharging)

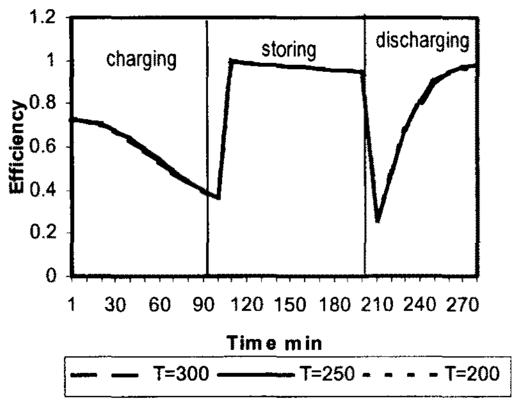

Fig. 7. Variation of (charging, storing, discharging) efficiency with time for rock at different inlet air temperature for air mass flow rate of 0.3 kg/m^2-s

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 in (charging, storing, and discharging) modes as well as the (charging, storing, and discharging) efficiency. It can be concluded that energy storage characteristics in fixed bed are affected by air mass flow rate but do not affected by inlet air temperature, and also it can be concluded that, in charging mode the higher air mass flow rate values the higher will be the solid temperature and the lower will be the charging efficiency. Finally in discharging mode the higher air mass flow rate values the higher the discharging efficiency and the lower the solid temperature.

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