TRANSIENT RESPONSE OF A PACKED BED AS A THERMAL ENERGY STORAGE SYSTEM: EXPERIMENTAL AND NUMERICAL STUDY

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ABSTRACT

Experimental and numerical study of the transient performance of a packed bed thermal storage system was carried out. Experiments were carried out to measure the transient temperature distributions inside a cylindrical packed bed with air as a working fluid. The packing was composed of rock grains of irregular sizes ranging between 14 and 20 mm. The bed container was constructed from a PVC cylinder with 1 m overall height and 0.15 m inside diameter. Measurements of the bed temperature were conducted at different axial and radial positions and at different operating parameters.

The present problem was modeled using two time-dependent coupled partial differential equations of the energy conservation of air and solid phases. The fluid energy equation was transformed by finite difference approximation and solved by Alternating Direction Implicit scheme (ADI) while the solid energy equation was solved using fully explicit scheme. The solution provides predictions for the dimensionless temperature distributions for both fluid and solid phases within the packed bed in the radial as well as in the axial direction for both charging and recovery modes at different operating parameters. The influence of aspect ratio, the flowing air velocity, the inlet air temperature, bed size and bed thermal capacity are also investigated.

Three correlations were obtained from the present results for the bed charging duration, effectiveness, and the storage efficiency as functions of the different operating and design parameters.

NOMENCLATURE

SI system of units was used for the whole parameters within the present paper.

A_p	particle surface area
c	specific heat
C_1 , C_2	constant in equation (16)
D	bed diameter
d	particle diameter
H	bed height
h	convective heat transfer coefficient
k	thermal conductivity
m_f	fluid mass flow rate
n_p	number of particles per unit volume of the bed
R	outer radius of the bed
r	radial coordinate
T	temperature
t	time
u	fluid velocity through the bed
x	axial coordinate

Superscripts:

n	previous time
n+1	current time
r	for radial direction
x	for axial direction
—	average value

Greek letters:

α	interphase surface area per unit bed volume
β	variable in Eq. (16)
Δ	incremental step
ε	average void fraction
Φ_1-Φ_6	coefficients in Eq.(13) and given by Eqs.(14)
γ	variable in Eq. (12)

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Subscripts:

C	at charging mode
e	effective value
f	for fluid phase
i,j	nodal point numbers
in	at bed inlet
o	superficial value
out	at bed exit
R	at recovery mode
s	for solid phase

η	storage efficiency
λ	thermal conductivity ratio
ν	kinematic viscosity
θ	bed effectiveness
ρ	density
τ	charging duration (hours)

Dimensionless terms:

AR	aspect ratio (H/D)
Nu_d	Nusselt number (hd/k_f)
Pr	Prandtl number ($\mu c_p/k_f$)
Re_o	superficial Reynolds number ($u_o d/\nu$)

1. INTRODUCTION

Development of very efficient and not harmful to the environment energy supply systems is now desirable. Interest has recently increased in methods of replacing the fossil fuel with renewable energy sources in most of thermal energy systems. Although, solar energy is considered the infinite and clean source of thermal energy it is an intermittent energy source. Therefore, energy storage systems are critically necessary for solar energy utilization to meet the increasing demand of world energy. Sensible thermal energy storage in solid materials may be the simplest and cheapest of all the alternative thermal storage systems. Also, packed beds provide an effective means of energy storage for air systems and in some cases liquid systems, such as solar domestic water and space heating. Packed beds have a wide range of applications as heat transfer and energy storage devices. Employed as a regenerators, packed bed is subjected to the flow of the heat transfer fluid, which alternately stores and recovers energy from a packing of discrete particles.

Many of the previous analytical and numerical studies of packed beds have been limited to a lumped model or at most one dimension model. A survey of the previous models till 1983 was summarized and classified by Beasley and Clark, [1]. In contrast to these studies, Beasley and Clark [1] carried out an analysis, with experimental results, to study the transient response of a packed bed thermal storage unit. This analysis was performed on a two dimensional model (axial and radial dimensions) with arbitrary time varying fluid inlet temperature for both charging and recovery modes. The result show that the spatial variations in void fraction have a significant effect on the bed performance. Beasley et al. [2] carried out a computational one dimensional model to predict the transient response of the packed bed of spheres containing a phase change materials. Also, an experimental study was conducted to measure the temperature distributions in the bed for a step change in the inlet air temperature at different air mass flow rates.

The two dimensional effect on the transient response of a packed for low temperature applications has been investigated by Khan and Beasley [3] and El-Sharkawy and Co-workers [4,5,6]. Thermal energy storage systems for the medium temperature applications with air as a working fluid for both charging and recovery modes were experimentally investigated by Steiner et al. [7]. The experimental storage bed was operated in the temperature range of 150 °C to 450 °C, the storage capacity was about 400 MJ. A computer simulation of a high temperature thermal energy storage systems was developed by Adabiyi et al. [8] with sensible and phase change materials. Also, a parameteric study was carried out to determine the effect of several design and operating parameters on the first and second law efficiencies of the packed bed. The transient analysis of rock bed air heaters in three different configuration was performed by Choudhury et al. [9]. The analysis has been carried out for both summer and winter weather conditions.

In fact, numerous studies have been performed either experimental or analytical, however, non of them provided engineers and designers with precise correlations for the bed performance characteristics as functions of the operating and design parameters. Hence, the present experimental and numerical study was carried out to achieve this purpose. In the present study, the transient response of a packed bed subjected to arbitrarily time-varying inlet fluid temperature at different operating and design parameters was determined for charging and recovery modes. Also, the bed performance characteristics represented by the charging duration, bed effectiveness and the bed efficiency were correlated with the design and operating parameters.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental part of the present work was carried out to measure the transient temperature distribution inside a vertical cylindrical packed bed composed of rock grains of irregular sizes ranging between 14 and 20 mm. The bed container was constructed from a PVC cylinder with 1 m overall height and 0.15 m inside diameter. This geometry was chosen to provide an aspect ratio ranges from 1 to 6. Figure (1) shows the experimental setup.

Air flow was supplied to the bed via a centrifugal air blower with variable mass flow rate. The mass flow rate of the inlet air was controlled by using an inlet gate valve to provide a range from 0.015 to 0.15 kg/s. This air mass flow rate was measured by an orifice meter and the inlet air was heated by means of electric heaters wrapped around a horizontal brass tube of 40 mm diameter and 3 m long . Step change in the inlet air temperature was accomplished through varying the heater power via voltage regulators to insure a uniform air inlet temperature ranging from 40 to 100 ^{o}C. The bed was instrumented with copper-constantan thermocouples of 0.5 mm diameter distributed at different locations in both radial and axial directions as shown in Fig.(1). Measurements of the bed temperature at both radial and axial directions at different operating parameters such as bed height (aspect ratio), fluid inlet temperature and air mass flow rate were carried out at both charging and recovery modes.

3. MATHEMATICAL FORMULATION AND SYSTEM MODELING

The proposed system is a vertically oriented cylindrical packed bed of spherical particles with air as a working fluid as shown in Fig.(2). The following axisymmetric energy equations which govern the two-dimensional packed bed are:

For fluid phase;

$$\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x} = \frac{k_e^x}{\rho_f c_f}\frac{\partial^2 T_f}{\partial x^2} + \frac{k_e^R}{\rho_f c_f}\left(\frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2}\right) + \frac{h\alpha}{\rho_f c_f \varepsilon}(T_s - T_f) \qquad (1)$$

where, $\alpha = n_p A_p = 6(1\text{-}\varepsilon)/d$

For solid phase;

$$\rho_s c_s\,(1-\varepsilon)\frac{\partial T_s}{\partial t} = h\alpha(T_f - T_s) \tag{2}$$

These governing equations include the effects of radial and axial thermal dispersion and subjected to the following boundary and initial conditions:

3.1. Boundary Conditions

The present system, shown in Fig.(2), is analyzed as a two dimensional problem with insulated surface. Therefore,
at r =R;

$$\frac{\partial T_f}{\partial r} = 0 \quad \text{and} \quad \frac{\partial T_s}{\partial r} = 0 \tag{3}$$

Also, at the bed center line L'Hospital rule from Hornbeck [10] is applied and the second term of the right hand side of Eq.(1) $\frac{k_e^R}{\rho_f c_f}\left(\frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2}\right)$ becomes; $2\frac{k_e^R}{\rho_f c_f}\left(\frac{\partial^2 T_f}{\partial r^2}\right)$. Therefore at the center line, Eq.(1) becomes;

$$\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x} = \frac{k_e^x}{\rho_f c_f}\frac{\partial^2 T_f}{\partial x^2} + \frac{2k_e^R}{\rho_f c_f}\left(\frac{\partial^2 T_f}{\partial r^2}\right) + \frac{h\alpha}{\rho_f c_f \varepsilon}(T_s - T_f) \tag{4}$$

At the inlet and outlet of the packed bed the fluid temperatures are assigned to the value of the inlet fluid temperature. Also, the temperatures at the bed outlet are assigned to values at the previous time. Therefore,
at x =0;

$$T_f(0,r,t) = T_{in}(t) \tag{5}$$

and at x=H;

$$T_f(H,r,t) = T_f(H,r,t-\Delta t) \tag{6}$$

3.2. Initial Conditions

The bed temperatures for both the fluid and solid phases are assumed to be uniform at the beginning of charging or discharging mode. Therefore,

at t = 0; $\quad T_f(x,r,0) = T_s(x,r,0) = T_0 \quad (7)$

3.3. Bed Performance Characteristics

The bed performance characteristics can be represented by the charging duration, bed effectiveness and the bed efficiency which are defined as follows:

1- Charging duration (τ): is defined as the time at which the bed reaches the state of thermal saturation.

2- Bed effectiveness (θ): is defined according to the mode of operation as;

for charging mode,

$$\theta_C(t) = \frac{\overline{T}_s(t) - T_o}{\overline{T}_{f,in}(t) - T_o} \tag{8}$$

for Recovery mode,

$$\theta_R(t) = \frac{\overline{T}_{f,out}(t) - \overline{T}_{f,in}(t)}{T_o - \overline{T}_{f,in}(t)} \tag{9}$$

3- Bed efficiency (η): which is also defined according to the mode of operation as;

for charging mode,

$$\eta_C(t)=\frac{\rho_s V_{st} c_s[\overline{T}_s(t)-T_o]}{\int_0^t m_f c_f[\overline{T}_{f,in}(t)-T_o]\,dt} \qquad (10)$$

for Recovery mode,

$$\eta_R(t)=\frac{\int_0^t \dot{m}_f c_f[\overline{T}_{f,out}(t)-\overline{T}_{f,in}(t)]\,dt}{\rho_s V_{st} c_s[\overline{T}_s(0)-T_\infty]} \qquad (11)$$

4. FINITE DIFFERENCE APPROXIMATION AND METHOD OF SOLUTION

The governing equations for both fluid and solid phases Eqs.(1) and (2) are approximated by using finite difference technique. The formulation utilizes a central difference approximation for the first and second derivatives. The simplicity of the solid phase equation, Eq.(2), allows an explicit statement for the solid temperature at the general node i,j, shown in Fig.(2), at the current time t+Δt (time iteration n+1) as;

$$Ts_{i,j}^{n+1}=\frac{1}{(1+\gamma\Delta t)}(Ts_{i,j}^{n}+\gamma\Delta t T_{i,j}^{n+1}) \qquad (12)$$

where, $$\gamma=\frac{h\alpha}{(1-\varepsilon)\rho_s c_s}$$

Substituting Eq.(12) into the finite difference form of Eq.(1), yields the following general expression for the fluid temperature at the general node i,j;

$$\Phi_1 T_{i,j}^{n+1}+\Phi_2 T_{i,j+1}^{n+1}+\Phi_3 T_{i,j-1}^{n+1}+\Phi_4 T_{i+1,j}^{n+1}+\Phi_5 T_{i-1,j}^{n+1}=\frac{1}{\Delta t}T_{i,j}^{n}+\Phi_6 Ts_{i,j}^{n} \qquad (13)$$

where;

$$\Phi_1=\frac{1}{\Delta t}+\frac{2k_e^x}{\rho_f c_f(\Delta x)^2}+\frac{2k_e^r}{\rho_f c_f(\Delta r)^2}+\frac{h\alpha}{\rho_f c_f \varepsilon}\left(1-\frac{\gamma\Delta t}{1+\gamma\Delta t}\right) \qquad (14\text{-a})$$

$$\Phi_2=\frac{u}{2\Delta x}-\frac{k_e^x}{\rho_f c_f(\Delta x)^2} \qquad (14\text{-b})$$

$$\Phi_3=-\left(\frac{u}{2\Delta x}+\frac{k_e^x}{\rho_f c_f(\Delta x)^2}\right) \qquad (14\text{-c})$$

$$\Phi_4=-\frac{k_e^r}{\rho_f c_f}\left(\frac{1}{2r\Delta r}+\frac{1}{(\Delta r)^2}\right) \qquad (14\text{-d})$$

$$\Phi_5=\frac{k_e^r}{\rho_f c_f}\left(\frac{1}{2r\Delta r}-\frac{1}{(\Delta r)^2}\right) \qquad (14\text{-e})$$

$$\Phi_6=\frac{h\alpha}{\rho_f c_f \varepsilon}\left(\frac{1}{1+\gamma\Delta t}\right) \qquad (14\text{-f})$$

Most of the previous models for the transient response of packed beds have assumed the void fraction, velocity and transport coefficient to be uniform throughout the cross section of the packing. However, measurements indicated that the void fraction and the average fluid velocity have significant radial variations. Khan and Beasley [3] found that the mean void fraction for a packed bed is a function of the bed to particle diameter ratio D/d. Therefore, the correlation of Beavers et al. [11] was used in the present model as;

a) for D/d <28;

$$\varepsilon = 0.4272 - 4.516\text{x}10^{-3}\,(D/d) + 7.881\text{x}10^{-5}\,(D/d)^2 \tag{15-a}$$

b) for D/d ≥ 28; the mean void fraction is independent on the bed-to-particle diameter ratio and has a constant value,

$$\varepsilon = 0.3625 \tag{15-b}$$

Also, the velocity profile in the randomly packed bed of uniform spheres was taken from the measurements of Newell and Standish [12].

Furthermore, the effective thermal conductivity in both the axial and radial direction was calculated using the following equation obtained from Cheng[13]:

$$\frac{k_e}{k_f} = [1-\sqrt{1-\varepsilon}] + \frac{2\sqrt{1-\varepsilon}}{1-\lambda\beta}\left[\frac{(1-\lambda)\beta}{(1-\lambda\beta)^2}\ln\frac{1}{\lambda\beta} - \frac{\beta+1}{2} - \frac{\beta-1}{1-\lambda\beta}\right] \tag{16}$$

where, $\beta = 1.25\left(\frac{1-\varepsilon}{\varepsilon}\right)^{10/9}$ and $\lambda = \frac{k_f}{k_s}$

Moreover, in the present model the heat transfer coefficient between the solid particles and the flowing fluid was calculated from [1] as:

$$Nu_d = 2.0 + C_1\,Re_o^{1/2}\,Pr^{1/3} + C_2\,Re_o\,Pr^{1/2} \tag{17}$$

where,

Re_o is Reynolds number based on the particle diameter and the superficial flow velocity and it is given by; $Re_o = \frac{u_o d}{\nu}$.

C_1, C_2 are constants having the values of 1.354 and 0.0326 respectively, [14].

On substitution of Eqs.(15), (16) and (17) into the difference equation, Eq.(13), yields a system of simultaneous linear equations for the fluid temperature.

The Alternating Direction Implicit (ADI) method was applied to solve this system of the linear equations at each time step which was solved radially at one half of the time step, Δt/2, and axially at the full time step, Δt. Therefore, the system of linear equations was decomposed into two tridiagonal systems of linear equations due to the application of the ADI method. These tridiagonal systems of equations were solved by using Gauss elimination method.

5. MODEL VALIDATION

The stability and convergence of the present model were initially checked by adjusting the grid size with the time step. The grid size was varied from (10x10) to (70x70) and the time step was also varied from 1 to 30 s within the present ranges of the different operating parameters. It was found that after a grid size of (30x30) the present model is relatively insensitive to the spatial increment sizes and a time step of 12 s is sufficient to ensure convergence and stability of the present numerical solution.

Also, the consistency and reliability of the present predictions were evaluated by comparing them with the present experimental results and with other previous results. Figure (3) shows the comparison of the present predictions with the present experimental data at different values of the fluid mass flow rate to storage volume ratio. Figure (4-a) shows the comparison with the experimental data of [15] and Fig.(4-b) illustrates the comparison with the predicted results of [6] for the same operating conditions. The comparisons show fair agreement with both the present and the previous experimental data of [15] at both charging and recovery modes. The present model overpredicts the two dimensional temperature distributions compared with the results of [6] by a maximum deviation of 12% , this may be attributed to the differences in the methods of solutions.

6. RESULTS AND DISCUSSIONS

The proposed model for the transient thermal response of the packed beds was applied for both charging and recovery modes at different operating conditions. These conditions include initial conditions, time varying inlet fluid temperature, different fluid mass flow rates, different storage volumes and different aspect ratios within the ranges experienced in solar-thermal storage applications.

Figure (5) shows the variation of the transient dimensionless average temperature of the bed (the time varying bed effectiveness) for different aspect ratios and different Reynolds numbers for a fixed bed diameter of 0.375 m. The aspect ratio was varied from 1.0 to 10, and Reynolds number (Re_o) takes the values of 260, 580, 1600, and 3200, respectively. It was noticed that the increase in the aspect ratio decreases the charging duration (the time at which the bed reaches its maximum temperature, the state of thermal saturation,). Also, as the mass flow rate increases the bed storage temperature takes higher values with less charging duration. This may be due to the increase of the interphase heat transfer coefficient between the flowing fluid and solid particles. Also, the bed storage temperature decreases with the increase in the aspect ratio and this is in fact due to the increase in bed storage volume.

Figure (6) shows the time varying bed effectiveness and storage efficiency for a fixed bed storage volume at different aspect ratios and at different flowing fluid mass flow rates. The storage volume was taken a value of 0.4142 m^3 and the fluid mass flow rate was ranged from 0.015 to 0.15 kg/s. It is noticed that at the lower range of mass flow rate the aspect ratio is more effective on the bed performance while at the higher range its effect is insignificant. Also, the decrease in the mass flow rate of the air enhances the storage efficiency and in the same time increases the charging duration. This may be due to the decrease in the loss of the available energy which carried by the incoming fluid.

The effect of storage volume on the storage efficiency and bed effectiveness at a fixed aspect ratio and at a fixed mass flow rate is illustrated in Fig.(7). The increase in the storage volume leads to an enhancement in the bed effectiveness. This is due to the relatively high thermal capacity of the bed with larger storage volume.

Figure (8) shows the temporal bed performance at different mass flow rate for storage volume having a value of 0.4142 m^3. It is shown that the increase in the air mass flow rate decreases the charging duration on the expense of the storage efficiency. Also, it was found that the bed effectiveness at the sate of thermal saturation is slightly affected by the fluid mass flow rate.

Figure (9) shows the bed effectiveness and storage efficiency at different pairs of mass flow rate and storage volume. These pairs were adjusted to give a fixed ratio.

It is clearly indicated that no significant change in the bed performance for the different cases. This means that the fluid mass flow rate/storage volume ratio is considered to be an important design parameter for the thermal energy storage in packed beds. This in fact is considered the main corollary of the present study.

The bed performance for different inlet fluid temperature is depicted in Fig.(10). The inlet temperature was varied from 50 to 500 °C. It is noticed that the effectiveness is slightly influenced by the inlet temperature, while the storage efficiency increases with increasing the inlet fluid temperature specially at the charging period. This may be due to the enhancement in the interphase heat transfer rate as a result of increasing the fluid temperature.

The effect of variable fluid inlet temperature on the bed performance at a fixed value of mass flow rate to storage volume ratio is shown in Fig.(11). A sinusoidal variation of the inlet temperature was adapted to simulate the solar collector outlet conditions. It is shown that both the bed effectiveness and the storage efficiency follows the variation in the fluid inlet temperature.

Figure (12) shows the bed performance at both charging and recovery modes at different ratios of the mass flow rate to storage volume. The increase in this ratio decreases the charging duration and enhances the bed effectiveness at state of thermal saturation. The results show that this new design parameter is more effective on the bed performance characteristics.

Moreover, the predicted results for the bed performance characteristics at the charging mode were correlated as functions of both the operating and design parameters and the following corrlelations were obtained:

$$\tau = 0.0089 \left(\frac{\rho_s c_s V_{st}}{m_f c_f} \right)^{0.62} \left(\frac{d}{D} \right)^{-0.25} \left(\frac{k_f}{k_s} \right)^{0.068} \qquad \text{hour} \tag{18}$$

$$\theta = 16.58 \left(\frac{\rho_s c_s V_{st}}{\tau\, \dot{m}_f c_f} \right)^{-0.347} \left(\frac{d}{D} \right)^{0.026} \left(\frac{k_f}{k_s} \right)^{0.045} \tag{19}$$

$$\eta = 0.0115 \left(\frac{\rho_s c_s V_{st}}{\tau\, \dot{m}_f c_f} \right)^{0.407} \left(\frac{d}{D} \right)^{0.0015} \left(\frac{k_f}{k_s} \right)^{0.025} \tag{20}$$

A comparison between the predicted and the correlated values is shown in Fig.(13). The comparison shows that these correlations may be valid within the range of the investigated parameters of (m_f from 0.015 to 5.0 kg/s, V_{st} from 0.04 to 10 m^3, d from 10 to 50 mm, D from 0.15 to 1.5 m, k_s from 0.88 to 385 W/m.K, ρ_s from 1920 to 7854 kg/m^3 and c_s from 434 to 903 J/kg.K) with a maximum deviation of 20%.

7. CONCLUSIONS

In view of what has been presented the following conclusions can be drawn:

1- The present numerical model has shown that significantly accurate prediction of the charging and recovery periods is possible, as the results show reasonable accordance with both the experimental data and predictions of other authors.

2- The fluid mass flow rate to the storage volume ratio is considered to be an important design parameter for the thermal storage in packed beds.

3- There is no significant effect of the aspect ratio on the bed performance for packed beds with constant storage volume.

4- Three dimensionless operating and design parameters were found to be the most effective parameters on the packed bed performance as a thermal storage system.

These parameters are the bed to fluid thermal capacity ratio, particle to bed diameter ratio and fluid to solid thermal conductivity ratio.

5- Three correlations for the bed charging duration, bed effectiveness, and the system storage efficiency were obtained.

REFERENCES

1- Beasley, D.E. and Clark, J.A. "Transient Response of a Packed Bed for Thermal Energy Storage", Int. J. Heat Mass Transfer, Vol. 27, No. 9, pp. 1659-1669, 1984.

2- Beasley, D.E., Ramanarayanan, C. and Torab, H., "Thermal Response of a Packed Bed of Spheres Containing a Phase Change Material", Int. J. of Energy Research, Vol. 13, pp. 253-265, 1989.

3- Khan, J.A. and Beasley, D.E., "Two Dimensional Effects on The Response of Packed Bed Regenerators", Trans. of ASME, Vol. 111, pp. 328-336, May 1989.

4- El-Sharkawy, A.I., Tadros, W. H. and Abdel-Rehim, Z.,"An Experimental Investigation of Cement Coated Aluminum Wire Mesh as Storing Medium in Thermal Storage System", Proceedings of the 5th Int. Conf. on Energy and Environment, Vol. 1, pp. 291-303, Cairo, Egypt, 1996.

5- Abdel-Salam, M.S, Aly, S.L., El-Sharkawy, A.I. and Abdel-Rehim, Z.,"Thermal Characteristics of Packed Bed Storage System", Proceedings of the 5th Miami Int. Symposium on Multi-Phase and Particulate Phenomena, Miami Beach, Florida, 1988.

6- Aly, S. L. and El-Sharkawy, A.I., "Effect of Storing Medium on Thermal Properties of Packed Beds", J. of Heat Recovery Systems, Vol. 10, No. 5, pp. 509-514, 1990.

7- Steiner, D., Wierse, M. and Groll, M., "Development and Investigation of Thermal Energy Storage Systems for the Medium Temperature Range", IECEC PAPER No. ES-165, Vol. 2, pp. 193-198, ASME 1995.

8- Adebiyi, G. .A., Nsofor, E.C., Steele, W.G., Jalalzadeh, A. and Ali, A., "Parametric Study on the Operating Efficiencies of A Packed Beds for High Temperature Sensible Heat Storage", Proceedings of the 1993 ASME, Winter Annual meeting, pp. 59-71, 1993.

9- Choudhury, C., Garg, H.P. and Prakash, J., "Transient Analysis of Rock Bed Air Heaters for Intermediate Temperature Applications", J. of Energy Research., Vol. 17, No. 5, pp. 377-392, July 1993.

10- Hornbeck, R.W., " Numerical Marching Techniques for Fluid Flows with Heat Transfer", NASA, Sp-297, P.198, Washington, D. C., 1973.

11- Beavers, G.J., Sparrow, E.M., and Rodenz, D.E., "Influence of Bed Size on the Flow Characteristics and Porosity of Randomly Packed Beds of Spheres", J. of Applied Mech. Vol. 40, P.655, 1973.

12- Newell, R. and Standish, N., "Velocity Distribution in Rectangular Packed Beds and Non-ferrous Blast Furnaces", Metall. Trans. Vol. 4, pp. 1851-1857, 1973.

13- Cheng, P. "Heat Conduction in a Packed Bed with Wall Effect", Int. Comm. Heat Mass Transfer, Vol. 13, pp. 11-21, 1986.

14- Galloway, T.R. and Sage, B.H., "A Model of the Mechanism of Transport in Packed, Distended and Fluidized Beds," ,Chem. Eng. Sci., Vol. 25, P. 495, 1970.

15- Heikal, H., Abou-Ziyan, and Abdel-Naiem, M. "Characteristic of a Rock Bed Storage System for Various Solar Application", Proceedings of the 5th Int. Conf. on Energy and Environment, Cairo, Egypt, 1996.