International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622
International Conference On Emerging Trends in Mechanical and Electrical Engineering
(ICETMEE- 13th-14th March 2014)

RESEARCH ARTICLE OPEN ACCESS

Parametric Study of Rock Bed Thermal Regenerator for Space Heating

Neeraj Tewari, Manish Bhendura, Mithleshupadhyay, D.S. Murthy
Mechanical Engineering Department, College of Post Graduate Studies,
G B Pant University of Agriculture & Technology, Pantnagar, Uttarakhand-263145

Abstract
Rock beds are generally used for space heating, which stored heat energy when hot gas flows through it and deliverhot air when cold air passes through it, in periodic manner.This hot gas can be an outlet air of solar air heater, exhaust gas of industries, and waste heat of any process. Present work deals with the study of various vital thermal energy storage system parameters such as rock bed size, rock particle diameter and number of beds to optimize the performance of regenerator for space heating. Besides this, mass velocity of air in charging and discharging of rock bed, pressure drop across bed, cycle time of charging and discharging the rock bed are also studied. The desired human comfort conditions inside a room, having dimensions of 4x4x4 m^3 occupied by 4 persons has been taken into consideration for formulating the necessary conditions.

I. Introduction

During winter season, daytime is somehow comfortable but nights are very cold and temperature drops below human comforts. Therefore it becomes essential to use a heat pump or heating device during night to maintain the temperature at human comfort. These heating devices directly (fuel) or indirectly (electricity)works on conventional fuels which are continuously depleting day by day with increasing rate. Solar energy can be an effective alternate for space heating during night by storing heat during daytime.

Rock bed is one of promising medium to store solar energy. It consists of small rock particles of approximately same size in a chamber, which store heat when hot air passes through it, called charging of rock bed. This stored amount of heat is extracted by passing cold air across the rock bed, called discharging of rock bed. The temperature of this cold air raiseafter taking heat from rock bed, and can be served for the purpose of space heating.

For efficient storage of heat energy, the designing of rock bed is very crucial, since various factors are affecting the performance of the rock bed. The governing parameters for the effective performance of the rock bed are:

- air flow rate per unit of face area
- rock equivalent diameter
- bed length
- bed face area

A lot of theoretical and experimental studies had been performed on the rock bed till now. Schumann [9] presented one–dimensional two-phase model for packed bed system by ignoring the thermal Capacity of the fluid, axial conduction in the fluid and axial conduction in the solid. Furnas[5] conducted the first experimental study for heat transfer from a fluid stream to a bed of broken solids. Lof and Hawley[7] determined the heat transfer between air and loose solids in an experimental study. Coutier and Farber [3] gave a numerical model for calculating volumetric convective heat transfer coefficient. Torab and Beasley[10] conducted second law efficiency analysis of sensible heat storage packed beds. Some of valuable works published for optimization of various parameters of rock bed areChoudhary et al.[2], and Aldo Steinfeld et al[6].

Present study using mathematical modeling for rock bed heat regenerator from Murthy et al [8] and optimizing the various parameter of rock bed for space heating at night during winter season, by developing a computer program in MATLAB for charging and discharging of rock bed.The optimization of rock bed is performedfor a typical hill area residential room (4x4x4 m^3) occupied by four persons.

II. System Model

Storage in rock bed is accomplished by heating the rock with hot air with the help of solar air heater when solar insolation is available (day) and then utilizing it as a source of heating when solar insolation is absent (night). Rock bed acts as a regenerator in charging and discharging processes. A schematic of rock bed storage technique is as shown in Fig.1.

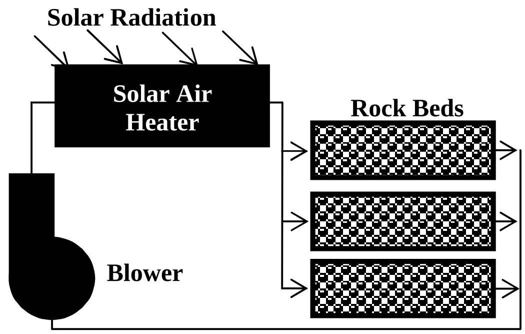

Fig. 1 Rock Bed Storage System for Space Heating

III. Space heating load calculation

For a family of 4 members the value of ventilation loadis taken to be 0.56cmm/person and the metabolism rate is taken to be 90 W/person [1]. Due to temperature gradient inside heated space and surrounding there will be transmission losses. Combined conduction and convection losses from walls of the space under study are considered.

Standard values of overall heat transfer coefficient and other cooling loads are taken from [1]. Values of various loads considered in this study are:

Ventilation load = 4 x 0.56 = 2.24 cmm = 506.58 W
Transmission load = 2464 + 374.8 = 2838.8 W
Appliances load = 200 W (Assumed)
Internal heat gain = 90 x 4 + 200 = 560 W
Net heating load = (Ventilation Load)
+(Transmission Load)
– (Internal Heat Gain)
= 2.785 kW

Required cmm to maintain room temperature at 21 ^{0}C [1]

$$?? \; ? = \frac{? \; ? \; ?}{0.0204 \times (?_? - ?_?)}$$
= 7.185 = 0.1437 kg/s

IV. Mathematical Model

Many authors have investigated different models based on the set of two coupled partial differential equations: one for the gas and the other one for the solid. For present study mathematical model of heat transfer in rock bed developed by Murthy*et al.*[8] is taken.

The energy equations associated with charging and discharging of rock bed to each phase i.e. gas and solid in the mathematical model taken are:

For gas:

$$?_{?,???} \times \frac{?^2?_?}{??^2} - ?_{??} \times ?_{??} \times ?_? \times \frac{??_?}{??} + h \times \frac{?_?}{?} \times ??_? - ?_?? = ?_{??} \times ?_? \times \frac{??_?}{??}$$

For solid:

$$? \times ?_{??} \times (1 - ?) \times \frac{??}{??} = h \times ?_? \times ??_? - ?_??$$

Initial and boundary conditions:

At t = 0, $Tg = Tgo \& Ts = Tso$ $0 \leq x \leq L$

At x = 0, t > 0 $\quad ?_{?,???} \frac{??_?}{??} = ?_{??} ?_? ?_? ???_? - ?_{?0}?$

The equations shown are coupled partial differential equation in space and time. In this present Study the mathematical model which consists of two partial differential equations is coded and solved using a computer program in MATLAB.

The pressure drop across the bed is calculated using the formula given by [4].

$$P = \frac{L_b G^2}{\rho_g dp} ??(1.75) * \frac{(1 - \square)}{\square^3} + (150) * \frac{(1 - \square)}{\square^3} * \frac{\mu}{Gdp}??$$

For calculating the value for the volumetric convective heat transfer coefficient expression suggested by [3] is used which is as:

$$h_v = 700 * ?\frac{G}{dp}?^{0.76}$$

Validation of MATLAB Program:

The temperature profiles obtained in present work from the MATLAB program have been compared with the profiles obtained from a previous research work done by Steinfeld*et al.* [6] in Fig. 2 and Fig.3 From these figures it can be observed that the temperature profiles obtained in present modelling and previous work are very close to each other, which in turn indicates that results obtained are in good agreement with the previous work.

For the purpose of calculating the deviation from previous work, a comparison for 1200 seconds has been done on temperature at different length of column. It is observed that a maximum of 12.43% variation is obtained.

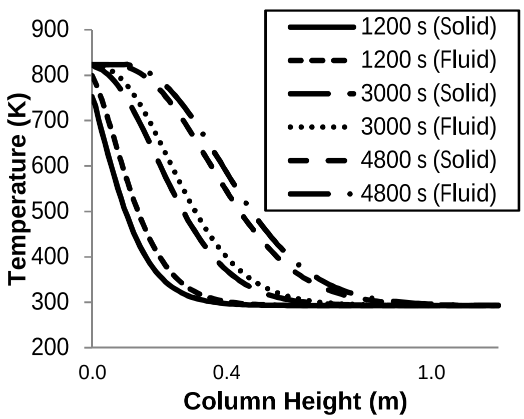

Fig.2 Charging rock bed temperature profiles of present work

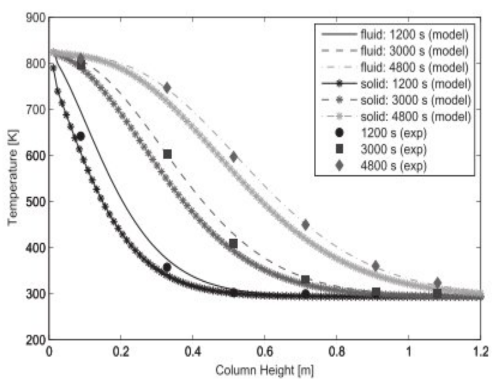

Fig. 3 Charging rock bed temperature profiles ofSteinfeld*et al.* [6]

Fig. 2 shows three different gradients of temperature in charging of rock bed with different particle diameter keeping all other parameters i.e. length of the bed, diameter of the bed and mass velocity same. Similar trends of charging profile with varying particle diameter is obtained in previous work of [6]. Thus results are validated as per the results in Fig.2.

As the rock particle diameter, dp is decreasing the temperature gradient across bed is increasing. This is due to increased surface area for smaller rock particle. Lower the value of particle diameter higher will be the surface area and bed get heated uniformly and in relatively shorter time as compare to bigger particle diameter.

V. Result and Discussion

For the study and optimization purpose rock bed is heated with two different mass velocities i.e. 0.225 kg/m^2-s and 0.450 kg/m^2-s. Charging of rock

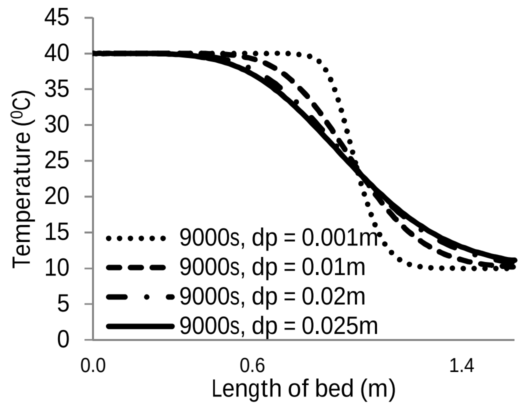

Fig. 4 Variation of temperature profiles at 9000 seconds (2.5 hours) with different particle diameters with G=0.225 kg/m^2-s, D_b=1.12 m, L=1.6 m

bed in minimum time was the objective as major part of solar insolation is available for 4 to 5 hours in a single day and it is found that 0.450 kg/m^2-s mass velocity of hot air charged the bed in 14400s (4 hours) with particle diameter of 0.01 m, 0.02 m and 0.025 m. Temperature profiles of bed with mass velocities 0.225 kg/m^2-s with particle diameter, 0.01m, 0.02m and 0.025m are shown in Fig. 5 to 7.

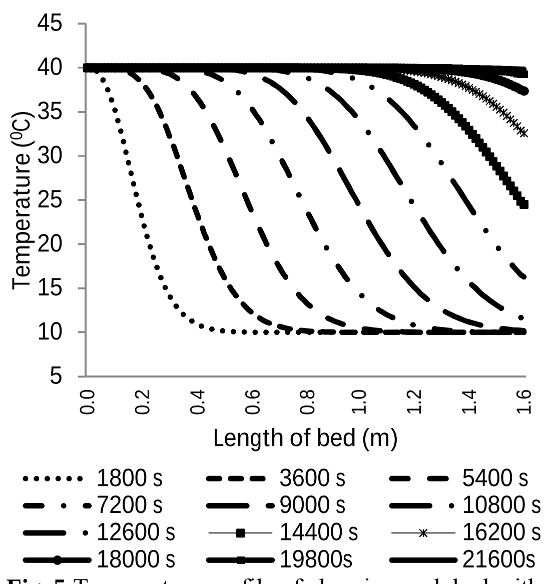

Fig. 5 Temperature profile of charging rock bed with 0.225 kg/m^2-s mass-velocity, L=1.6 m, D_b=1.12 m, ϵ=0.40, dp=0.01 m

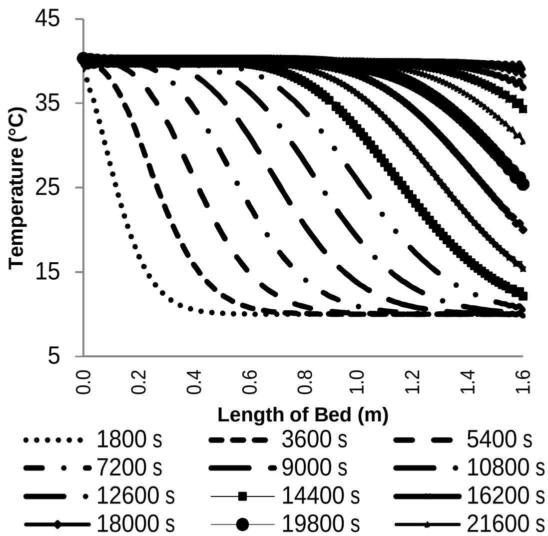

Fig. 6 Temperature profile of charging rock bed with 0.225 kg/m^2-s mass-velocity, L=1.6 m, D_b=1.12 m, ϵ=0.40, dp=0.02 m

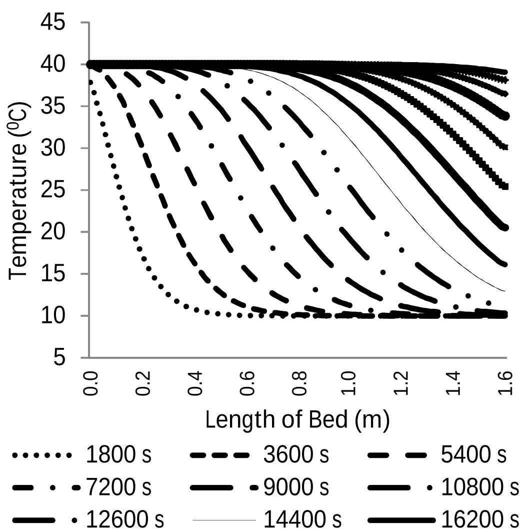

Fig. 7 Temperature profiles of rock bed charging for G=0.225 kg/m^2-s,dp=0.025 m, D_b=1.12 m, L=1.6 m, ϵ=0.40

Fig. 8 to 10 shows the temperature profiles of rock bed in charging with particle diameter of 0.01 m, 0.02 m, 0.025 m, 0.05 m and mass velocity of 0.45 kg/m^2-s. It is clear from the figures that charging time, when bed obtains the maximum temperature, is reduced as compare to charging with 0.225 kg/m^2-s mass velocity as shown in Fig. 5 to 7.

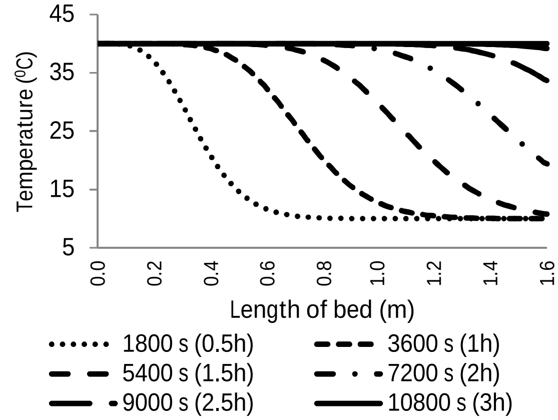

Fig. 8 Temperature profile of charging rock bed with 0.450 kg/m^2-s mass velocity, L=1.6 m, D_b=1.12 m, ϵ=0.40, dp=0.01m

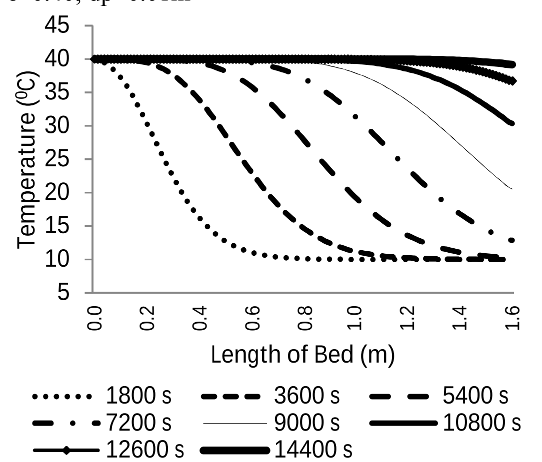

Fig. 9 Temperature profile of charging rock bed with G=0.450 kg/m^2-s, dp=0.02 m, D_b=1.12 m, L=1.6 m, ϵ=0.40

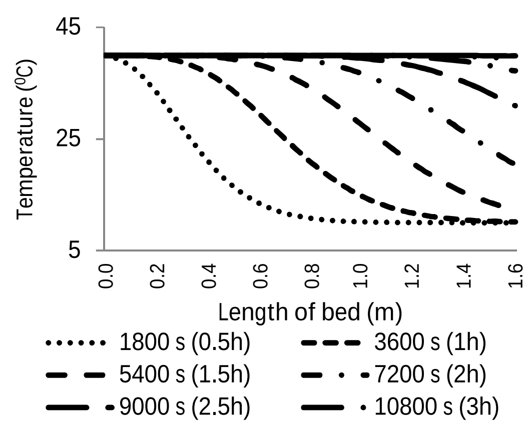

Fig. 10 Temperature profile ofrock bed charging at G=0.450 kg/m^2-s, L= 1.6 m, D_b= 1.12 m, dp= 0.025 m, ϵ=0.40

Fig. 11 to 13 shows the discharging temperature profiles with mass velocity 0.225 kg/m^2-s with different particle diameters.

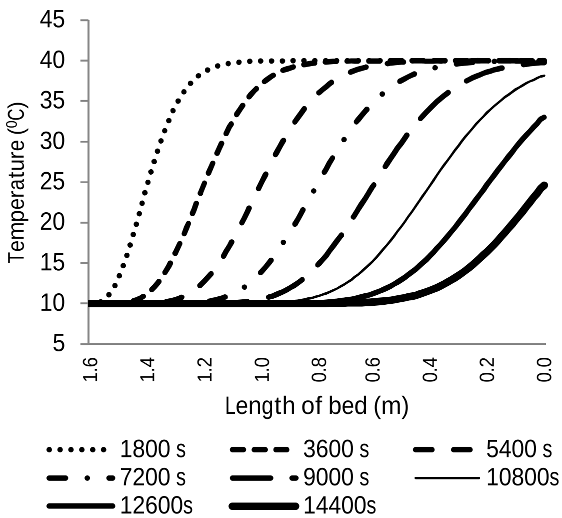

Fig. 11 Temperature profiles of discharging air with G=0.225 kg/m^2-s, D_b=1.12 m, L=1.6 m, dp=0.01 m, ϵ=0.40

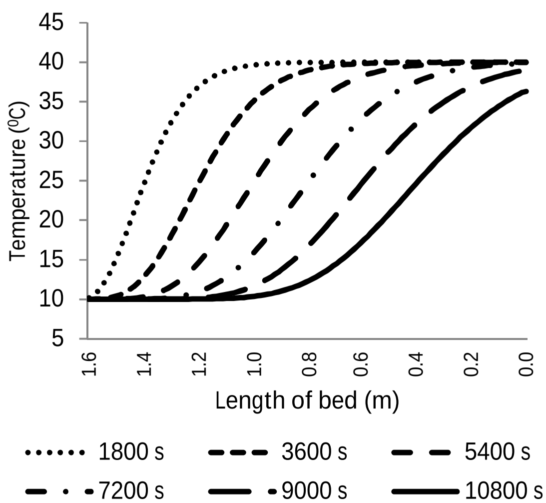

Fig. 12 Temperature profiles of discharging air with G=0.225 kg/m^2-s, D_b=1.12 m, L=1.6 m, dp=0.02 m, ϵ=0.40

For the space to be heated throughout the night, discharging time should be maximum. So the rock bed is discharged with half of the charging mass velocity (0.225 kg/m^2-s). If it is discharged with same mass velocity in charging (0.450 kg/m^2-s) either number of beds has to be increased or larger beds has to be used.

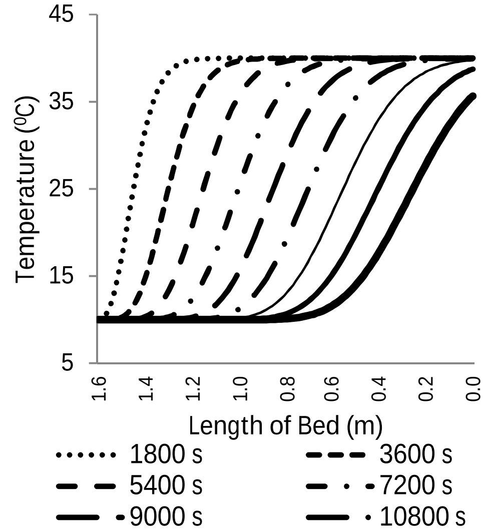

Fig. 13 Temperature profiles of discharging air with G=0.225 kg/m^2-s, D_b=1.12 m, L=1.6 m, dp=0.025 m, ϵ=0.40

Fig 14 represents the charging time of bed and pressure drop across bed. From this Figure it is clear that point at which mass velocity is 0.450 kg/m^2-s and particle diameter is 0.025 m in horizontal axis is the only point where both the optimization criteria described earlier are fulfilled. This is shown by a vertical line in this Figure.

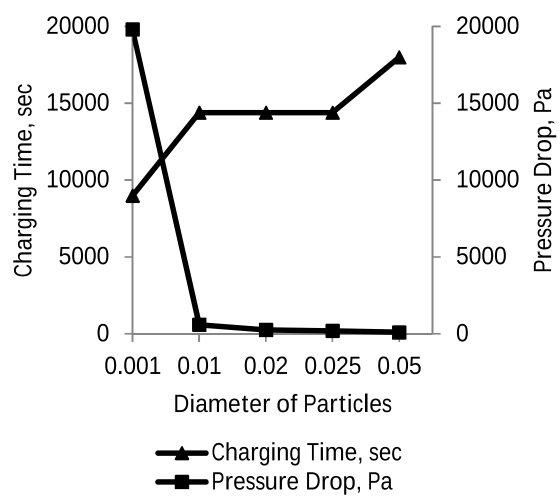

Fig. 14 Optimization of particle diameter and mass velocity

The optimized parameters in present work for air in charging the bed at 40^0C (constant) and discharging the bed at 10^0C (constant) are as follows:

- Length of bed = 1.6 m
- Diameter of bed = 1.12 m

- Number of beds = 3
- Mass velocity of hot air = 0.450 kg/m^2-s (Charging)
- Mass velocity of cold air = 0.225 kg/m^2-s (Discharging)
- Particle diameter = 0.025 m

VI. Summary and Conclusion

In present work a theoretical analysis of space heating of a room at night with 4×4×4 m^3 volume is done using a rock bed which gets charged at day time with the help of a solar air heater. A constant 40°C air is assumed to be coming at exit of solar air heater or charging the rock bed during the whole charging period. Heating load calculation of room at night time is done too where ambient temperature of night is assumed to be 10°C throughout.

Present work also includes parametric study of rock bed in charging and discharging mode and obtaining charging and discharging characteristics of rock bed with different particle diameter and mass velocity. Pressure drop across the bed is also calculated. The optimization of bed is done on the basis of space heating with minimum charging time (4 hours), maximum discharging time (greater than 8 hours) and with least pressure drop across the bed.

The results of the present work shows that if space, in winters, is to be heated with minimum power requirement and human comfort temperature throughout the night then the optimized bed parameters proposed can be adopted.

Nomenclature

A_c Cross sectional area of rock bed, m^2
a_s Specific area, m^2/m^3
C_{pg} Specific heat of air, J/kg-K
C_{ps} Specific heat of solid, J/kg-K
cmm Volume flow rate of air, m^3/min
D_b Diameter of rock bed, m
d_p Particle diameter, m
G Mass velocity, kg/m^2-s
h_p Particle heat transfer coefficient, W/m°C
h_v Volumetric heat transfer coefficient, W/m^3°C
$k_{g,eff}$ Effective thermal conductivity of air, W/m°C
L Length of rock bed, m
P Pressure drop across rock bed, Pa
T_{air} Air temperature, ^oC
T_{go} Air initial temperature, ^oC
T_{solid} Rock temperature, ^oC
T_{so} Rock initial temperature, ^oC
t_sSupply air temperature, ^oC
v Velocity of air in rock bed, m/s
μ Dynamic viscosity of air, kg/m-s
ρ_gDensity of air, kg/m^3
ρ_sDensity of solid, kg/m^3
ϵPorosity of rock bed

References

[1] **Arora, P.C. 2000.** Refrigeration and Air Conditioning, Second Edition.
[2] **Choudhary, C. Chauhan, P.M. and Garg, H.P. 1995.** Economic design of a rock bed storage device for storing solar thermal energy. *Solar Energy*. 55(1): 29-37.
[3] **Coutier, J.P. and Faber, E.A. 1982.** Two applications of a numerical approach of heat transfer process within rock beds. *Solar Energy*. 29(6): 451-62.
[4] **Ergun, S. 1952.** Fluid flow through packed columns. *ChemEng Sci*. 48(2): 89-94.
[5] **Furnas, C.C. 1930.** Heat transfer from a gas stream to a bed of broken solids. *IndEngChem J*. 721-31.
[6] **Hanchen, M. Bruckner, S. and Steinfeld, A. 2011.** High temperature thermal storage using a packed bed of rocks - Heat transfer analysis and experimental validation. *Applied Thermal Engineering*. 31: 1798-1806.
[7] **Lof, G.O.C. and Hawley, R.W. 1948.** Unsteady state Heat transfer between air and loose solids. *IndEngChem J*. 40(6): 1061-71.
[8] **Murthy, D.S., Siva Kumar, S.V.,Rao, D.P. and Keshav Kant, 2008.** Process intensification in a simulated moving bed heat regenerator. Transactions of ASME *Heat Transfer Journal*. Vol. 130, DOI:10.1115/1.2927397.
[9] **Schumann, T.E.W. 1929.** Heat transfer: A liquid flowing through a porous prism. *Heat Transfer*: 405-16.
[10] **Torab, H. and Beasley, D.E. 1987.** Optimization of a packed-bed thermal-energy storage unit. *JSolar Energy Eng*: 109.