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Packed Bed 태양에너지 저장시스템의 열성능에 관한 수학적 시뮬레이션

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Mathematical Simulation on Thermal Performance of Packed Bed Solar Energy Storage System

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Abstract >> Solar air heaters (SAHs) are simple in design and widely used for solar energy collection devices, and a packed bed is one of typical solar energy storage systems of thermal energy captured by SAHs. This paper presents mathematical modeling and simulation on the thermal performance of various packed bed energy storage systems. A MATLAB program is used to estimate the thermal efficiency of packed bed SAH. Among the various packed bed energy storage systems considered, the wire mesh screen packed bed SAH shows the best thermal efficiency over the entire range of design conditions. The maximum of thermal efficiency of packed bed SAH with wire mesh screen matrices has been found to be 0.794 for Re=2000 - 20000 and $\Delta T/I$=0.002 - 0.02.

Key words : Solar energy(태양에너지), Solar air heater(SAH, 태양공기히터), Packed bed type(충진형), Energy storage(에너지 저장), Thermal performance(열적 성능)

Nomenclature

A : Cross section area of packed bed, m^2
A_c : Collector area, m^2
C_p : Specific heat of air, J/kgK
C_s : Specific heat of storage material, J/kgK
F_R : Heat removal factor
I : Solar intensity, W/m^2
L : Length of packed bed, m
$\dot{m}$: Mass flow rate, kg/s
N : Number of bed elements
Q : Thermal energy storage, W
Q_u : Heat gain, W
Re : Reynolds number
T_{ai} : Air inlet temp. to bed, K
T_{amb} : Ambient temp., K
T_{bi} : Initial temp. of bed, K
T_{bm} : Mean temp. of bed, K
T_i : Collector air inlet temp., K
T_{mi} : Initial bed temp. of element 'm', K
T_{mm} : Mean bed temp. of element 'm', K

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T_{nm} : Mean bed temp. of n^{th} element 'm', K
T_o : Collector air outlet temp., K
t_{ch} : Charging time, min
U, U_l : Overall heat transfer coefficient, W/m^2K
V_b : Volume of packed bed, m^3
$\Delta T/I$: Temperature rise parameter, Km^2/W
Δt : Time interval, min
Δx : Thickness or height of bed element, m

Greek symbols

ρ : Density of air, kg/m^3
ρ_s : Density of storage material, kg/m^3
Ψ, Φ : Sphericity of material
ε : Void fraction
η_{th} : Thermal efficiency
$(\tau\alpha)$: Transmittance-absorptance product for absorber-cover combination

Subscript

a : Air
m : Mean value
SAH : Solar air heater
NTU : Number of transfer units

1. Introduction

Solar energy is one of the most important renewable energy resources. The total solar energy potential on earth surface is about 10,000 times the present world energy demand. Solar energy is free, clean and most abundant energy resource among renewable energy resources. Solar energy originates from the sun and travels as radiations[1,2]. Energy storage provides a mean for improving the efficiency of a wide range of energy systems. Typically energy storage is used when there is time or rate mismatches between energy supply and demand or where intermittent energy sources are available, like that of solar energy. SAHs can be fabricated using cheaper as well as lesser amount of material and is simpler to use than solar water heaters[3,4]. SAHs are generally considered to be useful for applications including space heating, crop drying, seasoning of timber, etc. The idea of using porous matrix as an absorber for incident solar radiations in SAH duct has been proposed by several investigators[5-7]. Metallic screen or other solid material forming packed bed in the heater flow passages has been used as heat absorbing material for solar radiations and the absorbed heat energy is transferred to the air that flows through the bed. The detailed information about several experimental works on packed bed solar energy storage systems with various geometrical parameters can be found in references[8-17]. In SAH systems the low density of air makes it impractical to store the heated air itself. It is therefore necessary to transfer the thermal energy from air to a denser medium. During charging mode, solar heated air is forced into the top of the container i.e. upper plenum and it then passes evenly down through the bed heating the storage and passes out through the lower plenum. Air is drawn off at the bottom and returns to the collectors. When energy is needed from storage, the airflow is reversed. Room air enters from bottom and flows to the top of the bed and is delivered into the building. After losing heat in the room again, room air comes to the bottom of the bed and the cycle is repeated. Charging and discharging process of the bed never takes place simultaneously[6-8,10].

As the hot air passes through the storage material, the bed temperature rises, and the hot air gets cooled. The cooled air, which leaves at the bottom of the bed, returns to the collector for getting reheated. Packed bed storage generally has thermal stratification i.e. top is warmer than the bottom, which improves the performance of the collector. The rate of heat transfer to or from the solid in a packed bed is a function of the physical and thermal properties of the fluid and solid, the temperature difference between the fluid and the solid, and mass flow rate of the fluid. The rate of heat transfer is also a function of the geometric characteristics of the packed bed material, which depends upon the shape and orientation of the packing material and on the bed porosity. The packing is usually random, where particles of apparently the same size and shape are packed in an arbitrary manner into the container [6,9,11-12,15-17].

This paper presents mathematical modeling and simulation on the thermal performance of various packed bed energy storage systems with variation of working parameters ($\Delta T/I$, Re and I) of SAHs.

2. Thermal performance analysis

The schematic diagram of typical packed bed solar air heating system is shown in Fig. 1. The performance of simple SAH is generally low due to low value of convective heat transfer coefficient between the absorber surface and flowing air which increases the absorber surface temperature, leading to higher thermal losses to the atmosphere and hence low thermal efficiency. The heat transfer coefficient of SAH can be increased by providing packed bed energy storage system, leading to higher collection efficiency. The correlations developed for various packed bed energy storage system by previous investigators have been used to predict the performance of SAH.

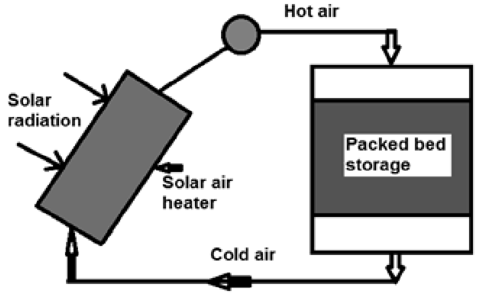

Fig. 1 Schematic of packed bed solar air heating system [7]

2.1 Mathematical model

The thermal performance of energy storage systems can be predicted on the basis of detailed consideration of heat transfer processes in the system. It may be noted that the results need to be presented as function of two design parameters namely temperature rise parameter ($\Delta T/I$) and insolation (I). The calculation starts with fixed value of design parameters ($\Delta T/I$ and I) and proceeds with the calculation of other parameters for system incorporating storage and collector. A calculation procedure is as follows. A set of the values of the packed bed and design parameters such as temperature rise parameter, $\Delta T/I$ and solar insolation, I are selected. It is generally required to size the bed corresponding to the amount of energy to be stored at the required temperature. The size of the bed should be fixed in such a way that the bed absorbs maximum amount of energy delivered by the flowing air during charging phase and mean temperature of the bed at the end of the charging should become nearly equal to inlet air temperature. Therefore, to evaluate the bed size, following energy balance equation has been used.

$$(\dot{m} C_p)_a (T_{ai} - T_{bi}) t_{ch} = (\rho C)_s (1-\epsilon) V_b (T_{bm} - T_{bi}) \quad (1)$$

The flow rate of air is calculated from the following Hottel-Williar-Bliss equation reported by Dhiman et al.[9] for useful energy gain in the packed bed SAH system:

$$Q_u = A_c[(IF_R(\tau\alpha) - F_R\dot{U}_l(T_i - T_{amb})] \quad (2)$$

Useful energy gain Q_u is also given by;

$$Q_u = (m\dot{C}_p)_a(T_o - T_i) \quad (3)$$

$$m_a = \frac{[F_R(\tau\alpha)_e I - \dot{F}_R U_l(T_i - T_{amb})]}{C_p(T_o - T_i)} \quad (4)$$

Where T_i is inlet air temperature to the solar energy storage system, which is assumed to be equal to the initial temperature of the bed i.e. T_{bi}, T_o is air temperature at outlet of the collector, required to be kept equal to 40°C i.e. the temperature of air at inlet to bed T_{ai}.

For predicting thermal performance of a packed bed SAH, many mathematical models have been reported in the literature. However, most of investigators have used Mumma and Marvin model reported by Maithani et al[18]. This model has been adopted to perform the present simulation study. In this work, a packed bed is assumed to be considered of 'N' number of elements of equal axial thickness 'x' as shown in Fig. 2. The following governing equations of Mumma and Marvin model are used to evaluate the temperature distribution for air and solid in the bed.

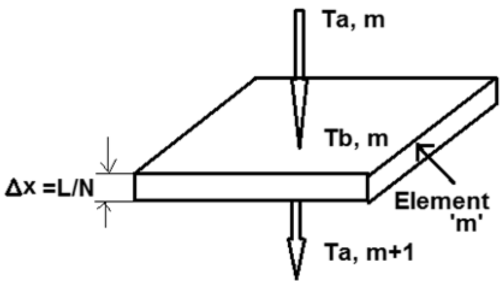

Fig. 2 Element 'm' of packed bed

$$T_{a,m+1} = T_{b,m} + (T_{a,m} - T_{b,m})\exp(-\phi_1) \quad (5)$$

where

$$\phi_1 = \frac{h_v AL}{N(\dot{m}C_p)_a} = \frac{NTU}{N}, \quad N = \frac{L}{\Delta x} \quad (6)$$

$$t_{b,m(t+\Delta t)} = T_{b,m(t)} \begin{bmatrix} \phi_2(T_{a,m} - T_{a,m+1}) \\ -\phi_3(T_{b,m} - T_{amb}) \end{bmatrix} \Delta t \quad (7)$$

where

$$\phi_2 = \frac{(\dot{m}C_p)_a N}{\rho_s AL(1-\epsilon)C_s}, \ \phi_3 = \frac{(U\Delta T)_m}{\dot{m}C_p}\phi_2 \quad (8)$$

Thermal energy gained in the bed is calculated by using the following general equation;

$$Q_u = \int_0^L (\rho C)_s (1-\epsilon) A (T_{a,m} - T_{i,n}) dx \quad (9)$$

Initially bed is assumed at uniform temperature of T_{bi} and has been divided into 'N' number of elements of equal thickness. The above governing equation for thermal energy stored *'Q'* can be written in finite difference form as;

$$Q_u = (\rho C)_s (1-\epsilon) A \frac{L}{N} \left(\sum_{n=1}^{N} T_{am} - NT_{bi} \right) \quad (10)$$

Available energy gained in the bed(Q_u) is calculated by using the following equation given by Torab and Baesley [9,10];

$$Q_u = \int_0^L (\rho C)_s (1-\epsilon) A \left[(T_{am} - T_{mi}) - T_{mi} \ln\left(\frac{T_{am}}{T_{mi}}\right) \right] dx \quad (11)$$

The above equation for available energy stored in the bed can be transformed to finite difference form as;

$$Q_u = (\rho C)_s (1-\epsilon) A \frac{L}{N} \left[\frac{\sum_{n=1}^{N} (T_{am} - NT_{bi}) - T_{bi}}{\ln\left(\frac{T_{1m} T_{2m} T_{3m} \cdots\cdots T_{Nm}}{T_{bi}} \right)} \right] \tag{12}$$

Thermal performance of the collector is therefore expressed in terms of useful energy gain from the collector and it can be determined as follows:

$$\eta_{th} = \frac{Q_u}{A_c I} \tag{13}$$

2.2 Development of computer program

The performance of packed bed solar energy storage system has been predicted by using a MATLAB program with the above discussed component models. The objective of developing the computer program is to obtain values of various performance parameters which are air mass flow rate, air temperature at the outlet of each element of the bed, mean temperature of the bed, thermal energy stored in the bed, and thermal efficiency of the collector. Table 1 shows thermo-physical properties of masonry brick material, and Fig. 3. depicts the flow chart for the program. The heat transfer correlations for the packed bed SAH storage systems can be found from the references[5-8, 12].

Table 1 Fixed parameters of packed bed storage SAH

Parameter		Value
Volume of packed bed (V_b), m^3		15
Length of packed bed (L), m		6
Number of bed elements (N)		60
Initial bed temp. (T_{bi}), K		298
Sphericity of material (ψ, ϕ)		0.55-1.0
Void fraction (ε)		0.31-0.63
Density, kg/m^3	storage material (ρ_s)	1920
	air (ρ)	1.1
Specific heat, J/kgK	storage material (C_s)	835
	air (C_p)	1008
Ambient temp. (T_{amb}), K		298
Bed inlet air temp. (T_{ai}), K		337
Solar insolation (I), W/m^2		1000
Collector area (A_c), m^2		20
$F_R \tau\alpha$ for collector		0.62
$F_R\ UL$ for collector		3.38
Collector air inlet temp. (T_i), K		298
Time interval ($\triangle t$), min		15

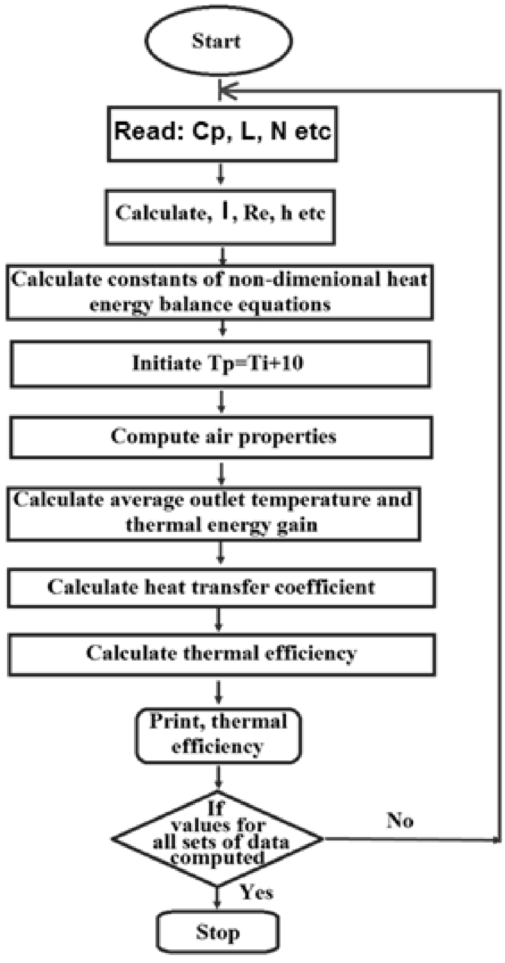

Fig. 3 Flow chart for computer program

3. Results and discussion

The effect of different packed bed materials, configurations and storage packing shapes for a SAH system on thermal performance has been simulated. The thermal efficiency values for different packed bed energy storage SAH systems as a function of Reynolds number (*Re*) and temperature rise parameter ($\Delta T/I$) have been compared to those of the SAH systems without storage systems. Also, thermal efficiency of packed bed solar energy storage system has been calculated using heat transfer correlations developed based on the previous investigators data. Performance plots have been prepared to illustrate the effect of various packed bed SAH systems and operating parameters on thermal efficiency as a function of Reynolds number and temperature rise parameter. Figs. 3 and 4 show the effect of Reynolds number and temperature rise parameter of SAH with various packed bed energy storage systems.

Fig. 4 shows the effect of Reynolds number on thermal efficiency (η_{th}) of different packed bed SAH systems with and without energy storage. Fig. 4 illustrates the variation of thermal efficiency with respect to Reynolds number for the constant solar intensity of I = 1000 W/m^2. Variation of thermal efficiency of packed bed SAH systems with respect to Reynolds number has also been plotted to show the enhancement in thermal efficiency due to the presence of packed bed SAH. It has been observed from the Fig. 4 that thermal efficiency of packed bed SAH system is higher than that of the system without packed bed. Thermal efficiency of packed bed SAH system has been found to increase from 0.583 to 0.794 with an increase in Reynolds number from 2000 to 20000. For the SAH system without packed bed, increase in thermal efficiency for corresponding values of Reynolds number has been found to be 0.364 to 0.585.

Fig. 5 has been drawn to bring out the effect of various packed bed SAH systems on thermal efficiency as a function of temperature rise parameters for fixed value of solar intensity, (I)=1000 W/m^2. Thermal efficiency of packed bed SAH system has been found to decrease from 0.794 to 0.583 with an increase in temperature rise

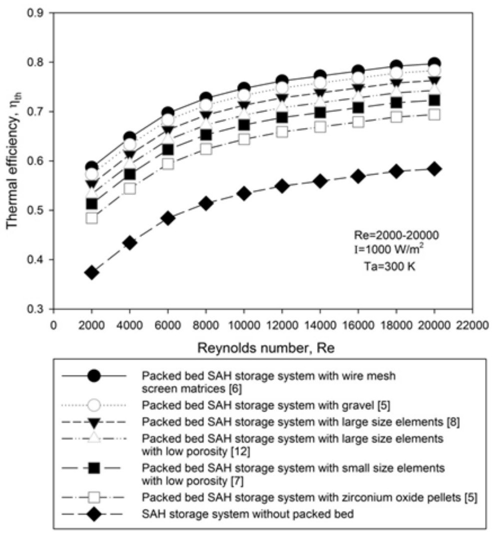

Fig. 4 Thermal efficiency of various packed bed SAHs as a function of Reynolds number

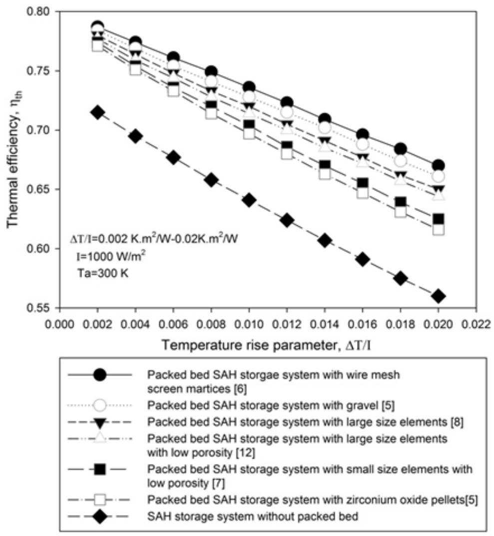

Fig. 5 Thermal efficiency of various packed bed SAHs as a function of temperature rise parameter

parameters from 0.002 to 0.02. For the SAH system without packed bed, thermal efficiency for corresponding values of temperature rise parameters decreases from 0.585 to 0.364. It is similarly observed from Figs. 4 and 5 that thermal efficiency of packed bed storage system with wire mesh screen matrices has higher than those for the other packed bed SAH systems.

Fig. 6 shows comparison of the thermal efficiency in packed bed SAH system with wire mesh screen matrix and without it.

The Figure shows the variation of thermal efficiency with Reynolds numbers and temperature rise parameters for packed bed SAH storage system where the maximum values can be clearly observed. The maximum thermal efficiency enhancement with packed bed SAH system has been found to be 0.794. Because, the wire mesh is normal wire woven or cross rod to form net like sheet with pores in them through which fluid can pass through. This type of flow over the wire will increase the convective heat transfer coefficient from the collector to the fluid. Former investigators reveal usage of wire mesh bed for improving heat transfer. In using wire mesh, the dimensions of the wire and the porosity of the wire mesh play a vital role in the performance of the SAH systems.

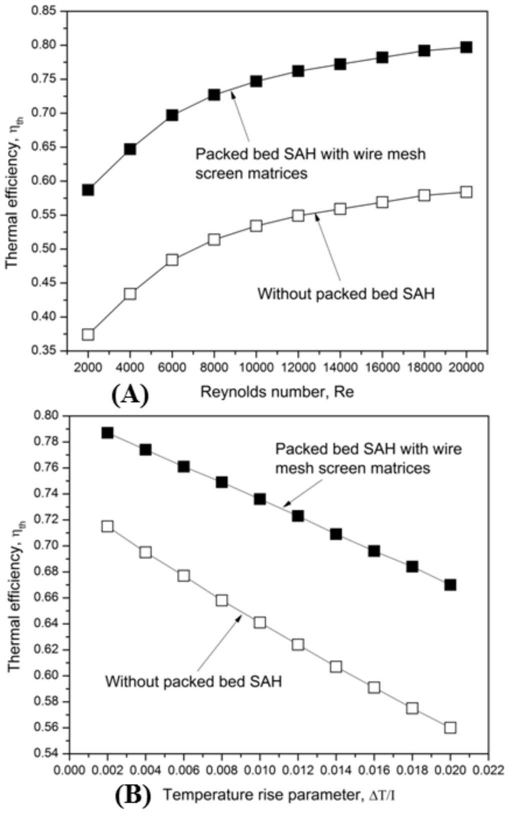

Fig. 6 Comparison of thermal efficiency of SAH systems with and without packed bed [(A) function of R_e, (B) function of $\Delta T/I$]

4. Conclusion

A mathematical modeling and simulation program has been developed in MATLAB for the calculation of thermal efficiency. Thermal performance of various packed bed energy storage systems for SAH has been estimated and compared based on this program. An optimization has been carried out to determine the packed bed energy storage system that has the maximum values of thermal efficiency. The optimum values of packed bed SAHs obtained from the thermal efficiency criteria are strong functions of temperature rise parameters and insolation. Besides, these two criteria result into different optimum values for a given value of these design parameters in a certain range of temperature rise parameter while these are the same in a certain other range of temperature rise parameter; these ranges being depend upon the insolation value. The thermal efficiency increases with increase in Reynolds number and becomes almost asymptotic in higher range of Reynolds number and thermal efficiency decreases with increase in temperature rise parameter. Packed bed SAH with wire mesh screen matrices has been found to be better thermal performance in comparison to other packed bed SAH system studied by other investigators under similar operating conditions. The maximum value of thermal efficiency of packed bed SAH system with wire mesh screen matrices has been found to be 0.794 for Re=2000 - 20000 and $\Delta T/I$=0.002 - 0.02.

References

1. A. Kumar, and M. H. Kim, Numerical optimization of solar air heaters having different types of roughness shapes on the heated plate - Technical note, Energy, Vol. 72, pp. 731-738, 2014.
2. A. Kumar, and M. H. Kim, Convective heat transfer enhancement in solar air channels, Applied Thermal Engineering, Vol. 89, pp. 239-261, 2015.
3. A. Kumar, and M. H. Kim, Effect of roughness width ratios in discrete multi V-rib with staggered rib roughness on overall thermal performance of solar air channel, Solar Energy, Vol. 119, pp. 399-414, 2015.
4. A. Kumar, R. P. Saini, and J. S. Saini, Heat and fluid flow characteristics of roughened solar air channel-A review, Renewable Energy, Vol. 47, pp. 77-94, 2012.
5. A. Kumar, R. P. Saini, and J. S. Saini, A review of thermohydraulic performance of artificially roughened solar air channels. Renewable and Sustainable Energy Reviews, Vol. 37, pp. 100-122, 2014.
6. L. Varshney, and J. S. Saini, Heat transfer and friction factor correlations for rectangular solar air heater duct packed with wire mesh screen matrices. Solar Energy, Vol. 62, pp. 255-262, 1998.
7. N. S. Thakur, J. S. Saini, and S. C. Solanki, Heat transfer and friction factor correlations for packed bed solar air heater for a low porosity system. Solar Energy, Vol. 74, pp. 319-329, 2003.
8. R. Singh, R. P. Saini, and J. S. Saini, Nusselt number and friction factor correlations for packed bed solar energy storage system having large sized elements of different shapes. Solar Energy, Vol. 80, pp. 760-771, 2006.
9. H. Torab, and D. E. Beasley, Optimization of a packed bed thermal energy storage unit. Journal of Solar Energy Engineering, Vol. 109, pp. 170-175, 1987.
10. P. Dhiman, N. S. Thakur, and S. R. Chauhan, Thermal and thermohydraulic performance of counter and parallel flow packed bed solar air heaters. Renewable Energy, Vol. 46, pp. 259-268, 2012.
11. S. Bouadila, S. Kooli, M. Lazaar, S. Skouri, and S. Farhat, Performance of a new solar air heater with packed-bed latent storage energy for nocturnal use. Applied Energy, Vol. 110, pp. 267-275, 2013.
12. S. Harmeet, R. P. Saini, and J. S. Saini, Performance of a packed bed solar energy storage system having large sized elements with low void fraction, Solar Energy, 87, pp. 22-34, 2013.
13. Ahmad, J. S. Saini, and H. K. Verma, Thermohydraulic performance of packed bed solar air heater. Energy Conversion and Management, Vol. 37, pp. 205-214, 1996.
14. S. M. Shalaby, and M. A. Bek, 2014, Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium. Energy Conversion and Management, Vol. 83, pp. 1-8, 2014.
15. S. Singh, and P. Dhiman, Using an analytical approach to investigate thermal performance of double-flow packed-bed solar air heaters with external recycle. Journal of Energy Engineering, Vol. 56, pp. 45-57, 2014
16. A. Saxena, G. Srivasatava, and V. Tirth, Design and thermal performance evaluation of a novel solar air heater. Renewable Energy, Vol. 77, pp. 501-511, 2015.
17. P. Dhiman, S. Singh, Recyclic double pass packed bed solar air heaters. International Journal of Thermal Science, Vol. 87, pp. 215-227, 2015.
18. R. Maithani, A. K. Patil, and J. S. Saini, Investigation of effect of stratification on the thermal performance of packed bed solar air heater, International journal of energy science, Vol. 3, pp. 267-275, 2013.