PERFORMANCE INVESTIGATION AND OPTIMIZATION OF LOW TEMPERATURE SENSIBLE HEAT SOLAR ENERGY STORAGE SYSTEM

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Abstract-Solar energy has a large potential, therefore it is a dominating source over other resource. However its intermittent nature demands a storages system along with collector in order to make it more reliable. Solar air heaters utilize the rock bed as their storage system. This stored energy in rock bed can be used for providing the continuous supply of thermal energy in the absence of sun and it can also be used in addition to the current supply. In order to design a packed bed energy storage system, the matter of concern is to maximize the heat transfer with minimum pressure drop or pumping power. The paper is aimed at investigating the behaviour of rock bed solar energy storage system, which is used to deliver the heat energy to a room. i,e the load (to heat a room) is supposed to be 250 KW and requirement duration is 24 hours. The overall performance of such systems is influenced significantly by the temperature distribution in storage unit which is affected by the system parameters i.e. void fraction and equivalent diameter of the bed. In this paper the performance of a rock bed solar energy storage system has been predicted and analyzed. Evaluation of performance is based on temperature distribution, thermal energy stored, volumetric heat transfer coefficient, pressure drop characteristics and available energy stored in the bed, as a function of system and operating parameters.

Keywords : storage system, equivalent diameter, bed temperature ,void fraction, energy stored.

1. Introduction

Rock bed contains storage material elements packed in a container made up of rock. During charging process, hot air from solar collector flows through the bed from top portion to bottom in order to transfer thermal form of energy to the storage material. Stored energy can be extracted by making flow of air from bottom to top of the rock bed during discharging phase. Heat transfer to and from a flowing fluid in a packed bed has been investigated theoretically and experimentally for various engineering applications. Schmidt and Willmott [13].Mawire and Mc Pherson [1] discussed the performance of storage materials for pebble bed thermal energy storage (TES) systems through simulation process. They observed a high pressure drop, which reduces the overall benefit of the solar energy utilization system. Harmeet Singh [2] reviewed the packed bed solar energy storage systems. The overall performance of such systems is influenced significantly by the temperature distribution in storage unit which is affected by the system parameters i.e. void fraction and equivalent diameter of the bed, sphericity and L/D ratio. Nusselt number and friction factor correlations for packed bed solar energy storage system having large size elements of different shapes have been developed by Singh [2].

A simple fluid and heat flow analysis for a packed bed has been presented by Howell et.al.[3]. Duffie and Beckman [4] explained a well-designed packed bed having several desirable characteristics which find its application in high heat transfer between the air and solid particles and promotes thermal stratification. The behavior of heat transfer in packed bed was studied by Schumann [6] in the form of mathematical model. The rate of heat transfer to and from the solid in the packed bed is a strong function of physical properties of the fluid and solid. Loff and Hawley [7] have given simple correlation for volumetric heat transfer coefficient between air and bed element. Mumma and Marvin [9] proposed a straight forward simulation method for the prediction of behavior of the packed bed element.

In the present work, the effect of thermal performance of the storage system has been investigated by using Mumma and Marvin [9] model using simulation..

2. Modelling and analysis of packed bed solar energy storage system.

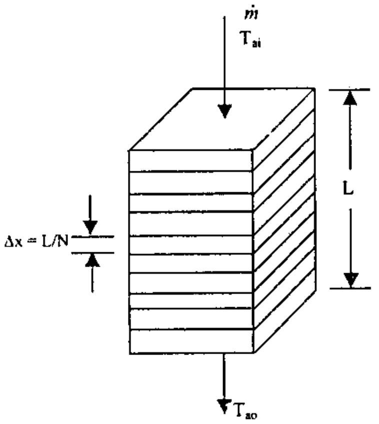

Fig 2.1 Packed bed system representation

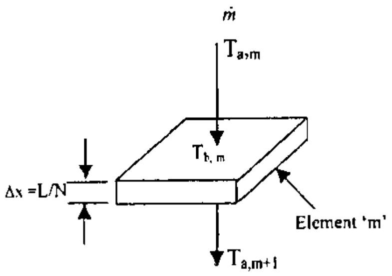

Fig 2.2 Element of the bed.

A typical packed bed unit of length or height 'L' and cross sectional area 'A', packed with rock particles having an equivalent diameter 'De' and a void fraction 'Ep' as shown in Fig. 2.1 is considered for analysis in the following sections. Initial temperature of the bed is Tbi, which is considered to uniform throughout the bed. The air enters at mass flow rate 'ṁ' and temperature Tai in the bed after leaving the collector. The temperature of air at exit of the bed is Tao. The bed is assumed to consist of 'N' number of elements of thickness Δx each. One of the bed element 'm' at initial uniform temperature of Tbm is shown in Fig. 2.2.

It is shown that the air enters into this bed element 'm' at temperature Ta,m+1 and exits at Ta,m+1 as it has been described by Howell et al[3]. It is assumed that during charging phase, temperature of air at the outlet of collector will behave as an inlet temperature to the bed and temperature of air leaving the bed will become an inlet temperature to the collector. No heat loss from the system to surrounding is assumed. The range of system and operating parameters and values of other parameters used in the present simulation study are given in Table 2.1 and 2.2. The charging time (tch) for the bed is considered as seven hours, taking into account the average sunshine hours. The charging time is considered to be the time during which the bed attains the same temperature as the air inlet and outlet. Therefore it should not be considered to the actual time of charging.

S. No.	Description	Parameter	Value
1	Volume of packed bed (m^3)	(V_b)	21
2	Length of packed bed, m	(L)	5
3	Number of bed element	(N)	60
4	Initial bed temperature (^{0}C)	(T_{bi})	25
5	Density of air, (kg/$m^{3)}$	(ρ_a)	1.1
6	Dynamic viscosity of air,(kg/s-m)	(μ_a)	1.865x10^{-5}
7	Inlet air temperature to bed, (^{0}C)	T_{ai} or T_{bi}	40
8	Ambient temperature, (^{0}C)	T_∞	25
9	Density of storage material,(kg/m^3)	ρ_s	2240
10	Specific heat of air, (J/kg^{0}C)	C_{pa}	1008
11	Specific heat of storage material, (J/kg^{0}C)	C_{ps}	810
12	Time interval,(minutes)	Δt	5

Table 2.1 Fixed parameters of bed

The simulation is based on a one- dimensional transient analysis of energy exchange between the air and the rock particles, using a finite difference method. Energy balance of air over the length Δx=L/N of element 'm' as reported by Singh et al.[11]

$$(\dot{m}C_p)_a dT_a = (\dot{m}C_p)_a (T_{a,m} - T_{a,m+1}) = h_v A \Delta x (T_{a,m} - T_{b,m}) (1)$$

Above Eq. can be integrated to achieve [11]

$$\int_0^{\Delta x} \frac{dT_a}{(T_{a,m}-T_{b,m})} = \int_0^{\Delta x} \frac{h_v A dx}{(\dot{m}C_p)_a} = \frac{h_v A L}{N(\dot{m}C_p)_a} = \frac{NTU}{N} = \Phi_1 (2)$$

Where NTU(no. of transfer units)= $\frac{h_v AL}{(\dot{m}C_p)_a}$ (3)

$$T_{a,m+1} = T_{b,m} + (T_{a,m} - T_{b,m})exp(-\Phi_1) \quad (4)$$

An energy balance on the storage material in element 'm' for time increment 'dt' can be written as[12]

Rate of change in internal energy of material = (rate of energy gain from air) — (rate of energy loss to surroundings).

$$(\rho C_p)_s(1-\varepsilon)A\Delta x \frac{dT_{b,m}}{dt} = (mC_p)_a(T_{a,m} - T_{a,m+1}) - (U\Delta A)_m(T_{b,m} - T_{amb}) \quad (5)$$

Bed temperature is given as [11]:

$$T_{b,m(t+\Delta t)} = T_{b,m(t)+} + [\Phi_2(T_{a,m} - T_{a,m+1}) - \Phi_3(T_{b,m} - T_{amb})]\Delta t \quad (6)$$

Where

$$\Phi_2 = \frac{(\dot{m}C_p)_a N}{(\rho C_p)_s AL(1-\varepsilon)} \Phi_3 = \frac{(U\Delta A)_m}{(\dot{m}C_p)_a}\Phi_2$$

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

$$Q = \int_0^L (\rho C_p)_s (1-\varepsilon)A(T_{m,m} - T_{mi})dx \quad (7)$$

Available energy stored in the bed (Qa) is calculated by using the relation as suggested by Torab and Beasley [10]

$$Q_a = \int_0^L (\rho C_p)_s (1-\varepsilon)A[(T_{mm} - T_{mi}) - T_{mi} ln \frac{T_{mm}}{T_{mi}}] \quad (8)$$

Hydrodynamic performance is concerned with the pressure drop or friction loss in the bed. A pressure drop is necessary in order to propel the air through the bed. The following correlation is used for pressure drop calculation.

$$\Delta P = \frac{LG^2}{\rho_f D_e}\left(21 + \frac{1750}{Re}\right) \quad (9)$$

Where $Re = \frac{GD_e}{\mu}$

2.1 Sizing of packed bed storage system

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 completion of the charging process should become nearly equal to inlet air temperature. Therefore, to evaluate the bed size, following energy balance equation has been used.The flow rate of air was calculated from the following Hottel-Williar-Bliss equation reported by Duffie and Beckman [12].

$$(mC_p)_a(T_o - T_i) = A_c[F_R(\tau\alpha)_e I - F_R U_l(T_i - T_{amb})] (10)$$

For calculation of size of the bed, Load parameter is assumed as 5KW for duration of 24 hours. Ambient conditions are maintained at the temperature of 25 °C, air after leaving the collector enters the bed at a temperature of 40 °C which is to be analysed and investigated. Whereas Initial temperature of bed is 25 °C

Therefore

Total load required = (load *duration) = 4.32*10^5 KJ

Energy stored in the bed = Mbed * Cps* (Tai-Tib)

- 4.32*10^5=Mbed*0.81(40-20)
- Mass of bed = 26.33*10^3 KJ
- Mass=density * volume = density of storage material (1-Ep)*Vbed
- Taking void fraction (ε)=0.45, (range of ε=0.3-0.5)
- (1-0.45)*22408*Vbed= 26.33 *10^3

Hence

•Volume of bed= 21.59m³

•Length=4.86m

- Diameter = 2.431m

3. Results and Discussion

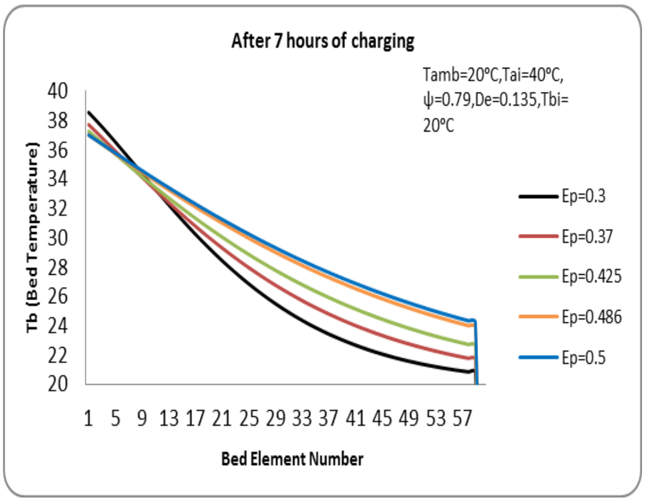

Fig 3.1.1 Temperature distribution in the bed for the values of different void fraction values.

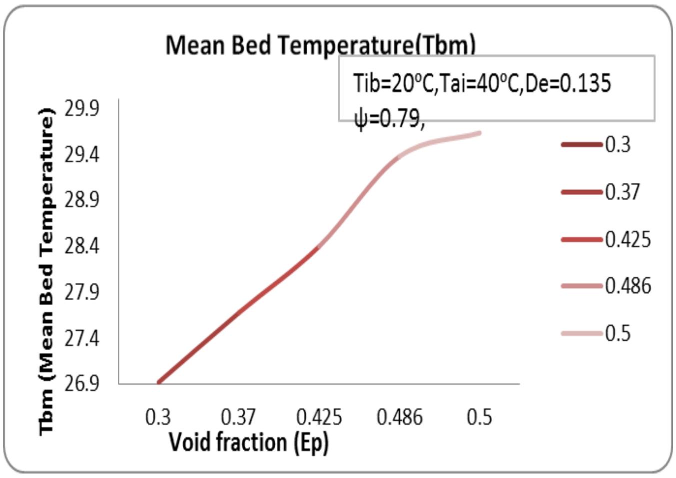

Fig 3.1.2 Mean bed temperature for different void fraction values.

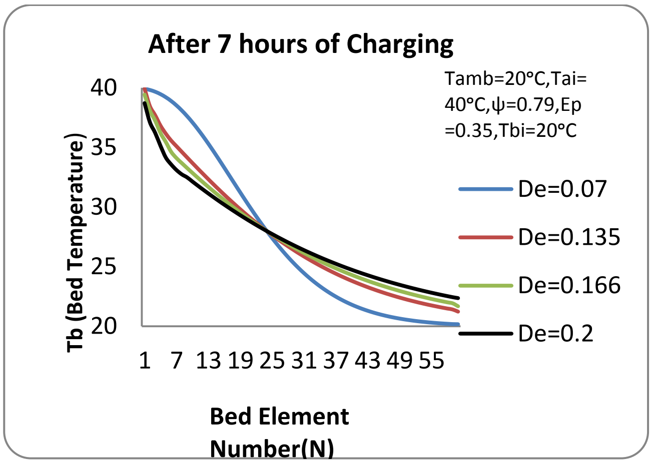

Fig 3.2.1 Effect of equivalent diameter on Bed temperature distribution .

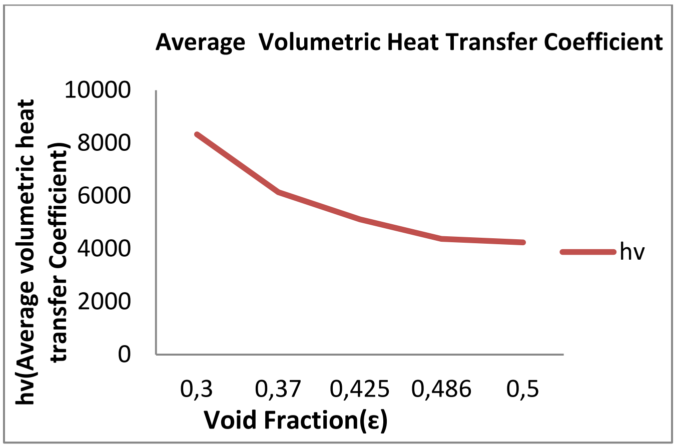

Fig 3.1.3 Effect of void fraction on volumetric heat transfer coefficient.

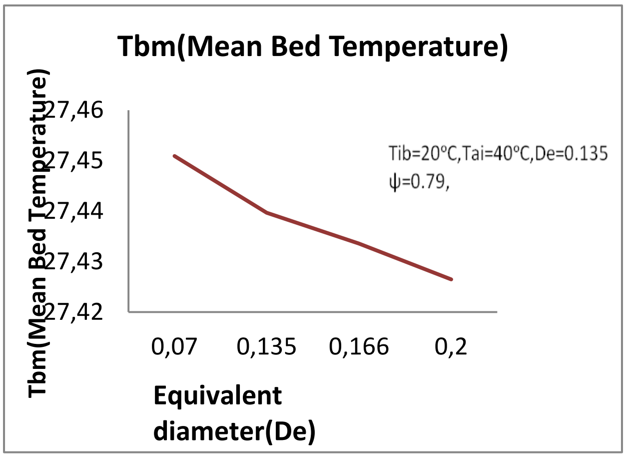

Fig 3.2.2 Effect of equivalent diameter on mean bed temperature.

An average temperature of each bed element during charging of bed in a given time interval is obtained with the help of mathematical simulation. From the Fig 3.1.1,it can be observed that the stratification in the bed reduces with increase in void fraction i.e. with increase in void fraction of the bed, temperature increases in lower portion of the bed. The bed at void fraction of 0.3 has the maximum stratification. The bed is least stratified at void fraction of 0.5. This is due to the fact that with increase in void fraction, heat transfer coefficient between air and the solid particles decreases as reported by Fig 3.1.3. As the amount of material packed in the bed reduces with increase of void fraction therefore an early charging of the bed is observed at higher void fractions. At maximum value of void fraction of 0.5, the bed got fully charged in less than seven hours. It is observed that with increase in void fraction, mean temperature of the bed increases Fig 3.1.2 depicts that with the same amount of energy transfer, the lesser amount of material packed at higher void fraction achieves high temperature.

*3.2 Effect of equivalent diameter on bed temperature and air temperature***.**

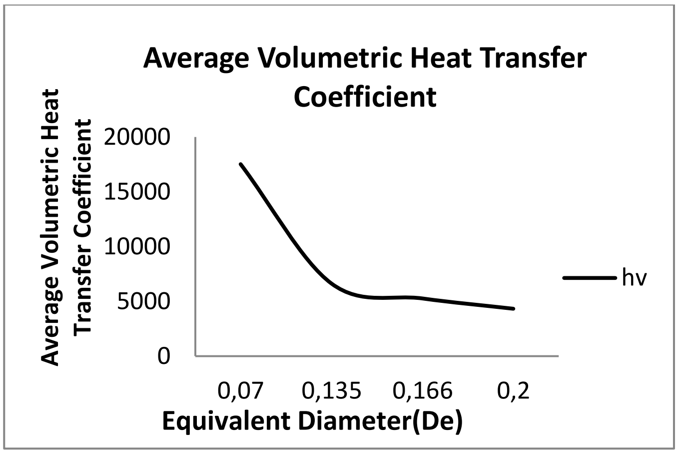

Fig 3.2.3 Volumetric heat transfer coefficient with different values of equivalent diameter.

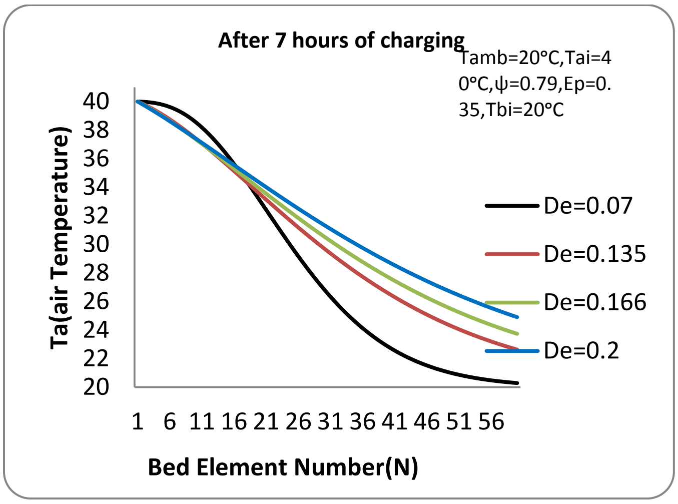

Fig 3.2.4 Effect of equivalent diameter on Air temperature distribution.

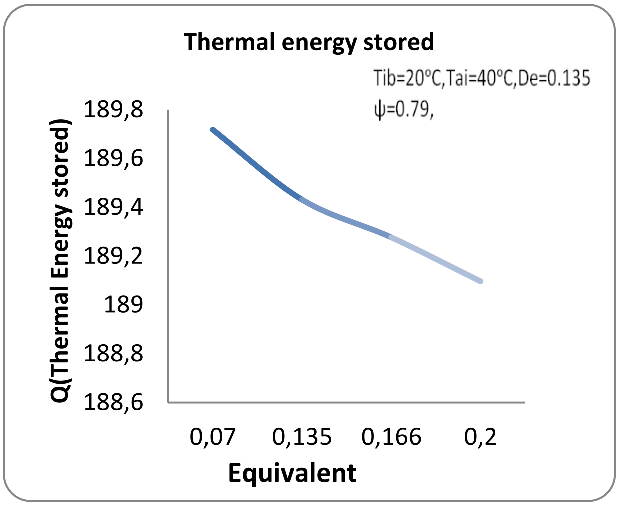

Fig 3.3.2 Thermal energy stored in the bed using bed elements of different equivalent diameter.

As equivalent diameter increases, the volume of the packed material increases. As from bed temperature distribution curve Fig 3.2.1, temperature at lower portion increases i.e temperature gradient of the bed decreases. As from the Fig 3.2.1 with the increase in equivalent diameter the Bed with least equivalent diameter is better due to high temperature difference. As from the Fig 3.2.2 with the increase in De the mean bed temperature decreases and volumetric heat transfer coefficient also decreases Fig 3.2.3.Mathematical simulation has been used to obtain temperature distribution of air along the bed during charging as in the Fig 3.2.4.Temperature distribution has been presented as a function of equivalent diameter. As the equivalent diameter increases, temperature variation decreases and the amount of heat transfer decreases.

The effect of variation in void fraction on the thermal energy stored in the bed has been shown in Fig. 3.3.1. It is indicated that the energy storage decreases with increase in void fraction for the bed packed with elements of a given shape. This also corresponds to the nature of variation of heat transfer coefficient with respect to the increase in void fraction. Fig 3.3.1 shows variation of thermal energy stored at the end of charging as function of void fraction. As depicted from the Fig 3.3.2, the effect of equivalent diameter is observed on the thermal energy stored in the bed and total thermal energy stored in the bed respectively. It is seen from the plots that maximum thermal energy stored in the bed is for the minimum value of equivalent diameter.

3.3 Thermal Energy Stored in the Bed

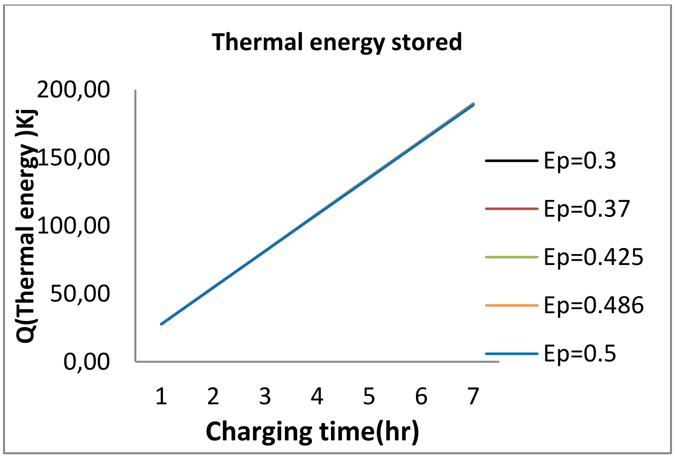

Fig 3.3.1 Thermal energy stored in the bed using bed elements of different void fraction.

3.4 Available energy stored in the bed

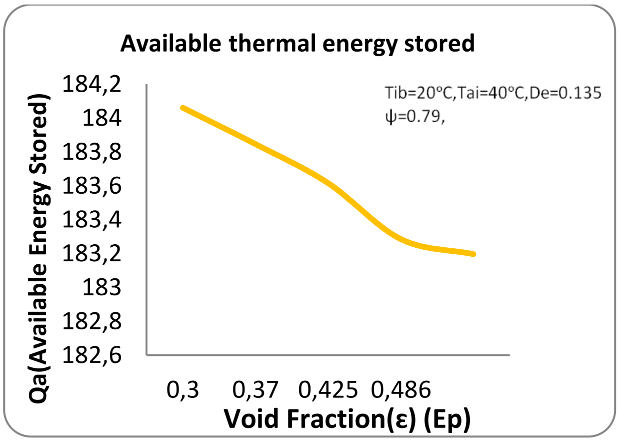

Fig 3.4.1 Available thermal energy stored in the bed using bed elements of different void fraction.

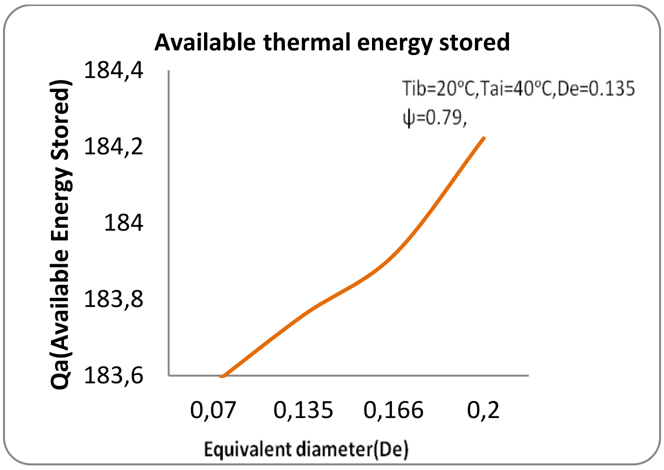

Fig 3.4.2 Available thermal energy stored in the bed using bed elements of different equivalent diameter.

The effect of system parameters on available energy stored inside bed is shown in Fig 3.4.1. According to the figure available energy stored in the bed comprising of bed elements at different void fraction. The available energy stored in the bed is a function of void fraction as can be seen from Fig. 3.4.1. It can be observed from Fig that at the end of charging, available energy stored in the bed is higher for higher void fraction of the bed. A comparison of Fig 3.3.1 with Fig 3.4.1, reveals that the effect of void fraction is totally different in the case of stored energy as compared to available stored energy. The value of stored thermal energy is seen to decline with increasing values of void fraction. The stored available energy monotonously increases with an increase of void fraction. This appears due to the storage of high grade thermal energy at higher values of void fraction under similar operating conditions. It can therefore be concluded that higher void fraction leads to the storage of high grade energy even when the amount of thermal energy stored is relatively smaller.

3.5 Pressure Drop characteristics

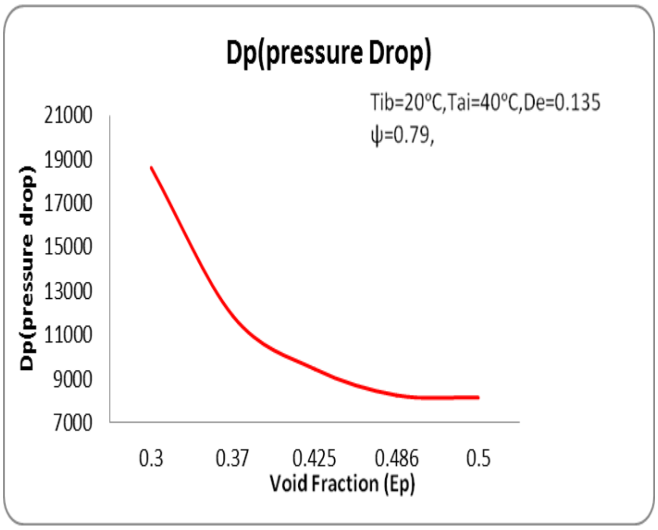

Fig 3.5.1 Pressure drop at the end of charging with the variation of void fraction

Pressure drop characteristics with the variation of void fraction and equivalent diameter is shown in the Fig 3.5.1, it appears that pressure drop decreases with increase in the value of equivalent diameter. As the effect of equivalent diameter is almost same as that of void fraction. But the increment is less as compared to that of in void fraction .Using equivalent diameter De=0.07 has the highest pressure drop value. And it decreases as the value of De increases. Pressure drop inside the bed can be reduced by using having large size bed elements. Pressure drop characteristics play an important role in investigation process of the rock bed solar energy storage system. The least values of equivalent diameter will produce maximum pressure drop. These values corresponds to the sphericity and other parameters which produce a severe effect on the thermal performance. Hence the overall performance is affected.

4. Conclusion

4.1Effect of Void Fraction

As the void fraction inside the bed increases, the amount of material packed reduces and as depicted from the temperature distribution curve the temperature at the lower portion of bed increases. With increase of the void fraction the volumetric heat transfer rate decreases due to which same energy is transferred to lesser amount of material therefore, charging time is less and hence mean bed temperature is high. In order to have less charging time the bed with high value of void fraction is satisfactory. The temperature of air at outlet of the packed bed increases as void fraction increases, therefore for a high thermal energy storage bed with low void fraction is good, while for a high amount of available energy high void fraction is required due to high grade thermal energy storage.

4.2 Effect of Equivalent Diameter

With increase in equivalent diameter of pebbles, the volume of the packed material increases. As from bed temperature distribution curve, temperature at lower portion increases, i,e temperature gradient of the bed decreases. Bed with least equivalent diameter is better due to high temperature difference or stratification. The mean bed temperature is minimum for greatest value of equivalent diameter and volumetric heat transfer coefficient also less. Due to the above mentioned facts the amount of thermal energy stored decreases, but the amount of available energy stored increases due to high grade thermal energy storage.

NOMENCLATURE

A = Cross sectional area of packed bed (m^2)
A_c = Collector area (m^2)
C_{pa} = Specific heat of air at constant pressure ($Jkg^{-1}K^{-1}$)
C_s = Specific heat of storage material ($Jkg^{-1}K^{-1}$)
D_e = Equivalent diameter of material element (m)
F_R = Heat removal factor (dimensionless)
G = Mass velocity of air ($kg\ s^{-1}m^{-2}$)
h_v = Volumetric heat transfer coefficient ($Wm^{-3}\ K^{-1}$)
L = Length or height of the bed (m)

m_a = Mass flow rate of air (kgs^{-1})
N = Number of bed elements (dimensionless)
NTU = Number of transfer units (dimensionless)
ΔP = Pressure drop in bed ($N\ m^{-2}$)
Re = Reynolds number (dimensionless)
T_{ai} , T_{ib} = Temperature of air at inlet to bed (°C, K)
T_{bi} = Initial temperature of the bed (°C, K)
$T_{a,m}$, T_{im} = Air temperature at inlet to bed element 'm' (°C, K)
$T_{a,m+1}$ = Air temperature at outlet of bed element 'm' (°C, K)
T_{bm} = Mean temperature of bed (°C, K)
T_i = Air temperature at inlet of collector (°C, K)
T_o = Air temperature at outlet of collector (°C, K)
T_{mi} = Initial temperature of bed element 'm' (K)
T_{mm} = Mean temperature of bed element 'm' (°C, K)
T_{nm} = Mean temperature of n_{th} element of the bed (°C, K)
$T_{b,m}(t)$ = Mean temperature of bed element 'm' at time t (°C, K)
$T_{b,m}(t+\aleph)$ = Mean temperature of bed element 'm' after time interval $\aleph$ (°C, K)
T_{amb} = Ambient temperature (°C, K)
t_{ch} = Charging time (s)
Δt = Time interval (s)
U ,U_l = Overall heat loss coefficient ($Wm^{-2}\,°C^{-1}$, $Wm^{-2}\,K^{-1}$)
V_b = Volume of packed bed (m^3)
V_s = Volume of storage material packed in the bed (m^3)
Δx = Thickness or height of bed element (m)
ρ_a = Density of air (kgm^{-3})
ρ_s = Density of storage material (kgm^{-3})
ε/E = Void fraction of bed (dimensionless)
μ_a = Dynamic viscosity of air ($kgs^{-1}m^{-1}$)
$(\alpha\tau)_e$= Effective transmittance-absorptance product (dimensionless)

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