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Theoretical Study of Thermal Performance of Rock Bed Storage

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Abstract

In this theoretical study, heat transfer and pressure drop in two cases of rock bed thermal storage has been studied, in the first case the equivalent diameter is changed when the mass flow rate per unit area is constant, and in the second case is inversely. The unsteady numerical simulation is employed to analyze the performance of the heat flow and temperature field in the storage. While the best thermal storage is obtain at equivalent diameter is (0.01) m. and show that the relation of pressure drop is decrease with increase in equivalent diameter except in a range of (0.025 to 0.038) m is constant.

Key words: Rock bed, thermal storage, Pressure drop.

دراسة أداء الخزن الحراري للفرشات المسامية الصخرية نظريا"

في هذه الدراسة النظرية تم حساب انتقال الحرارة وهبوط الضغط في المفروشات المسامية الصخرية للخزن الحراري بحالتين، لأولى بتغير القطر المكافئ وثبوت معدل جريان كتلة الهواء لكل وحدة مقطع المساحة، والثانية بعكسها. استخدمت معادلات الحل العددي المتغير مع الزمن لبيان الأداء الحراري و مجال توزيع درجات الحرارة داخل المفروش الحصى، وتبين من النتائج إن أفضل حالة لخزن الحرارة حصلت عند القطر المكافئ (0.01) متر للحصى. أما بالنسبة لعلاقة خسارة الضغط بالقطر المكافئ هي كلما زاد القطر قلت خسارة الضغط عدا الأقطار المحصورة ضمن الحدود (0.025 إلى 0.038) متر فان الخسارة ثابتة.

الكلمات الدالة: فرشات مسامية، مستودع حراري، انخفاض في الضغط .

Introduction

The limited amount of fossil energies has forced scientists all over the world to search for alternative renewable energy source. The use of renewable energies has, therefore, seriously been considered in the last three decades by researchers. The sun has been the major source of renewable energy from long time ago. This energy has had determinate contribution to the life of human being from the information of life on the earth up to now. Solar energy collectors are employed to gain energy incident solar radiation. Solar air heater is a type of solar collectors extensively used in many applications such as in industrial and agricultural field. The various configurations of solar heater have been developed to increase the heat transfer rate or to diminish heat loss like packed bed thermal storage. There are some works on both theoretically and experimentally studies of rock bed thermal storage. Sanderson [1] studied theoretically a simple model of packed bed which explains how a varying (D_R) (the equivalent sphere diameter of the packing) will influence the degree of axial dispersion. This model was further verified with experimental results in paper achieved by Sanderson et al. [2]. On a vertical flow packed bed consisted of hollow high density polyethylene spheres filled approximately 95% with water, and water was also used as the working fluid. The experimental result shows the effect of altering (D_R) on the degree of axial dispersion in thermally short packing's. The significance of thermally short system is discussed and the average temperature wave during heat exchanger operation is also demonstrated. They have shown that the one dimensional temperature profiles in the packing can be obtained using rectangular storage tank in conjunction with flow distributors. Choudhury C. et al.[3] studied the optimization of design and operational parameters of rock bed thermal energy storage device coupled to a two pass single cover solar air heater, i.e., charging time, rock bed size, and cross- sectional area for square cross section, rock size ,air mass velocity per unit bed cross-sectional area and void fraction. The optimization has been accomplished by investigation the effects of the above parameters on the total energy stored and the cost per unit energy stored in the rock bed for winter climatic condition of Delhi. Anthony G. Dixon[4] developed an improved equation of overall heat transfer coefficient in packed bad as new formula $\frac{1}{U}=\frac{1}{h_w}+\frac{R_t B_i+3}{3k_r B_i+4}$ and based on a single radial collection point whose position depends on the wall Biot number, which gives an error less than 3.8% in the exact asymptotic values of (U) over the entire range of (Bi).A formula is also gives (U'), the overall heat transfer coefficient based on the difference between tube wall and bed center temperatures where (Bi, h_w, R_t and k_r) are tube Biot number, wall heat transfer coefficient, tube radius, and effective radial thermal conductivity respectively. Hessari et al.[5] studied the behavior of packed bed by set of differential equations. A numerical solution is developed for packed bed storage tank accounting to the secondary phenomena of the thermal losses and conduction effect. The effect of heat loss to surrounding, conduction effect and air capacities are examined in the numerical solution. The solution indicates the profiles of air and rock bed temperatures with respect to time and length of the bed. The current study is including the effect of equivalent diameter of the rock (D_R) and mass of air flow rate (G) on the thermal performance of the cylindrical thermal storage as well as on the pressure drop (Δp) by two cases as shown in the table (2). In the first case they will be used a rock of four different in (D_R) as (0.01, 0.025, 0.038, and 0.05) m. with a (G) is a constant at 1.018 kg/s.m^2, and in the second case they will be used a rock of (D_R=0.01m) with a four different quantity of (G) as (0.51, 0.764, 1.018, and 1.53)kg/s.m^2.

The model

The rock bed backed thermal storage unit under investigation shown schematically in fig (1) with a model parameters illustrated in the table (1) for a particular application of a group of processes involving air flow through a porous media. In this model the thermal performance and pressure drop are studied in two cases. The air is supplied in different temperatures variable with time to the thermal storage bed as shown in figs (10 and 12). Starting from the initial time (t=0), the fluid is forced to flow in the porous bed through inlet section and the solid particles are at the

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same temperature. the bed contain the same mass and size of rock and had the same, uniform, cross sectional area. The assumptions of Schumann[6] have been employed to model rock beds. Schumann assumed that :

1. The fluid flowing through the bed was incompressible.
2. The temperature in the bed and in fluid was functions only of coordinate in the flow direction.
3. The Biot number of the rocks was sufficiently small so that the temperature distribution in the rocks was uniform.
4. The heat flow between the fluid and rock was proportional to the temperature difference between them.
5. The properties of the fluid and rock were constant.

Consider a cylindrical storage rock bed along (x) axis. An elemental volume located between the abscissa x and x+dx is considered for heat transfer evaluation. The governing differential equation for the energy supplied by air to the rock bed through convection (q_v) into the elemental volume during dt is [5]:

$$q_v = h_v A(T_a - T_R)dx.dt \quad \text{………... (1)}$$

Where:

h_v: Volumetric convective heat transfer coefficient, W/m^3.^{o}C.

A: Cross section area of bed, m^2

T_a: Air temperature, ^{o}C.

T_R: Rock bed temperature,^{o}C

x: Distance along the bed, m

t: Time, sec

The quantity of heat carried away by the air (q_a) is:

$$q_a = c_a GA\left(\frac{\partial T_a}{\partial x}\right)dx.dt \quad \text{…………. (2)}$$

Where:

G: The mass flow rate of air per unit cross sectional area, kg/s.m^2

c_a : The heat capacity of the air, J/kg.^{o}C

The heat loss to the surrounding(q_s) is:

$$q_s = UD\pi(T_a - T_\infty)dx.dt \quad \text{……………. (3)}$$

U : Overall heat transfer coefficient, W/m^2.^{o}C

T_∞ : Surrounding temperature, ^{o}C.

The energy balance for the air is obtained by summing up (1, 2 and 3):

$$q_v + q_a + q_s = \rho_a c_a Af\left(\frac{\partial T_a}{dt}\right)dx.dt \quad \text{....(4)}$$

ρ_a: The air density, (kg/m^{3})

f : The void fraction

The first energy balance differential equation is derived for air (gaseous phase):

$$\left(\frac{\partial T_a}{\partial t}\right) + \left(\frac{G}{\rho_a f}\right)\left(\frac{\partial T_a}{\partial x}\right) = \left(\frac{-h_v}{\rho_a c_a f}\right)(T_a - T_R) - \frac{\pi UD}{\rho_a c_a f}(T_a - T_\infty) \quad \text{……………..……… (5)}$$

Heat balance for the rock bed (solid state) is similarity obtained from:

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$$\frac{\partial T_R}{\partial t} = \frac{h_v}{\rho_R c_R (1-f)}(T_a - T_R) + \frac{k_R}{\rho_R c_R (1-f)}\left(\frac{\partial^2 R_R}{\partial x^2}\right) \qquad (6)$$

ρ_R: The rock density, (kg/m^3)

c_R: Specific heat of the rock, J/kg.^{o}C

k_R: Thermal conductivity of the rock, W/m.^{o}C

The equations (5 and 6) are solved by finite difference method, the initial conditions are:

$T_a(x,0) = T_a(x)$ and $T_R(x,0) = T_R(x)$

at t=0 ……………………………………(7)

When:

$T_a(x) = T_\infty$ and $T_R(x,0) = T_\infty$ …. (8)

And the boundary conditions are:

$T_a(x,0) = T_\infty$ and $T_R(x,0) = T_\infty$ at t=0 ……………. (9)

$T_a(x,t) = T_{in}(t)$ When x=H and t>0 .. (10)

Equations (5 and 6) can be written in terms of finite difference for nodes (n-1>x>1) as:

$$-W \cdot T_a(x-1,t+1) + H' \cdot T_a(x,t+1) + W \cdot T_a(x+1,t+1) - T_R(x,t+1) = L \cdot T_a(x,t) + k_1 T_\infty \qquad (11)$$

$$-C \cdot T_R(x-1,t+1) + F' \cdot T_R(x,t+1) - C \cdot T_R(x+1,t+1) - T_a(x,t+1) = E \cdot T_R(x,t) \qquad (12)$$

For lower surface of the bed (x=0)

$$A' \cdot T_R(x,t+1) + B \cdot T_R(x+1,t+1) - C \cdot T_R(x+2,t+1) - T_a(x,t+1) = E \cdot T_R(x,t) \qquad (13)$$

For upper surface of the bed (x=n)

$$A' \cdot T_R(x,t+1) + B \cdot T_R(x-1,t+1) - C \cdot T_R(x-2,t+1) - T_a(x,t+1) = E \cdot T_R(x,t) \qquad (14)$$

Where:

$$W = \frac{1}{2\Delta x} \qquad (15)$$

$$H' = 1 + k_1 + \frac{k_1}{\Delta t} \qquad (16)$$

$$L = \frac{k_3}{\Delta t} \qquad (17)$$

$$A' = \frac{1}{\Delta t} + \left(1 - \frac{k_2}{\Delta x^2}\right) \qquad (18)$$

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$$B = \frac{2k_2}{\Delta x^2} \qquad (19)$$

$$E = \frac{1}{\Delta t} \qquad (20)$$

$$F' = \frac{1}{\Delta t} + \left(1 + \frac{2k_2}{\Delta x^2}\right) \qquad (21)$$

$$k_1 = \frac{U}{Dh_v} \qquad (22)$$

$$k_2 = \frac{h_v k_R}{G^2 c_a} \qquad (23)$$

$$k_3 = \frac{\rho_a c_a f}{\rho_R c_R (1-f)} \qquad (24)$$

Loof and Hawley gave the volumetric heat transfer coefficient as [6]:

$$h_v = 650 \times \left(\frac{G}{D_R} \right)^{0.7} \quad \ldots\ldots\ldots\ldots\ldots\ldots (25)$$

Where D_R the equivalent spherical rock diameter (m) is:

$$D_R = \sqrt[3]{\frac{6M}{\pi n \rho_R}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

Where:

M: Mass of rocks (kg)

n: Number of rocks

Δx: Distance increment, m

Δt: Time increment, sec

To estimate pressure drop across inlet and outlet flow channels of the packed bed thermal storage may be used (Ergun equation) [7] as follows:

$$\Delta P = F \left(\frac{H}{D_R} \right) \left(\frac{G^2}{\rho_a} \right) \left(\frac{1-f}{f^3} \right) \ldots\ldots\ldots (27)$$

$$F = \frac{150(1-f)}{R_{ep}} + 1.75 \ldots\ldots\ldots\ldots\ldots (28)$$

$$R_{ep} = \frac{G D_R}{\mu} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

Where μ is viscosity of the air.

Results and discussion

This study considered two cases, the parameters of them illustrated in table (2).In both cases the inlet air temperatures(T_{in}) are same at each time during 48 hr as input data. The results obtained are plotted to compares the performance of the rock bed storage. Figures (2, 3, 4, and 5) represent temperature distribution along the height of the rock bed at every two hours for equivalent diameters (0.01, 0.025, 0.038, and 0.05) m. respectively. The sets of curves are divided in two parts with relative to time; first part of them is a similar shape curves of temperature distribution from the starting time up to (16) hrs. , this mean that no effect of dimension of equivalent diameter on the temperature distribution in the rock bed at this limited time but later on the effect of dimension of equivalent diameter is very obvious, where the value of temperature at each node is greater than other dimensions of (D_R). Figures (6, 7, 8, and 9) represent the change of temperature at each node in the bed rock with respect of time for equivalent diameter (D_R) (0.01, 0.025, 0.038, and 0.05) m. respectively. The results obtained are putted in the table (3). Which are represents the difference between the upper and the lower temperature. The results are indicate that the higher temperature differences are happen in the rock bed when (D_R =0.01m.).

Figure (10) shows the difference between inlet and outlet air temperatures through the rock bed system. It is indicated that the best outside temperature is found at (D_R= 0.01m).The second case the rock bed examined with variable mass flow rate per cross section area as shown in table (2). The result obtained shown in figure(11) which indicate a very low outside air temperature of the bed in condition of (G=0.51 kg/s.m^2), and by increasing the mass flow rate during the same interval of time (48 hrs).The outlet air temperatures are shown in table (4).

Figure (12) is representing the relation between pressure drop (Δp) and equivalent diameter (D_R) of the rocks in the case 1. From this relation the higher quantity of (Δp) is happen at (D_R=

0.01m), and it is reduce very quickly with increase in (D_R) up to (D_R= 0.025m), and in a range of (D_R= 0.025m) up to (D_R= 0.05m) the change of (Δp) is small.

Figure (13) is shown the relation between (Δp) and mass flow rate per cross area (G) in the case 2. It indicated that the quantity of (Δp) is increase as the quantity of (G) is increase.

For reason of solution of the equations (5 and 6) by finite difference method more suitable for large of interval of time, but this condition in analytic solution unsuitable because the results are un real, in addition to this reason the sensitivity of the model is not obtain correctly by analytic solution.

Conclusions

An analytical solution can be written for equations (5 and 6) with more boundary conditions of $T(0,t) = T(1,t)$ in the inlet air temperature. In this case, the solution is limited to relatively small values of the time. In order to extend solution to real case where an initial non-uniform spatial temperature distribution within the bed is considered at large time, initial boundary conditions are to be in corporate in the respected in the solution. The solution shows the response of the rock bed during the changing period (Energy recovery mode) and the profiles of air and rock bed temperatures with respect to time and length of the bed in the final equations (11,12,13,and 14), therefore, be expressed in finite difference form and solved by numerical method. Since the air is used as the heat transfer medium at low temperature, the effect of losses (heat loss, conduction through solid and heat capacity of fluid respectively) are found to be negligible in the solution of the case of air as a moving fluid. The best of heat recovery can be obtained at small equivalent diameter which controlled by the optimum head loss and this give suitable mass flow rate of air which can used in application of passive heating.

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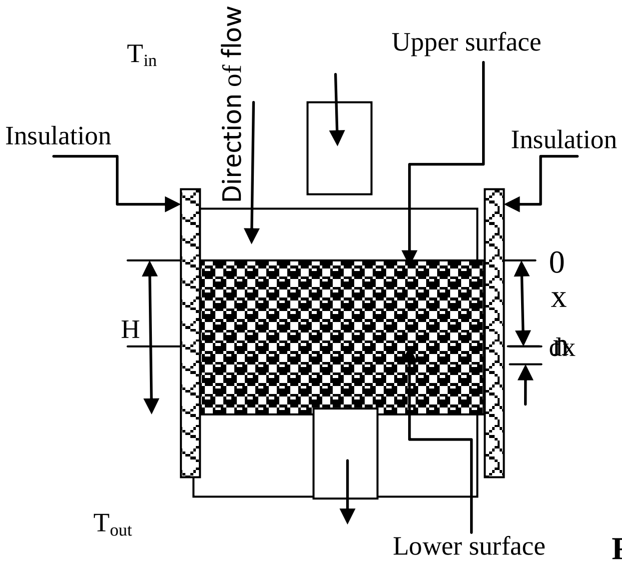

Fig. (1) Schematic of rock bed thermal storage

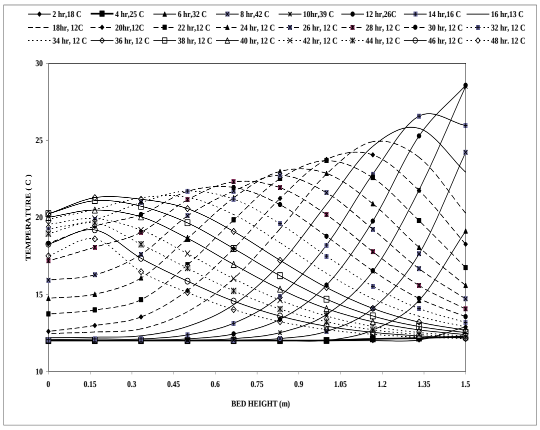

Fig. (2) Temperature distribution in the rock bed during 48 hrs, for D_R=0.01m.

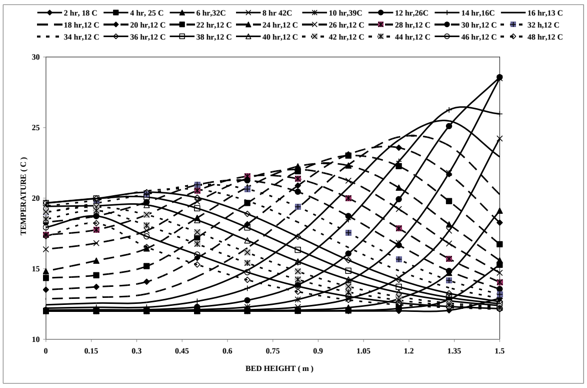

Fig. (3) Temperature distribution in the rock bed during 48 hrs, for D_R=0.025m.

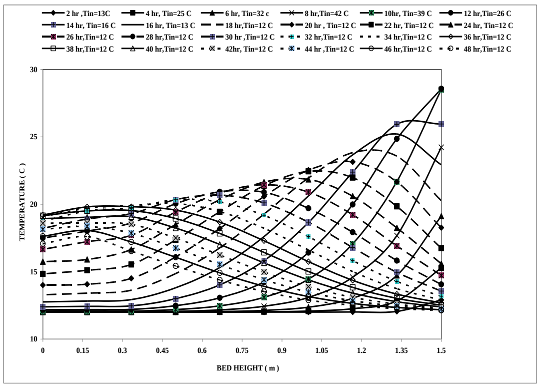

Fig. (4) Temperature distribution in the rock bed during 48 hrs, for D_R=0.038m.

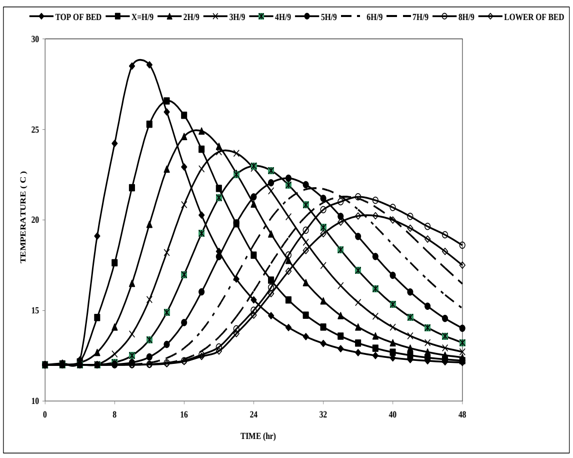

Fig. (5) Temperature distribution in the rock bed during 48 hrs, for D_R=0.05m.

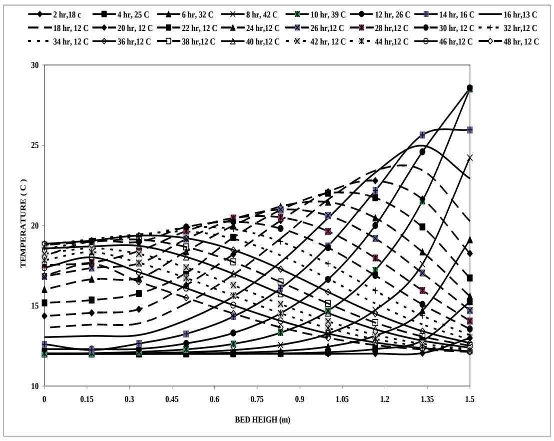

Fig. (6) Node temperature change with respect of time for D_R=0.01m.

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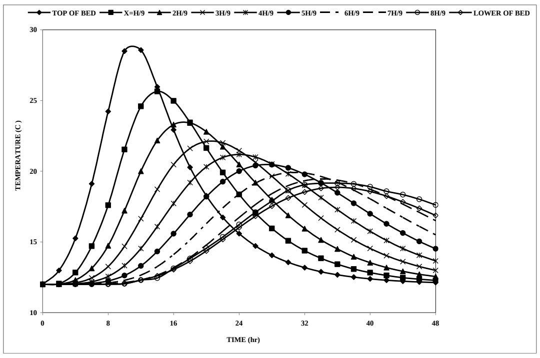

Fig (8) Node temperature change with respect of time for D_R=0.038m.

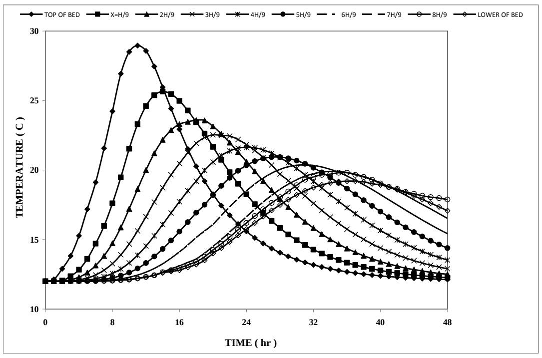

Fig. (9) Node temperature change with respect of time for D_R=0.05m.

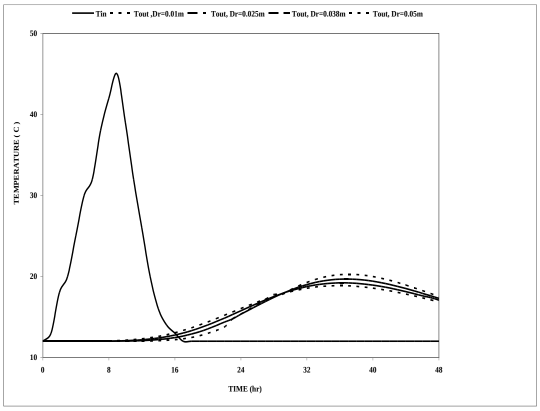

Fig. (10) Change in temperatures between inlet and outlet air in case1

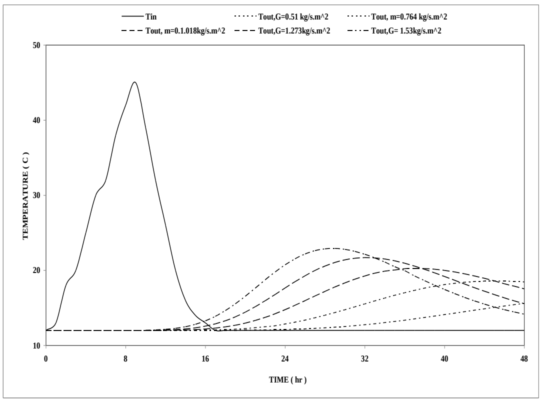

Fig. (11) Change in temperatures between inlet and outlet air in case2

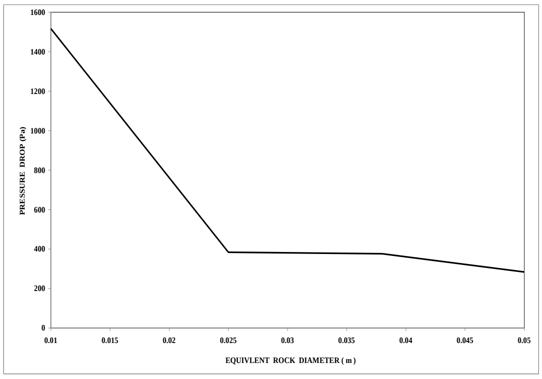

Fig. (12) Pressure drop with respect of equivalent diameter in case1.

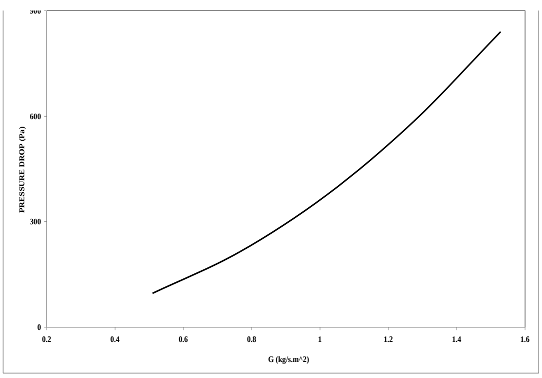

Fig. (13) Pressure drop with respect of mass flow rate per cross section area in case2.

Table (1) System description

Area of the packed bed (A)	$0.7854 m^2$
Specific heat of the rock (c_R)	837J/kg.°C
Specific heat of the air (c_a)	1012J/kg.°C
Density of the rock (ρ_R)	$2400 kg/m^3$
Thermal conductivity of the rock (k_R)	0.45W/m.°C
Diameter of the bed (D)	1m
Height of the bed (H)	1.5m
The void fraction (*f*)	0.45
Number of the nodes	9
Distance increment (Δx)	0.1666m
Time increment (Δt)	160 sec
Dynamic viscosity of the air μ	1.8463×10^{-5} kg/m.s

Table (2) Simulation parameters of two cases

Case						
Case1	G=1.018 $kg/s.m^2$	D_R (m)				
		0.01	0.025	0.038	0.05	
Case2	D_R= 0.01m	G($kg/s.m^2$)				
		0.51	0.764	1.018	1.273	1.53

Table (3) Different between upper and bottom temperatures in each equivalent diameter at the same time

D_R (m)	Time (hr)							
	6	12	18	24	30	36	42	48
0.01	7.11	16.5	7.81	0.84	-4.75	-7.55	-7.25	-5.37
0.025	7.11	16.49	7.4	0.273	-4.72	-6.99	-6.72	-5.17
0.038	7.09	16.33	6.73	-0.16	-4.5	-6.5	-6.34	-4.95
0.05	7.07	16.27	6.63	0.43	-4.56	-6.19	-5.95	-4.65

Table (4) Shown the outlet temperature from the rock bed at each mass flow rate per unit cross section area

G ($kg/s.m^2$)	Start time temperature °C	End time temperature °C	Max. temperature °C	Average temperature °C
0.51	12	15.6	15.6	12.8
0.764	12	18.44	18.59	14.32
1.018	12	17.53	20.26	15.52
1.273	12	15.55	21.7	16.13
1.53	12	14.16	22.91	16.4