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Thermal Performance of Low Cost Packed Bed Thermal Energy Storage Systems for Space Heating and Crop Drying Applications in the Rural Areas

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ABSTRACT

Low grade thermal energy is often required in the agricultural products, the conventional fuels most commonly used are diesel, petrol, bio-diesel, CNG, LPG, electricity, wood, agro waste etc. are available very costly day by day and are getting in the rural areas. The alternative is to use the solar energy thermal storage systems based on water is air required as a basic components in the low grade thermal energy utilization. A simple thermal analysis for open and close loop packed bed collector cum storage system has been carried out to study the performance of the system using different type of thermal energy storage materials such as rocks, pebbles, glass piece, stone pieces and fired brick. The effect of various parameter of packed bed, diameter of packed bed, porosity and mass flow rate on the volumetric heat transfer co-efficient, heat flux, efficiency of the system has been studied in details and time dependent periodic thermal model was developed. It was observed that fire brick gives better thermal energy storage effect than other storage material and hence it is recommended for open loop and close loop solar crop drying systems in the rural areas

Keywords: *Low Cost Solar System; Thermal Energy Storage Systems; Flow Through the Porous Media; Solar Thermal System Design.*

1.0 Introduction

Solar energy is intermittent in nature. For a variety of application the thermal energy might be most required when there is no sun radiation. The need of storage of sun energy is therefore desirable for various applications during off sun shine hours and cloudy season. This energy storage may be in form of sensible heat of solid and liquid medium, as heat of fusion in chemical energy of product and in a reversible chemical reaction. The choice of storage media depends upon the nature of the process. For water heating the energy storages in sensible heat of stored is logical while for the case of air heating collector cum storage system in the form of sensible or latent heat has been suggested such as sensible heat in the pebble bed heat exchangers.

A packed bed of rock pile or pebble bed storage unit uses the heat capacity of the bed of loosely packed particulate material to store energy. A fluid, usually air is circulated thought to add or remove energy. A variety of solid may be used such as rock, fired bricks, stone pieces, glass pieces etc. being the most widely used thermal energy storage energy materials due to low cost , easy available in the rural area.

In this paper the study of the effect of the storage media connected to an efficient solar energy collector using matrix absorbers solar air heater cum packed bed storage system using different energy storage material and performance of the system in terms time dependent thermal efficiency, time dependent energy flux has been calculated.

2.0 Packed Be D Enery Storage Unit Connected to a Solar Collecter in a Open and Close Loop Cycles

The studies on the rock bed storage system sop far deal with heat transfer or pressure drop in the storage system. Amongst these are the works of Lof et al (1948 , Close (1965) Hughes (1976), Chandra(1981), Farber(1982), Mishra (1992) etc. heating and cooling of packed bed have also been studied by Schuman (1929),

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Dukes(1976) and Lupin (1962). They studied the pressure drop across the packed beds. The experimental study by Chandra et al (1981) deal with heat transfer characteristics of the rock bed and also discusses the pressure drop across such systems. Mishra (1996) deals with the time dependent thermal model of open and close loop solar energy systems using rock beds. Solar collector cum storage system is more expensive due to cost of collector and cost of thermal energy storage unit. In this paper we considered solar matrix air heating absorber cum storage units of easily available thermal energy storage material in the rural/remote areas for crops drying applications and developed a time dependent thermal model to study its performance. The developed model is the modification of Schumann (1929) model by considering the effect of conduction in the thermal energy storage materials. The analytical expressions for various parameters have been obtained explicitly. Former work of (Kuhn et al (1978)) in this direction was done by numerically solving Schumann model with finite deference technique.

The model dev eloped in this paper has been tested corresponding to a data available for solar intensity and ambient temperature for a critical day of New Delhi (India) types climates. The effect of various parameters such as particle size porosity etc. on the thermal performance (in terms of time variation of efficiency, useful energy flux have been carried out for different energy storage materials).

3.0 Thermal Analysis of a Packed Bed Collector Cum Storage Systems Using Low Cost Absorber Materials

The analysis of packed bed energy storage systems have been performed under following mode of operation.

4.0 Different Matrix & Fluid Temperatures

In the configuration of the storage system, packed bed has been connected into a porous air heater, in which the performance of the system depends upon collector parameters and storage parameters. The energy balance equation for the bed temperature over the packed bed segment of thickness dX can be written as

$$h_v\left(T_f(X,t)-T_m(X,t)\right)+K_e\left(\frac{d^2T_m(X,t)}{dX^2}\right)-\frac{dQ}{dX}=\rho_m C_{pm}\left(\frac{dT_m(X,t)}{dt}\right)---(1)$$

Where T (x,t) is the local air temperature & dI/dx is the heat energy attained by the surfaces. The first term in the equation represents the heat retained in the bed while second term is for the heat transfer from the

hot air to the rocks. The third term represents the energy stored by the packed bed. The rock temperature is however related to air temperature by the following expression

$$-\beta\, \dot{m}_c c_{pf}\left(\frac{dT_f(X,t)}{dX}\right)=h_v\left(T_f(X,t)-T_{mi}(X,t)\right)---(2)$$

The (-) sign in equation (2) is due to the fact that hot air loses heat to the packed bed. Correlations relating volumetric heat transfer coefficient to the bed characteristics into the fluid flow conditions are given by G.O.G.Lof (1948), Farber & Courtier (1982) & Chandra (1981) as follow:

$$h_v=700\left(\frac{\dot{m}/A_c}{d}\right)^{0.70}\quad (W/(m^3K))---(3)$$

Eliminating bed temperature from eqs (2) - (1), one obtains a third order differential eqs. In terms of air temperature

Where

$$a_1=(h_v/(m_c/A_c)C_{pf}\beta),$$

$$a_2=(h_v/K_e)$$

$$a_3=-h_v/((m_c/A_c)C_{pf}\beta\, K_e)$$

$$y_1=\left(-a_3\mu\, I_{to}\right)/(\mu^3-a_1\mu^2+a_2\mu+a_3)$$

$$y_2(-a_3I_{tn}(n)\mu)/(-\mu^3+a_1\mu^2-a_2\mu+a_4$$

$$a_4=in\omega\rho_m C_{pm}a_3$$

$$a_5=\exp((-A_cU_lF')/(\dot{m}_c\ C_{pf}))$$

$$a_6=a_1$$

$$a_7(n)=-(a_2)+(in\omega\rho_m C_{pm})/K_e)$$

$$a_8(n)=in\omega\rho_m C_{pm}a_3$$

$$a_9(n)=T_{an}(n)+((\tau\alpha\ I_{tn}(n)/U_L)$$

Rearranging and separating the eqs. Into time dependent & time independent parts one can get solution of differential eqs.

The following boundry conditions are used

$$-K_m dT_m(d,t)/dX = h_f(T_f(d,t) - T_a(t))$$

$$\dot{m}C_{pf}(T_{co}(t) - T_f(0,t)) = h_f(T_{co}(t) - T_m(0,t))$$

$$-K_m dT_m(0,t)/dX = h_f(T_f(0,t) - T_m(0,t))$$

Assuming periodic nature of solar intensity, ambient temperature, bed temperature & fluid temperatures, Rearranging eq. (3) we get following third order differential eqs.

$$d^3T_{fo}(x)/dx^3 + a_1 d^2T_{fo}(x)/dx^2 + a_2 dT_{fo}(x)/dx + a_3 T_{fo}(x) = -a_3 I_{to} ---(4)$$

$$d^3T_{fo}(x)/dx^3 + a_6 d^2T_{fn}(x)/dx^2 + a_7 dT_{fn}(x)/dx + a_8 T_{fn}(x) = -a_9 I_{tn} ----(5)$$

The solution of above eqs (4, 5) are expressed in the following manner.

$$T_f = (C_1 \exp(\beta_1 X) + C_2 \exp(\beta_2 X + C_3 \exp(\beta_3 X) + y_1 \exp(-\mu X) +$$

$$\mathrm{Re}al \sum_{n=1}^{6} (C_4 \exp(\beta_4 X) + C_5 \exp(\beta_5 X + C_6 \exp(\beta_6 X) + y_2 \exp(-\mu X)\exp(in\omega t) --(6)$$

$$T_f = (C_1 \exp(\beta_1 X) + C_2 \exp(\beta_2 X + C_3 \exp(\beta_3 X) + y_1 \exp(-\mu X) +$$

$$\mathrm{Re}al \sum_{n=1}^{6} (C_4 \exp(\beta_4 X) + C_5 \exp(\beta_5 X + C_6 \exp(\beta_6 X) + y_2 \exp(-\mu X)\exp(in\omega t)$$

The arbitrary constants C1, C2, C3, C4, C5, and C6 can be determined from the following set of boundary conditions.

$$-K_m dT_m(d,t)/dX = h_f(T_f(d,t) - T_a(t))$$

$$\dot{m}C_{pf}(T_{co}(t) - T_f(0,t)) = h_f(T_{co}(t) - T_m(0,t))$$

$$-K_m dT_m(0,t)/dX = h_f(T_f(0,t) - T_m(0,t))$$

Application of boundary conditions in eqs. (5-6) yield the following, 3 X 3 matrixes for time independent part & time dependent parts. The packed bed material temperature & fluid temperature can be obtained by substituting x=d in equ. (6) and equ. (6) in equ. (2)

5.0 Results And Discussion

Values of parameter have been used for numerical computation to validate proposed thermal model taken from Mishra (1992, 96). The values of collector outlet temperature have been calculated because it depends upon the efficiency of collector cum storage unit and incidents of the radiation on the collector.

The outlet temperature variation oh the storage units with mass flow rate of air have been calculated along with corresponding variation of thermal efficiency and useful energy flux. It was observed that the effect of increasing the particle size on the volumetric heat transfer co-efficient between the particle and air along with temperature of particles, the heat transfer decreases with the increasing storage size particle effecting the bed temperature also. Similarly increasing he value of porosity effect the cooling effect of medium i.e. the temperature of air coming out the storage keeps on increasing porosity.

The temperature distribution of the storage material up to a thickness of 50 cm, it was observed that bed temperature remain constant which it drops suddenly due to size of particle and the spacing between the particles. The effects of porosity of the storage media effect the thermal performance of a thermal energy systems considerably. It is therefore obvious that the particle size and the porosity of the particle is kept to a minimum possible. One has to however balance it against increasing pressure losses and hence the fan power requirements.

Table (1) shows the variation of particle temperature corresponding to hourly variation of the solar flux and ambient for a typical day. It was observed that particle can be heated more than twenty two degree centigrade than above ambient temperature.

The time variation of thermal energy storage material with flowing air temperature with time along with solar flux shown in the tables (1-5) respectively.

The time variation of useful energy flux and thermal efficiency with time for different thermal energy storage material are shown in the tables (1-5) and figs. (1-6) respectively. It was observed that fire brick is a best material foe thermal sensible energy storage packed bed.

6.0 Conclusions

The thermal model was developed in this paper for finding thermal performance of matrix collector cum storage systems. Following conclusions are drawn;

1. Pebble bed and fire brick gives better thermal energy storage effect than other thermal energy storage materials for open loop and close loop solar crop drying systems in the rural and remote areas.
2. second thermal energy storage material is black painted broken glass pieces for space heating and crop drying applications in rural areas.

Table 1(a): Variation of Temperature Using Thermal Energy Storage Materials (Pebble and Glass Pieces, Rock Bed) and Ambient Temperature with Time

Time (Hr.)	PEBBLE BED	GLASS PIECE BED	ROCK BED
	Fluid Temp (°C)	Fluid Temp (°C)	Fluid Temp (°C)
7 AM	26.25	25.4	24.6
8	33.55	31.9	30.09
9	38.87	36.25	33.33
10	45.16	41.43	37.2
11	54.13	49.4	43.9
12	59.9	54.6	48.48
13	56.91	51.85	46.02
14	48.87	44.65	39.82
15	42.47	39.3	35.7
16	37.4	35.2	32.77
17	30.13	28.81	27.46
18	22.47	22.02	21.7

Table 1(b): Variation of Temperature Using Thermal Energy Storage Materials (Brick and Cork) and Ambient Temperature with Time

Time (Hr.)	BRICK BED	CORK BED	Ambient
	Fluid Temp (°C)	Fluid Temp (°C)	Temp (°C)
7 AM	26.74	24.9	21.94
8	34.45	29.1	25.63
9	40.2	27.96	23.87
10	47.05	26.6	22.4
11	56.5	31.5	27.15
12	62.55	36.4	31.4
13	59.46	33.5	28.8
14	51.01	28.1	23.04
15	44.1	28.37	23.9
16	38.55	30.5	26.17
17	30.84	27.27	22.96
18	22.47	22.02	21.7

Table 2(a): Variation of Various Thermal Energy Storage Materials (Pebble and Glass Pieces) Temperatures and Ambient Temperature with Time

Time	Ambient	PEBBLE	GLASS PIECES
(Hr.)	Temp (°C)	Temp (°C)	Temp (°C)
7 AM	21.94	17.2	18.85
8	25.63	24.3	24.45
9	23.87	30.65	28.98
10	22.4	37.2	33.1
11	27.15	47.99	40.8
12	31.4	59.59	49.8
13	28.8	63.847	52.9
14	23.04	59.5	49.09
15	23.9	53.09	44.36
16	26.17	47.9	41.23
17	22.96	40.5	36.08
18	19.18	30.35	28.3

Table 2(b): Variation of Various Thermal Energy Storage Materials (Brick, Rock and Cork) Temperatures and Ambient Temperature with Time

Time	ROCK	BRICK	CORK
(Hr.)	Temp (°C)	Temp (°C)	Temp (°C)
7 AM	20.8	16.4	20.9
8	24.7	24.3	25.47
9	27.23	31.55	25.37
10	28.57	39.5	23.03
11	32.83	51.7	26.56
12	38.9	64.7	32.99
13	40.75	69.53	32.83
14	37.5	64.9	27.7
15	34.67	57.64	26.9
16	33.89	51.4	29.7
17	31.25	42.8	28.14
18	26.13	31.44	23.3

Table 3(b): Variation of Various Thermal Energy Efficiency of Sensible Heat Storage Materials (Brick, Cork and Rock) with Time

Time	BRICK	CORK	ROCK
(Hr.)	Eff. (%)	Eff. (%)	Eff. (%)
7AM	29.26	18.17	16.23
8	26.12	10.4	13.2
9	30.7	7.7	17.77
10	32.6	5.55	19.5
11	30.6	4.53	17.45
12	29.57	4.7	16.21
13	31.7	5.5	18.118
14	34.68	6.28	20.8
15	34.2	7.5	19.94
16	31.7	11	16.85
17	37.35	20.4	21.29
18	0	21.76	0

Table 3(a): Variation of Thermal Energy Efficiency of Sensible Heat Storage Materials (Pebble, Glass Pieces and Rocks) with Time

Time	PEBBLE	GLASS PIECES	ROCK
(Hr.)	Eff. (%)	Eff. (%)	Eff. (%)
7AM	26.26	21.1	16.23
8	23.5	18.5	13.2
9	28.15	23.24	17.77
10	30.053	25.13	19.5
11	28.11	23.16	17.45
12	27.04	22.02	16.21
13	29.12	24.01	18.118
14	32.03	26.8	20.8
15	31.42	26.02	19.94
16	28.7	23.06	16.85
17	33.945	27.72	21.29
18	0	0	0

Table 4(a): Variation of Heat Flux of Various Thermal Energy Storage Materials (Brick and Cork) and Solar Flux with Time

Time	BRICK	CORK	Solar Flux
(Hr.)	Useful Flux (W/m2)	Useful Flux (W/m2)	(W/m2)
7AM	36.32	22.55	124.1
8	66.65	26.52	255.2
9	123.6	30.96	402.6
10	186.2	31.7	571.9
11	222.2	32.87	725.6
12	235.53	37.9	796.5
13	237.22	41.4	748.3
14	211.44	38.3	609.64
15	152.3	33.4	445.3
16	93.6	32.6	295.7
17	59.6	32.6	159.6
18	27.06	28.39	27.31

Table 4(b): Variation of Heat Flux of Various Thermal Energy Storage Materials (Pebble, Glass Pieces and Rocks) with Time

Time	PEBBLE	GLASS PIECES	ROCK
(Hr.)	Useful Flux(W/m2)	Useful Flux(W/m2)	Useful Flux (W/m2)
7AM	32.6	26.2	20.15
8	59.9	47.2	33.67
9	113.35	93.6	71.54
10	171.86	143.7	111.74
11	204.02	168.05	126.7
12	215.37	175.4	129.18
13	217.92	179.7	135.6
14	195.25	163.4	126.85
15	139.91	115.9	88.79
16	84.87	68.2	49.8
17	54.167	44.23	33.98
18	24.85	21.517	19.15

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