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THERMOHYDRAULIC PERFORMANCE OF PEBBLE BED SOLAR AIR HEATERS

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ABSTRACT
Packed bed solar air heater has better thermal performance in comparison to conventional air heaters due to high heat transfer area to volume ratio and turbulence in the air flow path of the bed, provides rapid exchange of heat between packing elements and air. This better thermal performance is associated with substantial increase in pressure loss. This paper deals with theoretical analysis of thermohydraulic performance of solar air collector having its duct packed with stone pebbles. Pebbles are cheap and easily available. In this investigation pebbles diameter and mass flow rate were ranging from 4 to 12 mm and 0.01 to 0.033 kg/s respectively. Cost analysis has also been carried out for unit energy cost delivered by the solar air heater. It has been observed that there is a significant effect of mass flow rate and pebble diameter on effective efficiency and cost per unit energy delivered by the packed bed solar air collector.

Keywords: Thermohydraulic performance, Pebble bed, Solar air heaters.

1. INTRODUCTION
Conventional solar air heaters have inherently low heat transfer coefficient between the absorber plate and air resulting in poor performance. There has been significant interest in packed bed solar air heaters because of some distinctive advantages over flat plate air heaters. Solar air heater using packed bed absorber of slit-and-expanded aluminum foil matrix [1], wire screen matrix [2-5], pebbles [6, 7], hollow spheres [8] and optically semitransparent material [9] has been investigated. These studies indicate that such systems have enhanced performance than that of plane absorbers. Packing the solar air heater duct results in higher efficiency but also in higher pressure drop and hence in larger running cost of the system has been reported by Choudhury and Garg [10]. Ahmad et al. [11] experimentally found that the thermohydraulic performance of iron screen matrix packed bed solar air heater is considerably reduced. In this present analytical investigation, an attempt has been made to predict the effective efficiency of solar air heater, having the duct packed with pebbles. Effects of various parameters on thermohydraulic performance and cost of unit energy delivered by the system had also been investigated.

2. ANALYSIS
The packed bed solar air heater model has been considered for this present investigation [10] is shown in Fig 1. The collector consists of a glass cover plate, a blackened absorber plate and a back plate with blackened pebbles packed in the airflow passage between the absorber and the black colored back plate.

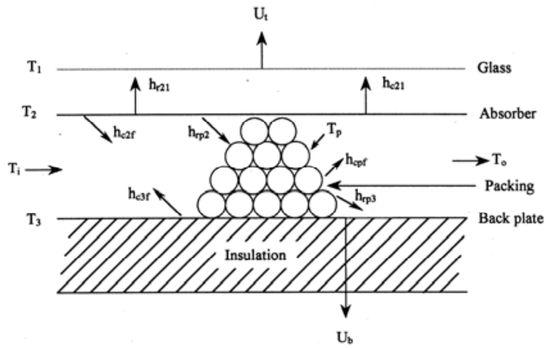


Fig 1. Cross section of the solar air heater model

The steady state energy balance equations for the different components of the system are as follows:
Cover plate,

$$I\alpha_1 + (h_{r21} + h_{c21})(T_2 - T_1) = U_t(T_1 - T_a) \quad (1)$$

Absorber plate,

$$I\tau_1\alpha_2 = (h_{r21} + h_{c21})(T_2 - T_1) + h_{rp2}(T_2 - T_p) + h_{c2f}(T_2 - T_f) \quad (2)$$

Packing,

$$h_{rp2}\left(T_2 - T_p\right) = h_{cpf}\left(T_p - T_f\right) + h_{rp3}\left(T_p - T_3\right) \qquad (3)$$

Back plate,

$$h_{rp3}\left(T_p - T_3\right) = h_{c3f}\left(T_3 - T_f\right) + U_b\left(T_3 - T_a\right) \qquad (4)$$

Air,

$$mC_P \frac{dT_f}{dy} = W\left[h_{c2f}\left(T_2 - T_f\right) + h_{cpf}\left(T_p - T_f\right) + h_{c3f}\left(T_3 - T_f\right)\right] \qquad (5)$$

where W, width of the collector, represents the collector area per unit length in the flow direction.

h_{r21}, h_{rp2}, h_{rp3} are the radiative heat transfer coefficients between absorber plate and glass cover plate, absorber plate and packing material, packing material and back plate respectively, $W/m^2 K$.

h_{c21}, h_{c2f}, h_{cpf}, h_{c3f} are the convective heat transfer coefficients between absorber plate and glass cover, absorber plate and air, packing material and air, back plate and air respectively, $W/m^2 K$.

T_1, T_2, T_3, T_a, T_f, T_p are the temperatures of cover plate, absorber, back plate, ambient air, inside collector air and packing materials respectively, K.

The boundary conditions for the above equations are $T_f = T_i$ at $y = 0$ and $T_f = T_o$ at $y = L$

By solving energy balance equations Eq. (1) to Eq. (5) outlet air temperature T_o, from the collector can be computed and the thermal efficiency can be obtained by using the relation:

$$\eta_{th} = \frac{Q_u}{IA_c} = \frac{mC_P\left(T_o - T_i\right)}{IA_c} \qquad (6)$$

Heat transfer coefficient from packing to air h_{cpf}, is given by [12]:

$$h_{cpf} = \left[\frac{1}{h_{pf}} + \frac{D_P}{BK_P}\right]^{-1} \qquad (7)$$

where, $h_{pf} = \dfrac{Nu_{pf} K_f}{D_P}$ (8)

and $Nu_{pf} = \dfrac{0.225}{P} \Pr^{1/3} \mathrm{Re}_p^{2/3}$ (9)

Since the enhancement of thermal performance in packed bed solar air heater is accompanied by significant increase of pressure losses. So the thermohydraulic performance parameter called "effective efficiency" has been employed to express the net useful thermal energy gain, taking into account the equivalent thermal energy required to produce the work energy necessary to overcome the additional friction or hydraulic losses as a result of packing the collector duct with packing materials. The thermohydraulic or effective efficiency can be expressed as [13]:

$$\eta_{eff} = \frac{Q_u - P_P/C}{IA_c} \qquad (10)$$

where, C is the conversion factor for converting the thermal energy to equivalent pumping power of the fan or blower [13] and expressed as:

$$C = \eta_f . \eta_m . \eta_{tr} . \eta_p \qquad (11)$$

η_f is the fan efficiency, taken as 0.65 [13], η_m is the motor efficiency, taken as 0.90 [13], η_{tr} is the transmission efficiency from power plant, taken as 0.925 [13] and η_p is the thermal efficiency of power plants, taken as 0.34 [13]. The pumping power P_P, is given by the following expression:

$$P_P = \frac{G \times \Delta P \times A_c}{\rho_f} \qquad (12)$$

for pebble bed air flow passage [14] pressure drop

$$\Delta P = f_p \frac{G_o^2}{\rho_f} \frac{L}{D_P} \frac{(1-P)}{P^3} \qquad (13)$$

and friction factor,

$$f_p = \left[150 \frac{(1-P)}{\mathrm{Re}_p} + 1.75\right] \qquad (14)$$

In general, economics being the driving force for any viable application. So it is important to analyze the system on the basis of economic consideration. The relevant parameter would then be evaluation of unit energy cost delivered by the system. The annual cost of delivering solar heat C_{sa}, that is the cost of owing, operating and maintaining the system, in Rupees (1 US$=47 Rupees) per year, can be formulated as [15]:

$$C_{sa} = \left(C_c A_c + C_e\right) I + P_a C_p + C_{mm} + C_{ml} \qquad (15)$$

I is the fraction of investment to be charged per year as interest and depreciation.

$$I(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (16)$$

It was assumed that the system runs, on the averages for 8 hrs/day. So the annual power requirement to run the system is $P_a = P_P \times$annual running hours (usually expressed in kWh/yr.).

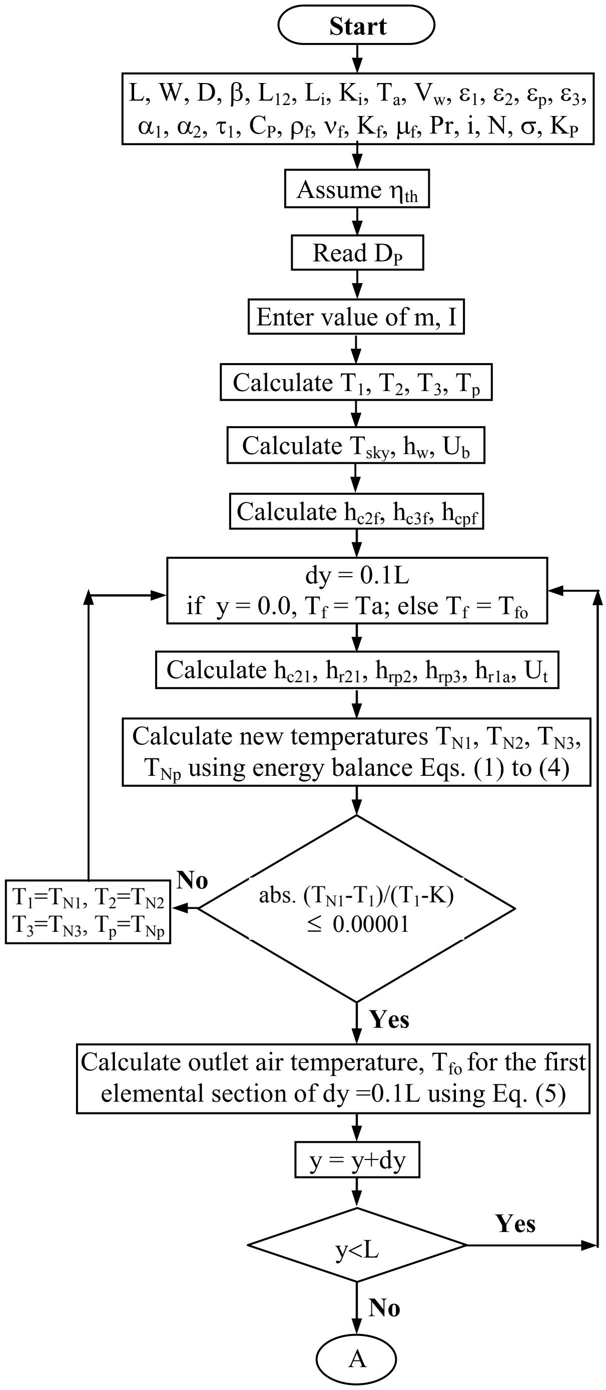
The cost per unit energy delivered by the solar system is given by:

$$C_u = \frac{C_{sa}}{E} \qquad (17)$$

E, is the annual heat energy delivered by the solar energy system and expressed as: E = Q_u × annual running hours (usually expressed in kWh/yr.). In an investigation on packed solar air collector, Hasatani [9] used glass beads as packing material and the diameters were 3.4 mm to 10 mm. In this work pebble diameter were taken from 4 mm to 12 mm and mass flow rate of air ranges from 0.01 to 0.033 kg/s.

3. RESULTS AND DISCUSSION

Thermal efficiency, thermohydraulic efficiency and cost per unit energy delivered by the packed bed solar air heater system for different bed and operating parameters had been obtained from a computer program developed in 'C' language. Major steps of the program are shown in flow chart (Fig 2.).



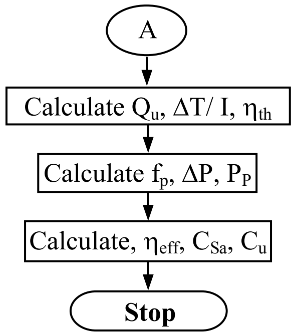


Fig 2. Flow chart of the computer program

Effect of mass flow rate of air on thermal efficiency for pebble bed collector is shown in Fig 3. It has been observed that thermal efficiency increases with increase in mass flow rate. This figure also tells the effect of

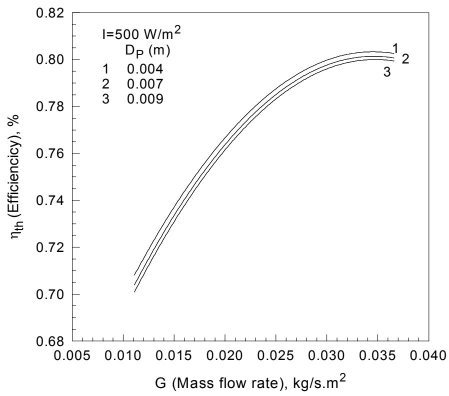


Fig 3. Effect of mass flow rate and pebble diameter on thermal efficiency

pebble diameter on thermal efficiency, which is higher for smaller pebble diameter. Smaller pebbles make the airflow path more tortuous and create more turbulence, hence better performance.

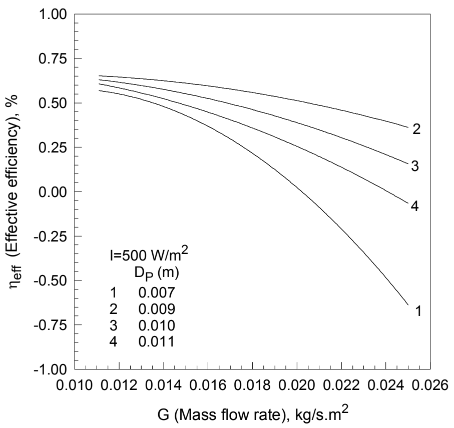


Fig 4. Effect of mass flow rate on effective efficiency

But effective efficiency monotonously decreases with increase in flow rate as can be seen from Fig 4. and at very high air flow rate thermohydraulic efficiency may even become negative. Because pebbles bed has very lower porosity, so rate of increase in pressure loss is much higher in comparison to rate of increase in heat transfer from packing to air. Fig 5. shows that effective efficiency increases with increase in pebble diameter, attains a maxima and subsequently decreases further increase in diameter.

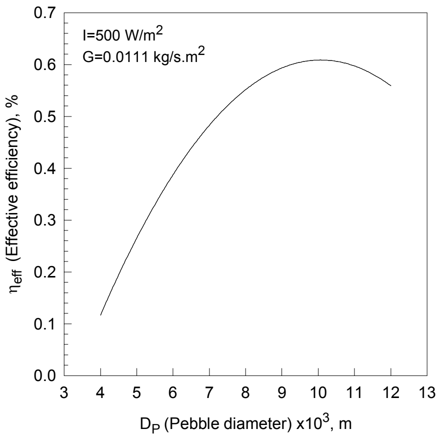


Fig 5. Effect of pebble diameter on effective efficiency

There is a significant effect of mass flow rate and pebble diameter on cost per unit energy delivered by the solar air heater. It is evident from Fig 6. that for smaller pebble diameter packing and higher mass flow rate, unit energy cost is much higher. This behavior can be attributed to the fact that at higher mass flow rate and smaller pebble diameter packing, pressure loss is higher and smaller pebbles make the air flow path more restricted leads to negative thermohydraulic efficiency.

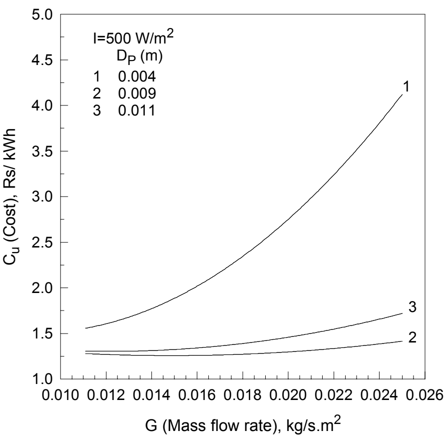


Fig 6. Effect of mass flow rate and pebble diameter on cost per unit energy delivered

4. CONCLUSIONS

Packing the solar air heater duct results in higher thermal efficiency but also in higher pressure drop and hence larger running cost of the system. So there should be a compromise between enhanced thermal efficiency and enhanced pressure loss, so that the energy spent in pumping the air through the collector is low enough to make the system cost effective.

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6. NOMENCLATURE

Symbol	Meaning	Unit
A_c	Collector area	(m^2)
B	A constant in Eq. (7) = 10 for spheres or pebbles	
C_c	Capital cost of collector	(Rs/m^2)
C_e	Capital cost of equipments	(Rs)
C_P	Specific heat of air	(J/kg.K)
C_p	Unit cost of electric power	(Rs/kWh)
C_u	Cost of unit energy delivered by the solar energy system	(Rs/kWh)
C_{ml}	Annual cost of maintenance with respect to labor	(Rs)
C_{mm}	Annual cost of maintenance with respect to material	(Rs)
C_{sa}	Annual cost of solar energy system	(Rs/yr)
D	Depth of collector bed	(m)
D_P	Pebble diameter	(mm)
f_p	Friction factor in packed beds	
G	Mass flow rate per unit area of collector	($kg/s.m^2$)
G_o	Mass velocity of air	($kg/s.m^2$)
h_w	Wind heat transfer coefficient	($W/m^2.K$)
h_{pf}	Air/packing film heat transfer coefficient	($W/m^2.K$)
h_{r1a}	Radiative heat transfer coefficient between cover plate and ambient air	($W/m^2.K$)
I	Solar radiation	(W/m^2)
i	Interest rate	(%)
K_f	Thermal conductivity of air	(W/m.K)
K_i	Thermal conductivity of insulation	(W/m.K)
K_P	Thermal conductivity of pebble	(W/m.K)
L	Length of collector	(m)
L_i	Thickness of insulation	(m)
L_{12}	Spacing between cover and absorber plate	(m)
m	Mass flow rate of air	(kg/s)
N	Life span of the solar energy system	(yrs.)
Nu_{pf}	Air/packing Nusselt number	
P	Porosity	
ΔP	Pressure drop	(N/m^2)
P_a	Annual electric power requirements to run the system	(kWh/yr)
P_P	Pumping power	(W)
Pr	Prandtl number	
Q_u	Useful heat gain	(W)
Re_p	Packed bed Reynolds number	
T_i	Inlet air temperature	(K)
T_o	Outlet air temperature	(K)
T_{N1}	New temperature of glass cover plate	(K)
T_{N2}	New temperature of absorber plate	(K)
T_{N3}	New temperature of back plate	(K)
T_{Np}	New temperature of packing material	(K)
T_{sky}	Sky temperature	(K)
U_b	Back loss coefficient	($W/m^2.K$)
U_t	Top loss coefficient	($W/m^2.K$)
V_w	Wind velocity	(m/s)
α_1	Absorptivity of glass cover plate	
α_2	Absorptivity of absorber plate	
β	Collector tilt angle	(deg.)
ρ_f	Density of air	(kg/m^3)
τ_1	Transmissivity of glass cover	
ε_1	Glass cover emissivity	
ε_2	Absorber plate emissivity	
ε_3	Back plate emissivity	
ε_p	Packing material emissivity	
μ_f	Viscosity of air	($N.s/m^2$)
σ	Stefan- Boltzmann constant	($W/m^2.K^4$)