THERMAL PERFORMANCE OF OPTICALLY SEMI-TRANSPARENT MATERIAL PACKED BED SOLAR AIR HEATER

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ABSTRACT
An analytical model for solar collector efficiency factor, F′, which measures the effectiveness of a collector absorber in transferring heat to the transport fluid for packed bed solar air heater, has been developed. Effect of parameters such as diameter of semi-transparent spherical glass beads, bed-thickness (depth), mass flow rate on thermal performance and collector efficiency are presented and results are compared with flat-plate (plane) collector. It is observed that performance of plane collector improves appreciably by packing it with optically semi-transparent materials.

KEYWORDS: *Solar energy, Packed-bed, Solar air heater, Plane collector*

I. INTRODUCTION

Solar air heaters can be used for many applications requiring low and moderate temperatures. Some of these have been space heating and cooling, agricultural drying, timber seasoning, process heat and power generation.

Several designs of solar air heaters have been developed and tested over the years. Many attempts [1, 2, 6, 9, 16, 18] have been made to improve their performance.

[6,16] have proposed the use of solid and hollow spheres, metallic screen as heat absorbing media in air-cooled solar collectors in order to improve solar energy collection with considerable reduction in cost per unit energy collected. Packed-beds absorb solar radiation “in depth” and have a high ratio of heat transfer area to volume and high heat transfer capability, resulting in relatively low matrix surface temperatures. This will decrease the heat losses associated with high surface temperatures and increase the overall efficiency of collectors.

An experimental investigation of an augmented integral rock system was presented by [3]. Experimental observations of fluid temperatures and energy storage with variation of air-mass flow rate, number of glazing and depth of rock-bed are presented. [2] Have tested the performance of packed bed solar air-heaters with iron chips, aluminum chips and pebbles. An optically semi-transparent materials packed-bed solar air heater was proposed by [9] and heat collection and storage characteristics were investigated theoretically and experimentally. It was observed from the experimental data analysis that the solar air heater, in which semi-transparent material like glass beads or a glass tubes was used for heat collection and storage material had higher efficiency of energy collection and the thermal storage than a usual flat plate collector.

[8, 19, 20] investigated experimentally the solar air heater having its duct packed with wire-screen matrices. [18] Evaluated experimentally the thermal performance of a solar air heater collector using a packed bed of spherical capsules with a latent heat storage system. Absorbers having a bed packed with crushed glass matrices by [15] have been reported.

[8] Have experimentally investigated the heat transfer and flow friction characteristics of solar air heater having its duct packed with wire mesh screen and the correlations have been developed for the

Colborn j factor and friction factor for a low range of porosities from 0.89 to 0.96 and packing Reynolds number range from 182 to 1168.
Similar type of experimental investigation on wire mesh screen work reported by [12,19] for different porosities range i.e. 0.667 to 0.880 and 0.599 to 0.816 respectively. [11] Experimentally investigated the thermohydraulic performance of packed bed solar air heaters having its duct packed with blackened wire screen matrices of different geometrical parameters. A design criterion is also suggested to select a matrix for packing the air flow duct of solar air heater which results in the best thermal efficiency with minimum pumping power penalty. [7] Experimentally investigated the thermal performance of double pass steel wire screen packed bed solar air heater and reported that the efficiency of the double pass is found to be higher than the single pass. [10] experimentally investigated the heat transfer, flow friction and exergy analysis of wire screen packed bed solar air heater for high porosity range (0.9614-0.9984) and for different shape and correlations have been developed for Colburn factor and friction factor in terms of porosity and operating parameters. The counter and parallel flow packed bed solar air heaters are investigated theoretically and experimentally by [13]. The effect of air mass flow rates and bed porosity on the thermal and thermohydraulic efficiencies of the counter and parallel flow packed bed solar air heaters are investigated. The theoretical predictions indicated that the agreement with the measured performance is fairly good.
[14] Developed a mathematical model to investigate the effect of system and operating parameters on the thermal and thermohydraulic performance of wire screen packed bed solar air heater for low porosity range (0.50 to 0.76). The analytical and experimental results are found to be compared well in the range of parameters investigated.
[17] Investigated experimentally the performance of solar air heater on the single and double pass collectors with plane and perforated covers and with wire mesh matrix instead of an absorber plate. They developed a model with different design configurations and analysed the experimental data and reported that the double pass solar collector with quarter perforated cover yields the maximum efficiency.
[18] conducted the experimental study to evaluate the thermal performance of a new solar air heater collector using a packed bed of spherical capsule with a latent heat storage system using both first and second law of thermodynamics, the energetic and exegetic daily efficiency were calculated in closed/opened cycle mode. The experimentally obtained results are used to analyze the performance of the system, based on temperature distribution in different localization of the collectors. The daily energy efficiency varied between 32% and 45%. While the daily exergy efficiency varied between 13% and 25%.
In the present investigation an analytical model for collector efficiency factor, F´ has been developed to predict the performance of packed-bed solar air-heaters. Effect of System and operating parameters on performance has also been investigated.

II. THEORETICAL ANALYSIS

2.1. Plane Collector

The following analytical equations are available in the literatures [1.5] for collector efficiency factor, F' for air heaters shown in Figs. 1.1and 1.2.

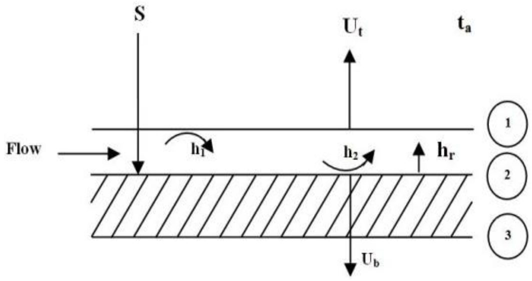

Fig.1.1 Plane Surface Absorber

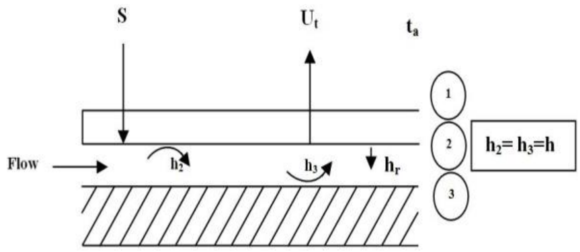

Fig.1.2 Plane Surface Absorber

(i) Flow over the Absorber (Fig. 1.1)

$$F' = \frac{h_r h_1 + h_2 U_t + h_r h_2 + h_1 h_2}{(U_t + h_r + h_1)(U_b + h_2 + h_r) - h_r^2} \tag{1A}$$

$$U_l = \frac{(U_b + U_t)(h_1 h_2 + h_1 h_r + h_2 h_r + h_2 h_r) + U_b U_t (h_1 + h_2)}{h_1 h_r + h_2 U_t + h_2 h_r + h_1 h_2} \tag{1B}$$

$$h_r = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_p} - 1} \tag{1C}$$

(ii) Flow under the absorber (Fig. 1.2)

$$F' = \left(1 + \frac{U_l}{h_e}\right)^{-1} \tag{2A}$$

$$h_e = h + \frac{h_r h}{h_r + h} \tag{2B}$$

where,
and h_r is given by Eq. (1C)

2.2 Packed-bed Solar Collector

Considering a packed-bed solar collector as shown in Fig. 1.3, the channel with a cover glass of width B, Depth D and length L with an aspect ratio comparatively small, is uniformly heated from upper surface by radiations.

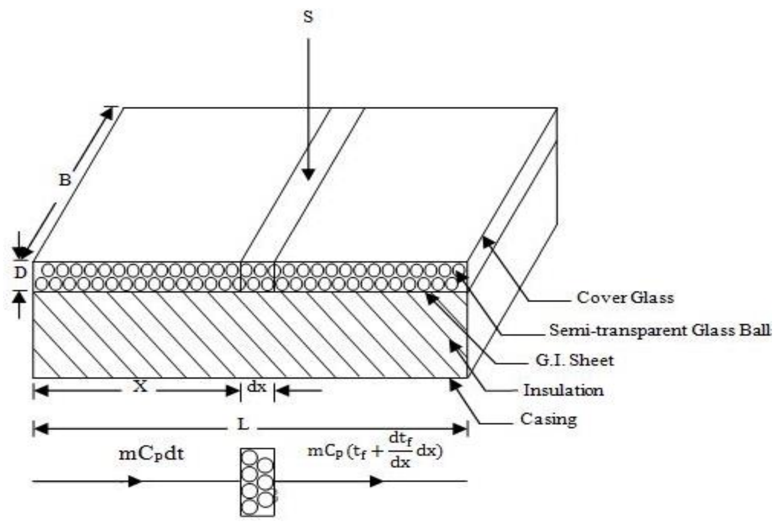

Fig. 1.3 Packed-Bed Absorber

Assuming that (a) the particles are small or have a high thermal diffusivity such that any given lump could be considered to be at the uniform temperature at any given instant; (b) the resistance to transfer of heat by conduction in the fluid itself or in the solid itself is negligible; (c) radiation effects are negligible and (d) the physical properties of packed material are independent of temperature.
Then the energy balance for element of length dx in the flow direction in steady state condition of the absorption matrix and fluid element are respectively given by the following equation:

For Packed Material:

Rate of solar energy absorbed by the matrix of width B, length dx = Rate of heat carried by flowing air due to convection + heat loss from matrix to surroundings.

or, $$S(Bdx) = h_v A dx (t_b - t_f) + U_L (Bdx)(t_b - t_a)$$

where, S = solar energy absorbed by the matrix = $I(\tau\alpha)_e$
t_b and t_f = temperatures of bed and air respectively.

or, $$S = h_v D(t_b - t_f) + U_L(t_b - t_a) \quad (3)$$

For Air:
Rate of heat carried by air due to convection = Rate of sensible heat increase of air through element of length, dx

or, $$h_v A(t_b - t_f)dx = mc_P \frac{dt_f}{dx} dx$$

or, $$h_v A(t_b - t_f) = mc_P \frac{dt_f}{dx} \quad (4)$$

Combining Eq. (3) and Eq. (4), rate of useful energy gain per unit area, qu is given by

$$\frac{T_f - T_a - \frac{S}{U_L}}{T_{fi} - T_a - \frac{S}{U_L}} = \exp.\left[-\frac{F' U_L A_c}{\dot{m} C_p} x\right] \quad (5)$$

Here F´ could be expressed as:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_l} + \frac{1}{h_v D}} \quad (6)$$

In order to predict the performance of packed-bed collectors, the volumetric heat transfer co-efficient, h_v must be known and it is evaluated by using the correlation

$$h_v = h.\frac{A_p}{v} \quad (7)$$

For calculating the value of convective heat transfer coefficient h, is expressed as [21].

$$Nu = \left(0.5\,Re^{1/2} + 0.2\,Re^{2/3}\right)Pr^{1/3} \quad (8)$$

where, Reynolds number (Re) and Nusselt number (Nu) are as follows:

$$Re = u^0 L^0 / \nu$$

The characteristic length L_0 can be expressed as

$$L^0 = D_p\left(\frac{p}{1-p}\right) \quad (9)$$

and, $$u^0 = Q \big/ p.A_{fr} \quad (10)$$

Hence, $$Re = \rho Q D_p / \mu A_{fr}(1-p)$$
$$= \frac{D_p.G}{\mu(1-p)} \quad (11)$$

and, $$Nu = hL^0 / k$$
$$= \frac{hD_p}{k}\left(\frac{p}{1-p}\right) \quad (12)$$

Here, G_o is the mass velocity equal to $\rho Q/A_{fr}$. Characteristic length and velocity is used for determining a Reynolds number and Nusselt number having the term (1-p) in the denominator. We must therefore expect that as the void fraction becomes large our characteristic length and velocity will become unsuitable for $(1\text{-}p)^{-1}$ varies exceedingly rapidly as p approaches unity.
The following correlation may be used for laminar flow in a rectangular channel duct [4].

$$Nu = 4.4 + \frac{0.00398\left(0.7Re.D_H / L^0\right)^{1.66}}{1 + 0.00114\left(0.7Re.D_H / L^0\right)^{1.12}} \tag{13}$$

and for turbulent flow, the relation is given as

$$Nu = 0.0158\,Re^{0.8}\left[1 + \left(\frac{D_H}{L}\right)^{0.7}\right] \tag{14}$$

$$Re = \frac{\rho v D_H}{\mu}$$

where,
U_L = 10 W/m^2.K assumed as constant in the present investigation, as it is weak function of bed temperature [20].

2.3 Temperature Distribution in Flow Direction

If we assume that F′ are temperature independent in position, then the solution for the temperature at any position x (subject to the condition that the inlet temperature is T_{fi}) is

$$\frac{T_f - T_a - \frac{S}{U_L}}{T_{fi} - T_a - \frac{S}{U_L}} = \exp.\left[-\frac{F' U_L A_c}{\dot{m} C_p} x\right] \tag{15}$$

If the collector has a length L in the direction of the flow, then the outlet temperature T_{fo} is found by substituting L for x in eq. (14).

$$\frac{T_{fo} - T_a - \frac{S}{U_L}}{T_{fi} - T_a - \frac{S}{U_L}} = \exp.\left[-\frac{F' U_L A_c}{\dot{m} C_p} L\right] \tag{16}$$

2.4 Collector Heat Removal Factor

It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful energy gain if the whole collector surface were at the fluid inlet temperature. This quantity is called the collector heat removal factor, F_R, and can be written as [5].

$$F_R = \frac{\dot{m} C_p \left[T_{fo} - T_a\right]}{A_c\left[S - U_L\left(T_{fi} - T_a\right)\right]} \frac{dT_f}{dx} \tag{17}$$

The collector heat removal factor can be expressed as [5,22].

$$F_R = \frac{\dot{m} C_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m} C_p}\right)\right] \tag{18}$$

The quantity F_R is equivalent to a conventional heat exchanger effectiveness, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer.

2.5 Collector Efficiency

The collector efficiency can be expressed as

$$\eta = \frac{\dot{m} C_p \left(T_{fo} - T_{fi}\right)}{A_c.I} \tag{19}$$

III. RESULTS AND DISCUSSIONS

Fig. 2 shows collector efficiency factor, (F′) calculated with help of eq. (1) for plane and eq. (7) for packed bed solar air heater as a function of bed-thickness. Curves show that collector efficiency factor (F′) of packed-bed collector increases slightly as thickness of bed increases, while for plane collector it decreases drastically. It may also be noted that as diameter of spherical glass beads decreases, collector efficiency factor is found to increase. This appears due to fact that decrease in diameters of beads increase the heat transfer area and more turbulence.

Fig. 3 shows the effect of mass flow rate on collector efficiency factor. Here curves show that as the mass flow rate of air increases, the collector efficiency factor increases for both plane as well as packed-bed collectors. It is seen that the increase in mass flow rate beyond 0.03 kg/s-m has little effects on collector efficiency factor for packed-bed collector, while for plane collector effects are more pronounced.

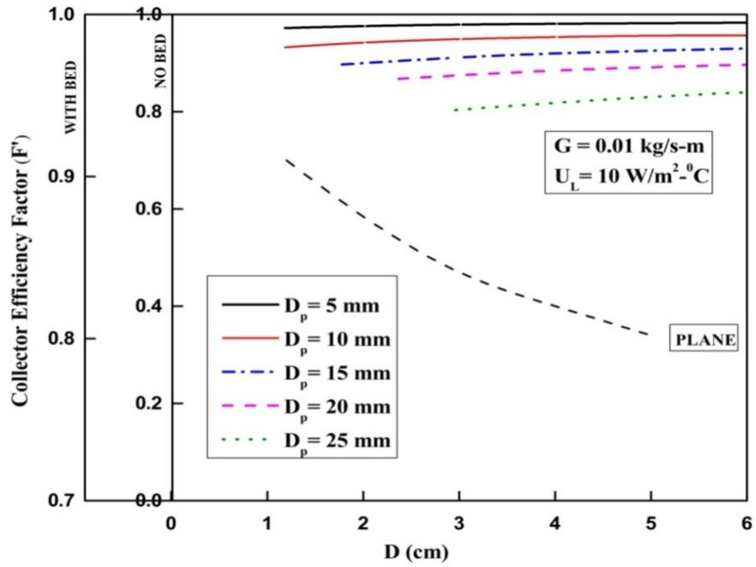

Fig. 2 Effect of bed thickness on collector efficiency factor

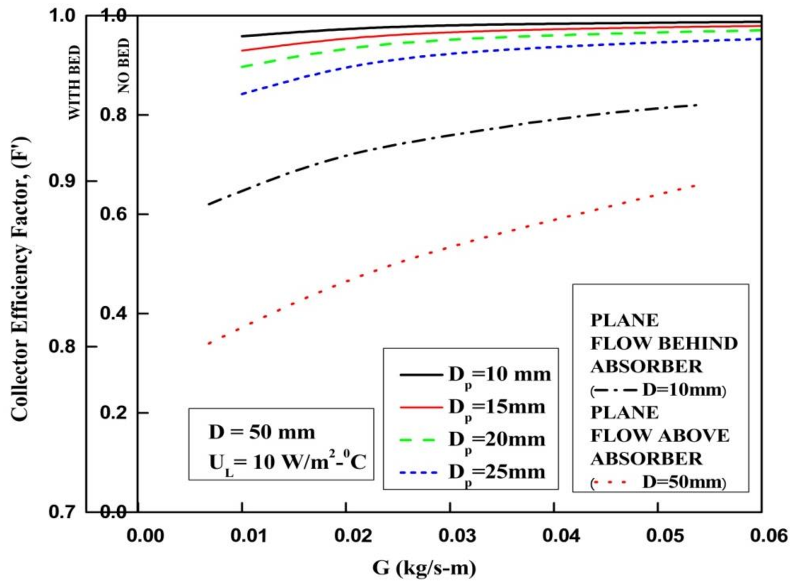

Fig. 3 Effect of mass flow rate on collector efficiency factor

Fig. 4 shows the effect of bed thickness on collector heat removal factor for different size of packing materials, from the figure it is seen that F_R increases as thickness of bed increases. The increase in the value of F_R attributed to the fact that any decline in the value of convective heat transfer coefficient as a result of decrease in superficial mass velocity of air is effectively compensated by corresponding increase in the heat transfer surface area of packing materials. It is also seen that as packing materials diameter decreases, collector heat removal factor increases. This results in fact is due to decrease in particle diameter, increases the surface area of packing materials and consequently increases the convective heat transfer rate from bed matrix to air.

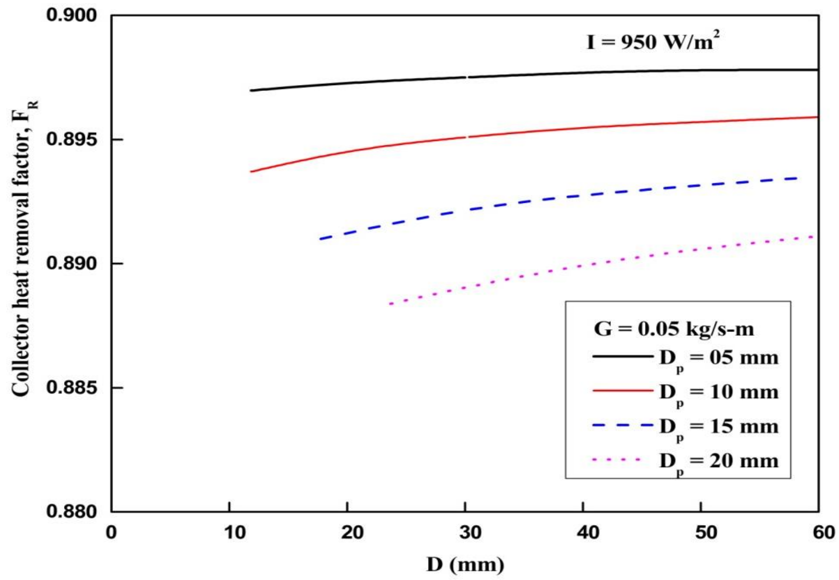

Fig. 4 Effect of bed thickness on collector heat removal rate

Fig.5 shows the collector heat removal factor as a function of specific mass flow rate for different values of glass beads diameter. From the figure it is found that F_R increases as G increases because of increase in convective heat transfer rate. A substantial enhancement of these parameters with smaller diameter of glass beads is the index of beneficial influence.

Fig. 6 shows the plot of the ratio of collector heat removal factor of packed bed collector to that of plane collector as a function of mass flow rate. Enhancement of performance upto 100% at low mass flow rate (0.01 kg/s-m) to 46% at high mass flow rate (0.05 kg/s-m) over plane collector with flow above the absorber is observed. It is 30.7% to 18.7% over plane collector with flow behind the absorber.

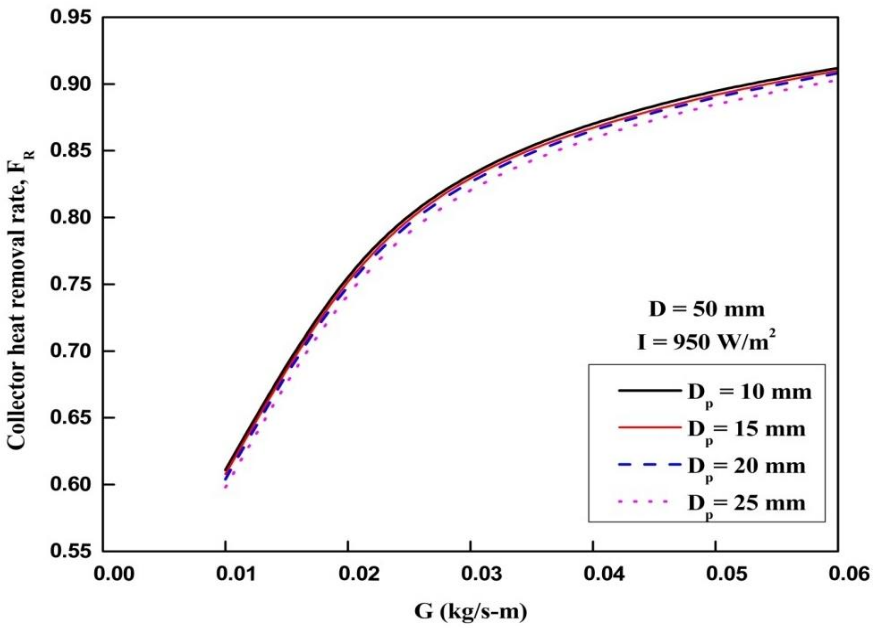

Fig. 5 Effect of mass flow rate on collector efficiency factor

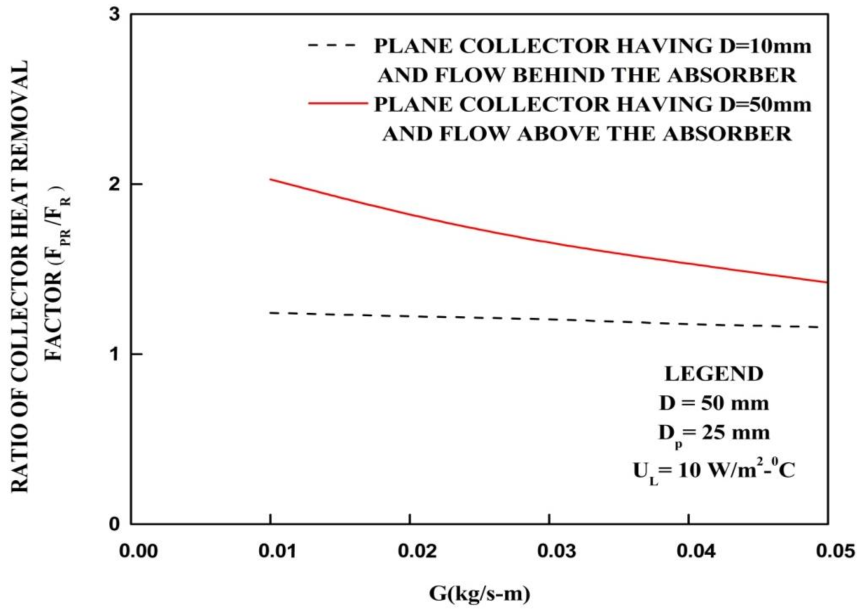

Fig. 6 comparison of performance between plane and packed-bed collectors

The effect of mass flow rate and diameter of glass beads on collector efficiency was shown in Fig. 7. It is seen that the efficiency increases for both plane as well as packed-bed collectors with an increase in mass flow rate and with a decrease in diameter of glass beads. This appears due to the fact that more turbulence is created in the flow as the diameter of glass beads decreases and the flow passage becomes more tortuous and narrower.

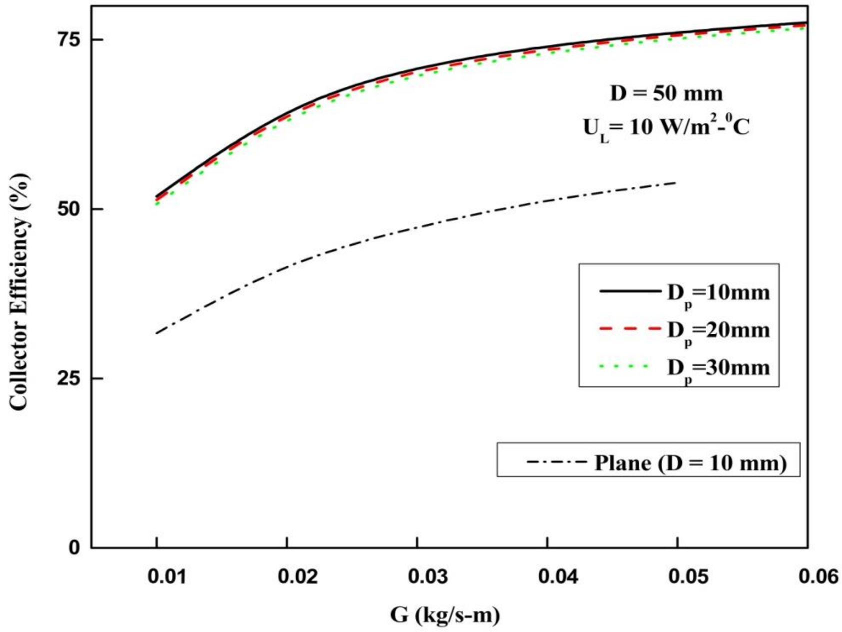

Fig. 7 Effect of mass flow rate on collector efficiency

IV. CONCLUSIONS

i) An analytical expression for collector efficiency factor for packed-bed solar air heaters has been developed which provides a means of analytical comparison of thermal performance of such collectors with that of plane collector.

ii) The performance of plane collector is found to improve appreciable by packing it with semi-transparent materials.

iii) Effects of system parameters such as depth of bed and diameter of packing materials on the thermal performance have been investigated.

V. SCOPE FOR FUTURE WORK

This work has tremendous scope in the energy crisis world. The following studies may be taken up.

i) The work can be extended for unsteady state two-dimensional problem.

ii) The system and operating parameters may be optimize to obtain maximum benefit from such a system.

iii) The work can further be extended to study the thermal storage characteristics of packed-bed solar air heater.

NOMENCLATURE

A_{fr}	Bed frontal/cross-section area of duct, m^2
A_c	Collector area, m^2
B	Width of collector, 1m
C_p	Specific heat of air, J/kg-^{0}C
D	Depth of collector, m
D_H	Hydraulic diameter
D_p	Diameter of glass beads, m
F′	Collector efficiency factor
F_R	Collector heat removal factor
F_{PR}	Collector heat removal factor for plane collector
G	Mass flow rate per unit width of collector, kg/s-m
G_o	Mass velocity of air in bed, kg/m-s^2
h_1 & h_2	Convective heat transfer coefficient between cover and air and absorber and air respectively, W/m^2-^{0}C
h_r	Radiative heat-transfer coefficient W/m^2-^{0}C [4]
h_v	Volumetric heat transfer coefficient, W/m^3-^{0}C
I	Insolation = 950 W/m^2; $(\tau\alpha)_e$ = 0.85
L	Length of collector, 1.5 m
m	Mass flow rate of air, kg/s
Nu	Nusselt number
Re	Reynolds number
S	Incident radiation absorbed by the matrix, W/m^2-^{0}C = $I(\tau\alpha)_e$
t_a	Ambient temperature, ^{0}C
t_b,t_f	Temperature of bed and air respectively, ^{0}C
T_1, T_2	Temperature of cover and absorber (plane) respectively, ^{0}K
U_L	Overall loss coefficient, W/m^2-^{0}C
v	Volume of the bed, m^3
V	Velocity of air in plane collector, m/s
μ	Absolute viscosity of air, kg/s-m
ρ	Density of air, kg/m^3
ε_c	Emissivity of cover 0.88
ε_p	Emissivity of absorber plate, 0.95
p	Porosity of bed matrix

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