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Thermal Modelling for Greenhouse Heating by Using Packed Bed*

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Abstract: This study presents thermal modelling of rock bed with water for heating agricultural greenhouse. Numerical computations have been carried out for an east-west oriented even span greenhouse for New Delhi (28.5° latitude), India. Effect of void bed fraction, area of collectors on plant, room air, water and rock bed temperatures have been studied in detail. On the basis of numerical results, it is inferred that the plant, room air and water temperatures of the greenhouse increases significantly with the increase of collector area and decreases with the increase of void bed fraction, while rock bed temperature increases with the increase of void bed fraction.

Key words: Solar energy, thermal modelling, packed bed storage, flat plate collector

Introduction

It is well know that due to decline of the world's fossil energy resources and the environmental impacts of the use of these resources, utilization and storage of renewable energies are by no means issues, which should be neglected. Out of the all alternatives to conventional forms of energy, the one receiving most serious consideration at least for greenhouse heating needs is solar energy. Greenhouse cultivation as well as other modes of controlled environment cultivation has been evolved to create favorable micro-climates in which crop production could be made possible all throughout the year or part of the year as required. As the solar energy is intermittent, it needs to be stored in clear days to use the energy stored for heating at night (Walton *et al*., 1979; Bouhdjar *et al*., 1996). Besides water and soil itself as the solar energy storage medium, rocks are usually utilized to serve the same purpose (Bredenbeck, 1984; Santamouris *et al*., 1994). Rock-bed is also considered to have the required characteristics such as higher thermal conductivity than those of water and phase change materials, rapid heat transfer, low cost and long life (Chandra *et al*., 1981; Garzoli, 1989). Although there are many studies available on the heating and cooling of packed beds, a rock bed thermal storage/retrieval system met the heating energy requirements of the energy-conserving greenhouse (Gupta and Chandra, 2002). Blackwell and Garzoli (1981) studied rock bed storage for greenhouse heating. The rock bed system is more economical than the LPG or petroleum based fuel burning heating systems (Kurklu *et al*., 2003).

In this study, the thermal performance of greenhouse heating with rockbed has been investigated theoretically in terms of room air temperature (T_r), plant temperature (T_p), water temperature (T_w), rock bed temperature (T_{rb}) and Thermal Load Leveling (TLL). Effect of void bed fraction and area of collectors on an even span greenhouse of effective floor area of 24 m^2 with solar collector has been considered for modeling. It is inferred that the plant temperature, room air temperature and water temperature of the greenhouse increases significantly with the increase of collector area and decreases with the increase of void bed fraction, while rock bed temperature increases with the increase of void bed fraction.

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Working Principle of a Greenhouse

A covered structure of plastic film, which is transparent to short wavelength radiation and opaque to long wavelength radiation, is used for heating a greenhouse. Out of the total incoming solar radiation, S(t), a fraction of solar energy $\{\gamma S(t)\}$, is reflected back from canopy and a part of rest radiation, $\{(1-\gamma)S(t)\}$, is transmitted inside the greenhouse. Out of this transmitted radiation, $\{(1-\gamma)\tau S(t)\}$, a fraction of this $\{F_n(1-\gamma)\tau S(t)\}$, is reflected. After reflection from the surface, part of incident solar radiation, $a_n F_n(1-\gamma_n)\tau S(t)$, is absorbed by itself and rest is conducted as shown in Fig. 1. There are convective and radiative losses from the surface to room air. $\{\alpha_g(1-F_n)(1-\gamma)\tau S(t)\}$ is reflected from the floor and $\{a_g(1-\gamma_g)(1-F_p)(1-F_n)(1-\gamma)\tau S(t)\}$ is absorbed by the floor. The absorbed energy is transferred to room air, water and rock bed below the floor. After absorption by the floor, this energy is used by convective and radiative means for heating of the room air. The convected and radiated energy from the floor raises the temperature of air inside greenhouse. The transmitted solar radiation through north canopy cover $F_n(1-\gamma)^2\tau^2 S(t)$ is generally significant during the winter month. Below the floor pebble-bed consists of a bed of loosely packed rock material through which the water flows as a heat transferred fluid. Rocks are the materials, which are loosely packed, take or give up heat from the water and have high energy storage capacity (Paksoy *et al*., 1995; Chandra and Willits, 1981). The energy stored in a packed bed storage system depends on the thermophysical properties of the material, heat transfer fluid etc. The solar radiation incident on Flat Plate Collector (FPC) absorbs maximum radiation through the glazing. The energy absorbed by the FPC is extracted by circulating a fluid, through a network of tubes in good thermal contact with the plate. The bottom and sides of the collector are covered with insulation to reduce the conductive heat loss. The collector is placed at an angle of 28.53° to receive maximum solar radiation (Tiwari, 2002).

Thermal Analysis

The energy balance equations for the different components of the packed bed greenhouse system, as shown in Fig.1, are written on the following assumptions:

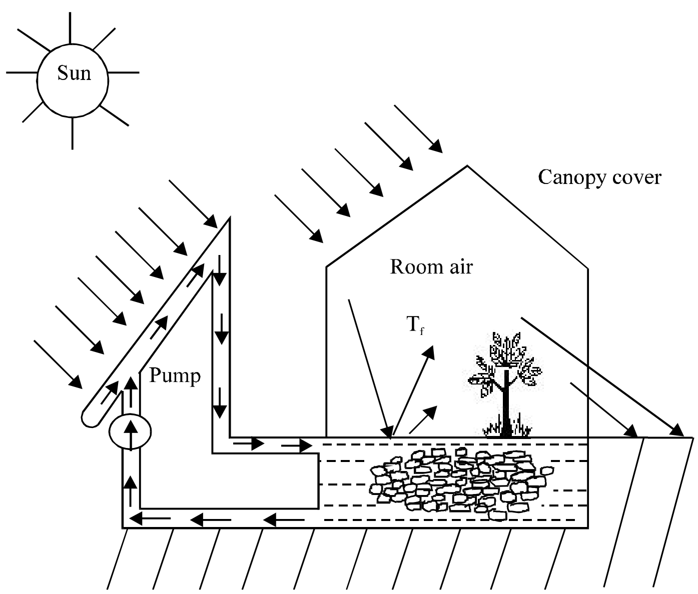


Fig. 1: Schematic view of active greenhouse system

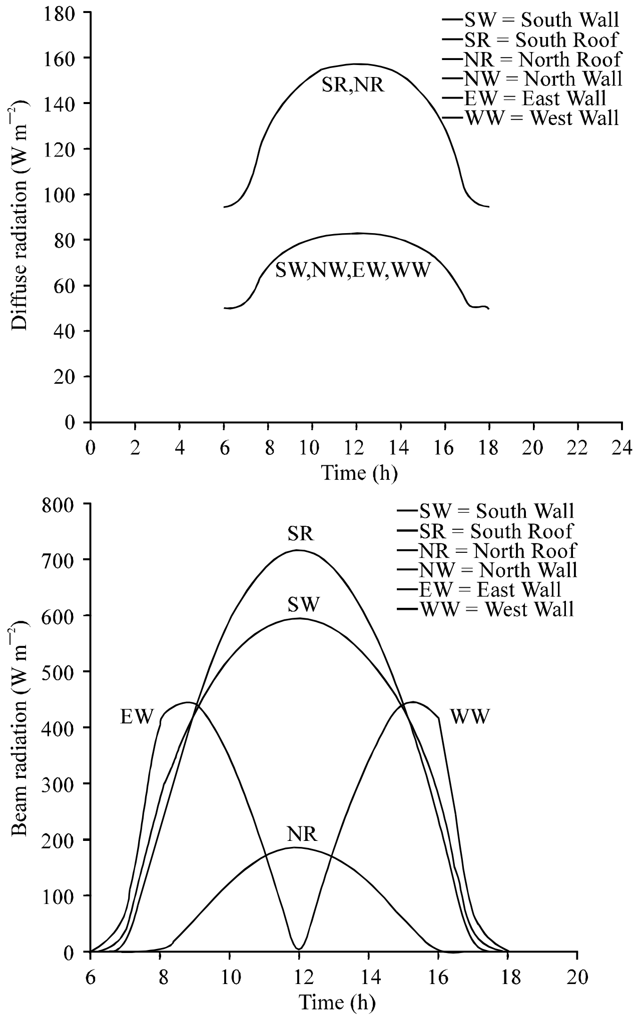


Fig. 2: Hourly variation of (a) diffuse radiation and (b) beam radiation on different walls and roops of greenhouse for a typical winter day in New Delhi

- Heat flow is one dimensional,
- No axial conduction or dispersion and no mass transfer,
- Thermal properties of plants in the greenhouse are the same as those of water,
- Greenhouse is east-west oriented,
- Pipes are perfectly insulated,
- No stratification in water mass below greenhouse.

Floor

$$(\tau\alpha)_b S(t) = A_b h_b (T_b - T_r) + A_b h_{bw} (T_b - T_w) \quad (1)$$

where $S(t) = \sum I_i A_i$, I_i is the total radiation on ith component of Fig. 1 which can be obtained by using Liu and Jordan (1962) formula for a given beam and diffuse radiation (Fig. 2). The hourly variation of S(t) has been shown in Fig. 3.

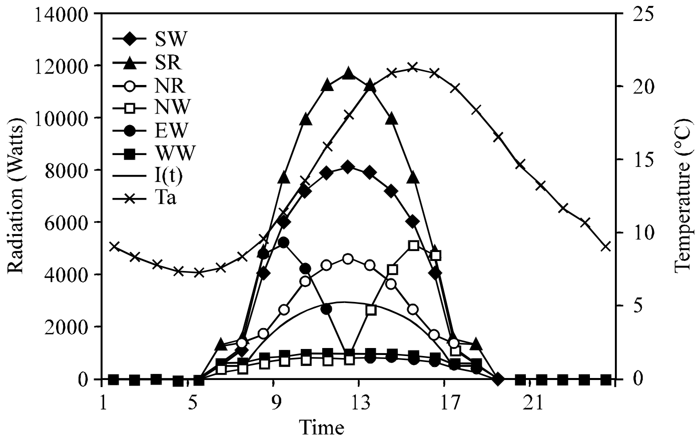


Fig. 3: Hourly variation of total solar radiation incident on greenhouse and collector area and ambient temperature for a typical winter day in New Delhi

Room air

$$A_p h_p (T_p - T_r) + A_b h_b (T_b - T_r) = \Sigma h(t) A_i (T_r - T_a) + 0.33 N_o V (T_r - T_a) + h_D A_D (T_r - T_a) \quad (2)$$

Water mass

$$V_w (\rho C_p)_w \varepsilon \frac{dT_w}{dt} + V_{rb} h_\upsilon (T_w - T_{rb}) = A_b h_{bw} (T_b - T_w) + \dot{Q}_{u,N} - h_{bw} A_{bs} (T_s - T_w) \quad (3)$$

ε is void fraction in a packed bed is defined as the ratio of volume of voids in bed to the total volume of bed (voids plus solids)

Packed Bed

$$V_{rb} (\rho C_p)_{rb} (1-\varepsilon) \frac{dT_{rb}}{dt} = h_\upsilon V_{rb} (T_w - T_{rb}) \quad (4)$$

Plant mass

$$\tau\alpha_p (1-\gamma_p) F_p (1-F_n)(1-\gamma) S(t) = A_p h_p (T_p - T_r) + M_p C_p \frac{dT_p}{dt} \quad (5)$$

The rate of useful energy gain of the collector can be evaluated by (Abdel-Khalik, 1976)

$$\dot{Q}_u = F_R A_c [(\tau_o \alpha_o) I(t) - U_L (T_w - T_a)]$$

or,

$$\dot{Q}_u = A_c [F_R (\tau_o \alpha_o) I(t) - F_R U_L (T_w - T_a)] \quad (6)$$

where I(t) is the total solar radiation falling on each collector which is given in Fig. 3.
For N identical set of collectors connected in series,

$$F_R (\tau_o \alpha_o) = F_{R,N} (\tau_o \alpha_o) \left[\frac{1-(1-K_K)^N}{NK_K} \right]$$

and

$$F_R U_L = F_{R,N} U_{L,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right]$$

Then Eq. 5 can be rewritten as,

$$\dot{Q}_{u,N} = NA_c\left[F_{R,N}\tau_o\alpha_o I(t)\left[\frac{1-(1-K_K)^N}{NK_K}\right] - F_{R,N}U_{L,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right](T_w - T_a)\right] \quad (7)$$

From Eq. 1, we get

$$T_b = \frac{(\tau\alpha)_b S(t) + A_g h_g T_r + A_g h_{gw} T_w}{A_g h_g + A_g h_{gw}} \quad (8)$$

By substituting the expression of T_b in Eq. 2, we get

$$T_r = \frac{(AH)_{br}(\tau\alpha)_{br} S(t) + A_p h_p T_p + (UA)_{wr} T_w + (AH)_{ra} T_a}{A_p h_p + (UA)_{wr} + (AH)_{ra}} \quad (9)$$

Eq. 3 and 4 can be rewritten with the help of Eq. 7-9 as

$$\frac{dT_w}{dt} + \frac{1}{V_w(\rho C_p)_w \varepsilon}\left\{\begin{aligned}&V_{rb}h_\upsilon - h_{bw}A_{bs} + (UA)_{aw} + \\ &(UA)_{pw} + NA_c F_{R,N} U_{L,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right]\end{aligned}\right\}T_w - \frac{V_{rb}h_\upsilon}{V_w(\rho C_p)_w \varepsilon}T_{rb}$$

$$-\frac{(UA)_{pw}}{V_w(\rho C_p)_w \varepsilon}T_p = \frac{1}{V_w(\rho C_p)_w \varepsilon}\left\{\begin{aligned}&-h_{bw}A_{bs}T_s + (AH)_{bw}(\tau\alpha)_b S(t) + (AH)_{rw}(\tau\alpha)_b S(t) \\ &+(UA)_{aw} + NA_c F_{R,N} I(t)(\tau_o\alpha_o)\left[\frac{1-(1-K_K)^N}{NK_K}\right] \\ &+\left[NA_c U_{1,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right] + (UA)_{aw}\right]T_a\end{aligned}\right\}$$

(10)

and

$$\frac{dT_{rb}}{dt} - \frac{h_\upsilon V_{rb}}{V_{rb}(\rho C_p)_{rb}(1-\varepsilon)}T_w + \frac{h_\upsilon V_{rb}}{V_{rb}(\rho C_p)_{rb}(1-\varepsilon)}T_{rb} + 0.T_p = 0 \quad (11)$$

Eq. 10 and 11 are in the form of a first order coupled differential equations as

$$\frac{dT_w}{dt} + a_1 T_w + a_2 T_{rb} + a_3 T_p = f_1(t) \quad (12)$$

and

$$\frac{dT_{rb}}{dt} + b_1 T_w + b_2 T_{rb} + b_3 T_p = f_2(t) \quad (13)$$

where a_1, a_2, a_3, b_1, b_2 and b_3 are constants during the same time interval and its expression are given as

$$a_1 = \frac{1}{V_w(\rho C_p)_w \varepsilon}\left\{V_{rb}h_\upsilon - h_{bw}A_{bs} + (UA)_{aw} + (UA)_{pw} + NA_c F_{R,N} U_{L,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right]\right\}, \quad (14)$$

$$a_2 = -\frac{V_{rb}h_\upsilon}{V_w(\rho C_p)_w \varepsilon}, \quad (15)$$

$$a_3 = -\frac{(UA)_{pw}}{V_w(\rho C_p)_w \varepsilon}, \quad (16)$$

$$b_1 = -\frac{h_\upsilon V_{rb}}{V_{rb}(\rho C_p)_{rb}(1-\varepsilon)}, \quad (17)$$

$$b_2 = \frac{h_\upsilon V_{rb}}{V_{rb}(\rho C_p)_{rb}(1-\varepsilon)}, \quad (18)$$

$$b_3 = 0 \quad (19)$$

$$f_1(t) = \frac{1}{V_w(\rho C_p)_w \varepsilon}\left\{\begin{array}{l} -h_{bw}A_{bs}T_s + (AH)_{bw}(\tau\alpha)_b S(t) + (AH)_{rw}(\tau\alpha)_b S(t) + (UA)_{aw} + NA_c F_{R,N} \\ I(t)(\tau_o\alpha_o)\left[\frac{1-(1-K_K)^N}{NK_K}\right] + \left[NA_c U_{1,N}\left[\frac{1-(1-K_K)^N}{NK_K}\right] + (UA)_{aw}\right]T_a \end{array}\right\} \quad (20)$$

and

$$f_2(t) = 0 \quad (21)$$

Then solving the Eq. 10 and 11 using the Matlab, the temperatures T_w, T_{rb} and T_p can be evaluated. After knowing the value of T_w and T_p, T_r can be evaluated by using the Eq. 9.

Thermal Load Levelling

Thermal Load Levelling (TLL) gives an idea about the fluctuation of temperature inside the greenhouse. The room temperature (T_r) is a function of time, the fluctuation in room temperature plays a vital role for plant health. The TLL for a greenhouse can be defined as:

$$TLL = \frac{T_{r,max} - T_{r,min}}{T_{r,max} + T_{r,min}} \quad (22)$$

For thermal heating of greenhouse TLL should be minimum for minimum fluctuation i.e., the minimum value of the numerator and maximum value of the denominator in Eq. 22 (Singh and Tiwari, 2000).

Results and Discussion

Equation 10 and 11 have been computed by using Matlab for a given design parameters of Table 1 and climatic parameters as shown in Fig. 2 and 3. After knowing the unknown constants, various temperatures namely plant (T_p), room (T_r), water temperature (T_w) and rock bed (T_{rb}) have been evaluated and the variation of these temperatures has been shown in Fig. (4-6). For comparison,

Table 1: Input parameters used for the computation

Parameters	Values	Parameters	Values	Parameters	Values
$(\tau\alpha)_b$	.112	A_b	24 m^2	F'	0.85
h_b	5.7 W/m^2°C	h_{bw}	100 Wm^{-2}°C	U_L	6 Wm^{-2}°C
A_p	72 m^2	h_p	15 W/m^2°C	γ_p	0.10
$\sum h(t)A_i$	70.88 m^2	V	60 m^3	$\dot{m}$	0.035 kg sec^{-1}
N_o	1	A_d	2 m^2	$(\rho)_{rb}$	2600 kg m^{-3}
h_d	1 Wm^{-2}°C	V_w	2.16 m^3	F_p	0.80
$(\rho)_w$	998 kg m^{-3}	$(C_p)_w$	4190 J kg^{-1}°C	M_p	1000 kg
ε	10%	V_{rb}	0.24 m^3	τ	0.65
$\tau_o\alpha_o$	0.8	A_c	2 m^2	$(C_p)_{rb}$	800 J kg^{-1}°C
K_K	0.0067	F_r	0.820		

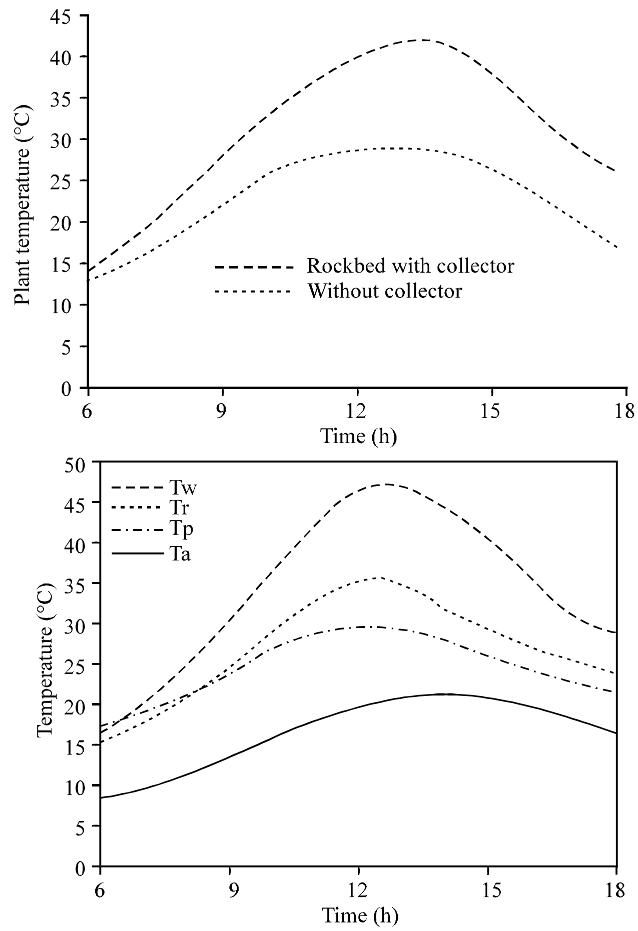


Fig. 4: Hourly variation of (a) plant temperature in a gren house without collector and rockbed with collector (b) plant, room, water and ambient air temperature

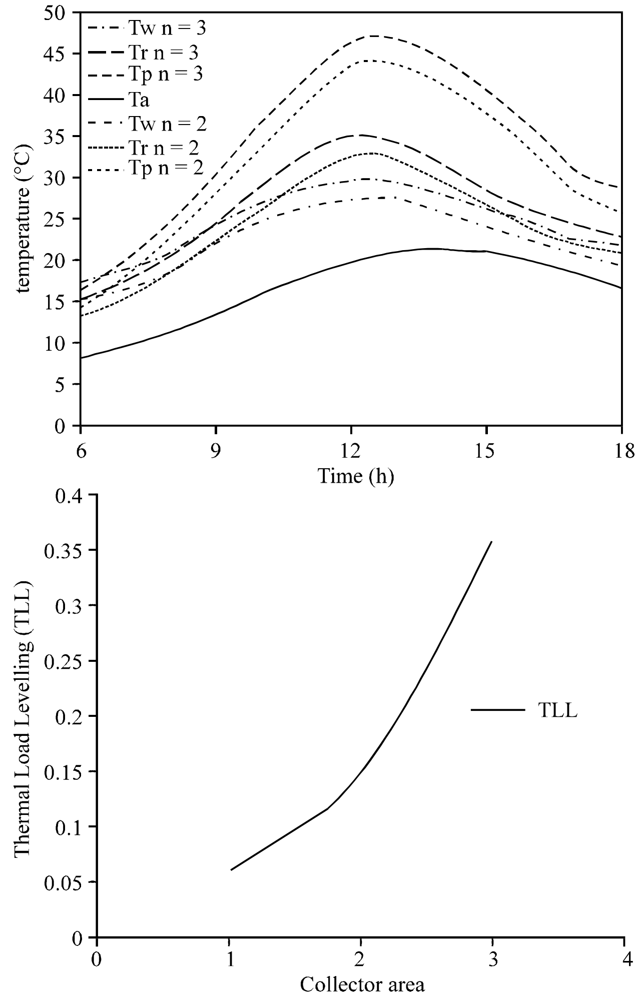
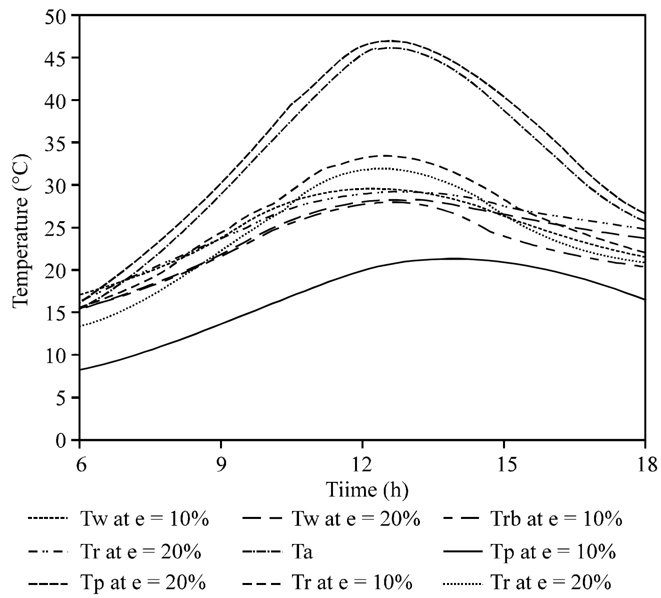


Fig. 5: Effect of (a) collector area on hourly variation of plant, room, water and ambient air temperature (b) collector area on thermal loud levelling TLL

the plant temperature with rockbed and without rockbed has also been shown in Fig. 4a. It can be observe that there is a significant rise in the plant temperature due to collector with rockbed as shown in Fig. 4a. The hourly variation of plant (T_p), room (T_r), ambient air (T_a) and water temperature (T_w) with rockbed have been shown in Fig. 4b. It can be observe that there is a significant rise in the plant temperature when collector is used this might be due to additional thermal energy available from the collector as shown in Fig. 4. It is clear that the plant temperature (T_p) is higher than room temperature because plant receives direct as well indirect thermal energy. The effect of collector area on hourly variation of plant temperature, room temperature and water temperature is shown in Fig. 5a. It can be seen from the figure that due to increase of collector area from N = 2 to 3 plant temperature (T_p), room air temperature (T_r) and water temperature (T_w) increases.

Figure 5b shows the effect of collector area on thermal load levelling. Thermal load levelling gives an idea of the fluctuations inside a greenhouse. It is important to observe from the figure, that thermal load levelling increases with an increase of collector area for thermal heating of the greenhouse.



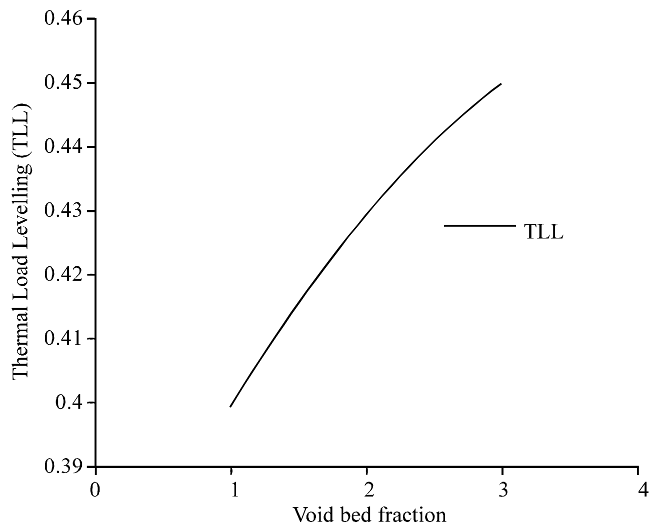


Fig. 6: Effect of (a) void bed friction on hourly variation of plant, room, water, rock bed and ambient air temperature (b) void bed friction on thermal load leveling TLL

Figure 6a shows the effect of void bed fraction on hourly variation of plant temperature, room temperature, water temperature and rock bed temperature. This shows that the plant temperature (T_p), room air temperature (T_r), water temperature (T_w) decreases with the increase of void bed fraction while rock bed temperature increases. Figure 6b shows the effect of void bed fraction on thermal load levelling. It can be observe from the Fig. 6, that thermal load levelling increases with the void bed fraction for thermal heating of the greenhouse.

Conclusions

On the basis of present study, it has been observed that the collector with packed bed gives the better performance in the terms of plant temperature, room air temperature, water temperature (Fig. 4) and thermal load levelling (Fig. 5b and 6b).

Nomenclature

A_i: Area of walls and roofs of greenhouse
A_d: Area of door (m^2)
A_b: Area of greenhouse floor (m^2)
A_{bs}: Area of bottom side (m^2)
A_c: Area of collector (m^2)
A_p: Total surface area of plants (m^2)
C: Specific heat (J kg^{-1}°C)
F_R: Collector heat removal factor
F': Collector efficiency factor
F_p: Fraction of solar energy falling on the plants
h_d: Overall heat transfer coefficient from door to ambient air (Wm^{-2}°C)
h(t): Overall heat transfer coefficient from room air to ambient air through canopy (Wm^{-2}°C)
h_p: Convective heat transfer coefficient from plant to room air (Wm^{-2}°C)
h_b: Convective heat transfer coefficient from ground to room air (Wm^{-2}°C)
h_{bw}: Convective heat transfer coefficient from ground to water (Wm^{-2}°C)
h_v: The volumetric heat transfer coefficient between bed and the fluid (Wm^{-2}°C)
I(t): Total solar radiation available on collector (W)
I: Total radiation on different walls and roofs of greenhouse.
$\dot{m}$: Flow rate (kg s^{-1})
M_w: Mass of the water (kg)
M_p: Mass of the plant (kg)
N: Number of collectors
N_o: Number of air changes
$\dot{Q}_u$: Rate of useful thermal energy supplied by ground collector to greenhouse (W)
S(t): Total solar radiation available on greenhouse canopy cover (W)
t: Time (s)
T: Temperature (°C)
T_a: Ambient air temperature (°C)
T_b: Floor temperature (°C)
T_w: Water temperature (°C)
T_{rb}: Temperature of rock bed (°C)
T_p: Plant temperature (°C)
T_r: Room air temperature (°C)
U: Overall heat loss or gain (Wm^{-2}°C)
U_t: Overall heat loss (Wm^{-2}°C)
U_L: Overall heat loss coefficient of collector (Wm^{-2}°C)
V: Volume of greenhouse (m^3)
V_w: Volume of water (m^3)
V_{rb}: Volume of rock bed (m^3)

Greek Letters

α: Absorptivity
τ: Transmissivity of canopy cover

γ: Reflectivity
ε: Bed void fraction
$\tau_o\alpha_o$: Transmittance-absorptance product
$(\rho C_p)_w$: Heat capacity per unit volume of the water (J/m^{-3}°C)
$(Pc_p)_{rb}$: Heat capacity per unit volume of the rock bed (J/m^{-3}°C)

Subscripts
a: Ambient air
b: Floor
bs: Bottom side
p: Plant
r: Room
w; Water

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