Performance Evaluation of Greenhouse having Passive or Active Heating in Different Climatic Zones of India

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ABSTRACT

This study was carried out to determine the performance of different shapes of greenhouses having equal floor area as well as the central height. A numerical analysis has been carried out using Matlab and Borland C++ corresponding to the climatic conditions of five different climatic zones of India, represented by New Delhi (28.5^0 latitude), Kolkata (22.5^0 latitude), Jodhpur (26.3^0 latitude), Chennai (13.0^0 latitude) and Srinagar (34.5^0 latitude). The plant, room air and water temperature have been evaluated with solar collector. Numerical computations have been carried out for a typical winter day of different climatic zones of India. A total of three types of greenhouse (even span, uneven span and modified IARI) with the same cross-section (6 m×4 m×3 m), were selected and thermal load leveling for different climatic zones were calculated. Greenhouse with combination of phase change material (PCM) and insulation as a north wall is also evaluated for cold climatic zone of Srinagar for thermal heating. Based on the analysis it is inferred that uneven span greenhouse is most suitable from heating point of view.

Keywords: Flat plate collector, greenhouse, phase change material, solar energy, thermal modelling

1. INTRODUCTION

Greenhouses provide a suitable environment for the intensive production of various crops. They are designed to control solar radiation, temperature, humidity and carbon dioxide levels in the aerial environment. The availability of solar radiation and its daily and yearly distribution has a tremendous influence on productivity and quality of plant growth and also on comfort living (Kania and Giacomelli, 2001). The greenhouse air temperature mainly depends on the distribution of solar radiation after transmission through the greenhouse cover which in turn depends on shape and size of greenhouse, motion of the sun and weather conditions (Tiwari and Goyal, 1998). Greenhouse's design, orientation and type of glazing will affect the amount of light transmitted into the structure (Giacomelli and Roberts, 1993). The design and selection of a controlled environment greenhouse depends upon the climatic conditions of each zone and plants requirement. India has six climatic zones on the basis of rainfall, relative humidity, ambient air temperature and insolation. These zones are, hot and dry (Jodhpur), warm and humid (Chennai), moderate (Bangalore), cold and cloudy (Srinagar) and composite (New Delhi) (Bansal and Minke, 1988).

The temperature inside the greenhouse can be increased and decreased as per heating and cooling of the greenhouse air. Heating of greenhouses is one of the most important activities during winter season and it is an essential requirement for proper growth and development of winter growing crops (Tiwari, 2003). Heating of a greenhouse can be accumulated either by passive or active mode. Passive mode uses the sun's rays to heat a surface inside the greenhouse directly, storing the heat in a mass of concrete, rock, or water if required Ismail and Goncalves (1999), Abak et al. (1994). In passive mode greenhouse temperatures at different layers of basement including air gap, phase change material (PCM) and soil have also been estimated by Kumari et al., (2006 a). In an active mode, an additional thermal energy is fed inside greenhouse from air heating system in addition to direct thermal heating. Thermal heating of greenhouses using the active method has been investigated by many researchers, Kurpaska and Slipek (2000), Santamouris et al. (1996), Connellan (1986). Bargach et al. (1999) studied flat plate collectors to improve the inside greenhouse microclimate. Kumari et al. (2006 b) studied the performance of a greenhouse integrated with solar collector for thermal heating. A very useful method for evaluation of the whole solar domestic hot water (SDHW) system combining solar collectors, pipelines, heat exchangers and accumulation, up to the water outlet points yielding 10% accuracy of temperature prediction for Central-East European climatic conditions was done by Wójcicka-Migasiuk and Chochowski (2000). The location of the heating pipes for greenhouse heating was investigated by Popovski (1986) who concluded that a low location of the heating pipes has significant advantages, since it minimises radiation to the transparent cover and maximises radiation to the crop, while reducing the light occultation and the direct radiation exchanges with outside. Hussaini and Suen (1998) used shallow solar ponds as a heating source for greenhouses in cold climates.

The objective of the present paper is to evaluate the distribution of solar radiation (considering area of a section), for three different shapes of the greenhouse with the same floor area (6 m × 4 m) and the same central height (3 m). Analysis has been carried out for different climatic zones of India using passive or active modes in the greenhouse heating. It has been inferred that the uneven span greenhouse is most suitable from heating point of view.

2. MATERIALS AND METHODS

2.1. Place

Depending upon the importance of the location from an agricultural point of view, five locations were selected, as given in Table 1, for the present study.

Table 1 Locations of the places selected for the present study

Place	Longitude (deg)	Latitude (deg)
Delhi	77.20	28.58
Srinagar	74.83	34.08
Jodhpur	73.02	26.30
Kolkata	88.33	22.53
Chennai	80.18	13.00

2.2. Shapes of Greenhouse

In the present study three shapes as shown in Fig. 1 have been considered (even, uneven, modified IARI) and the orientation is always in the east–west direction, Tiwari and Goyal (1998), Tiwari et al. (2003). The various design parameters of the greenhouses have been given in Table 2.

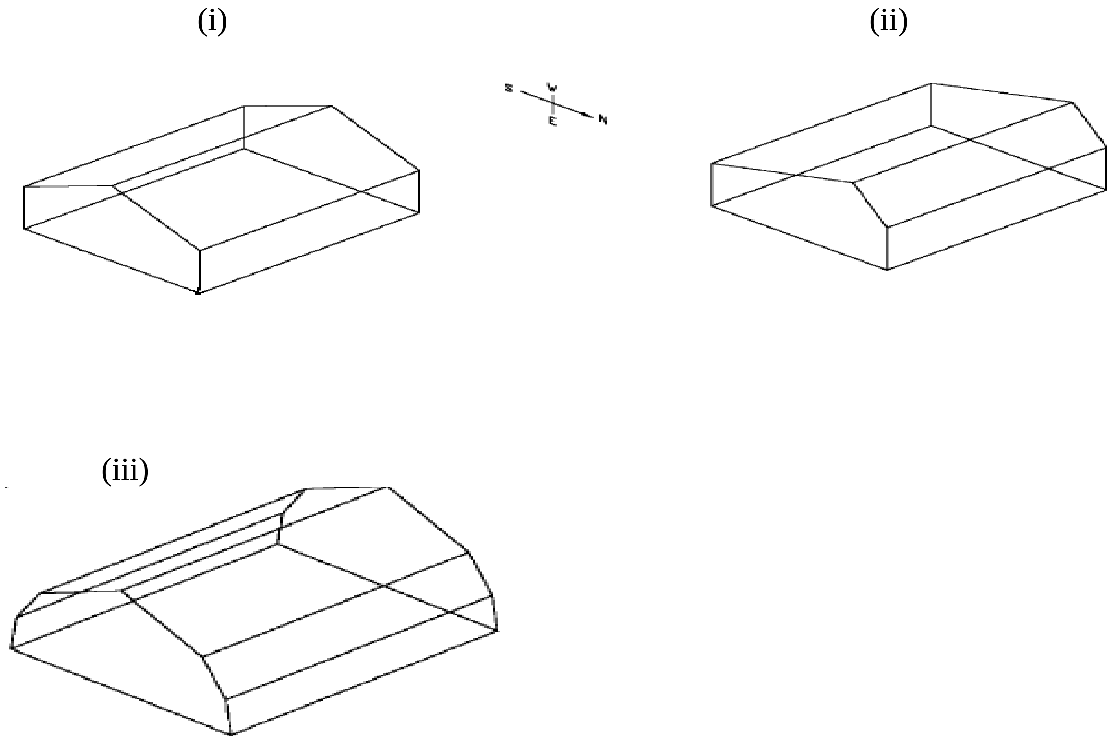

Fig. 1 Sectional distribution of different shapes of greenhouse
(i) Evenspan (ii) Uneven span (iii) Modified IARI

Table 2 Design parameters of different greenhouses

	Even span	Uneven span	Modified IARI
Length of greenhouse(m)	6.00	6.00	6.00
Width of greenhouse(m)	4.00	4.00	4.00
Central height of greenhouse(m)	3.00	3.00	3.00
Width of South wall/North wall(m)	1.80	1.80	1.23
Beta angle of South wall/North wall(deg)	90^{o} for both	90^{o} for both	87^{o} and 93^{o}
Beta angle of South roof/North roof (deg)	$31^{o}/149^{o}$	$21^{o}/159^{o}$	$54^{o}/126^{o}$
Width of South roof/North roof(m)	2.33 for both	3.35/1.48	1.47 for both
Beta angle of South roof (2nd)/North roof (2nd)			9^{o} / 171^{o}
Width of South roof (2nd)/North roof (2nd) (m)			1.22 for both

Beta angle is the angle between the plane and horizontal surface in the clockwise direction.

2.3. Calculation of Solar Altitude and Solar Azimuth Angles

To calculate the sun angles required values of declination angle (δ), hour angle (ω), solar altitude (α) and solar azimuth (γ) at different time of the day for a typical day winter month were calculated by using the following expression Tiwari (2002).

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right],$$

$$\omega = (ST - 12)15^\circ,$$

$$\sin\alpha = \cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi$$

or

$$\alpha = \sin^{-1}(\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi),$$

$$\cos\gamma = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi}$$

or

$$\gamma = \cos^{-1}\left(\frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi}\right)$$

where is: ST – solar time

A computer program has been made in Borland C++ to calculate various angles. For calculations, local time is taken as solar time (ST).

2.4. Calculation of Total Solar Radiation on the Greenhouse

The total solar radiation incident on a surface consists of beam solar radiation, diffuse solar radiation and solar radiation reflected from the ground and the surroundings. These were evaluated by using the following expressions:

R_b is defined as the ratio of flux of beam radiation incident on an inclined surface to that on a horizontal surface.

$$R_b = \frac{\cos\theta_i}{\cos\theta_Z},$$

where θ_Z and θ_i are the angles of incidence on the horizontal and inclined surfaces respectively.

R_d is defined as the ratio of the flux of diffuse radiation falling on the tilted surface to that on the horizontal surface.

$$R_d = \frac{1+\cos\beta}{2}$$

R_r is the reflected component comes mainly from the ground and other surrounding objects.

$$Rr = \frac{1-\cos\beta}{2}$$

where β is the inclination (slope) of the surface.
The total radiation on a surface of arbitrary orientation is calculated by using Liu and Jordan (1962),

$$I_T = I_b R_b + I_d R_d + \rho R_r (I_b + I_d)$$

where R_b , R_d and R_r are known as conversion factors for beam, diffuse and reflected components respectively and ρ is the reflection coefficient of the ground.

Different steps were taken to calculate the total solar radiation (as shown in the flow diagram)

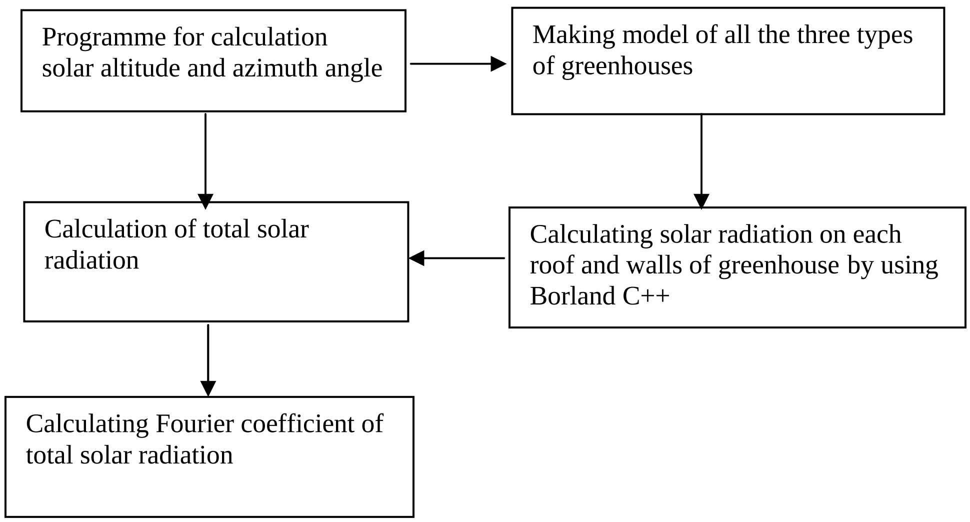

Fig. 2 Flow chart to calculate the total solar radiation.

After knowing beam and diffuse radiation on horizontal surface, total radiation on a surface of arbitrary orientation was calculated by Liu and Jordan formula. Total solar radiation (S_t) on the greenhouse is total sum of solar radiation falling on different sections (each wall and roof) of the greenhouse.

or

$$S_t = \sum_{i=1}^{6} I_{T\,i} A_i$$

where

$$I_{T\,i} = \sum_{i=1}^{6} I_b R_b + I_d R_d + \rho R_r (I_b + I_d)$$

2.5. Fourier Series

Fourier series is an expansion of a periodic function f(x) in terms of an infinite sum of sine and cosine terms. Fourier series make use of the orthogonality relationships of the sine and cosine functions. The computation and study of Fourier series is known as harmonic analysis.

The motion of a body is called periodic if its motion is repeated again and again after equal interval of time, i.e. if at equal intervals of abscissa x, the value of each ordinate f(x) repeats itself. For instance f(x) = f(x + t) for all x, then y = f(x) is called a periodic function having period T. Also $\sin x$ and $\cos x$ are periodic functions having a period 2π. Mathematically it is expressed as

$$f(t) = A_o + A_1 \cos\omega t + A_2 \cos 2\omega t + A_3 \cos 3\omega t ------------ A_n \cos n\omega t$$
$$+ B_1 \sin\omega t + B_2 \sin 2\omega t + B_3 \sin 3\omega t ------------------------ B_n \sin n\omega t \quad (1)$$

or $f(t) = A_o + \sum (A_n \cos n\omega t + B_n \sin n\omega t)$ (2)

where $\omega = \dfrac{2\pi}{T}$

In complex form the periodic function or Fourier series can also be expressed as follows;

$A_n \cos n\omega t + B_n \sin n\omega t$

= A_n (Real part of $e^{in\omega t}$) + B_n (Real part of $-ie^{in\omega t}$)

= Real ($A_n e^{in\omega t}$) $- i$ Real ($B_n e^{in\omega t}$)

= Real {[$A_n - iB_n$] $e^{in\omega t}$ }

= Real $\sqrt{(A_n{}^2 + B_n{}^2)} e^{in\omega t} e^{-i\phi_n}$

= Real C_n $e^{in\omega t} e^{-i\phi_n}$ (3)

where

$C_n = \sqrt{(A_n{}^2 + B_n{}^2)}$, is called the complex Fourier coefficient of f(t)

and

$\phi_n = \tan^{-1}\left(\dfrac{B_n}{A_n}\right)$, is called Phase factor.

Since solar radiation and ambient air temperature are periodic in nature the parameters depending on these can also be represented mathematically in the form of Fourier series (Threlkeld, 1970; Baldasano et al., 1998). These can be represented as

$$S(t) = S_{to} + \mathrm{Re} \sum_{n=1}^{6} S_{TN} e^{in\omega t} \quad (4)$$

and

$$T_a = T_{ao} + \mathrm{Re} \sum_{n=1}^{6} T_{AN} e^{in\omega t} \quad (5)$$

where,

$T_{AN} = T_{an} e^{-i\psi_n}$, $S_{TN} = S_{tn} e^{-i\phi_n}$, $\psi_n = \tan^{-1}\left(\frac{B_n}{A_n}\right)$ and $\phi_n = \tan^{-1}\left(\frac{B_n}{A_n}\right)$

Since first six harmonic terms are sufficient (Khatry et al., 1978) to reproduce the original functions to a very good extent, only first six harmonics were considered in all the expressions.

2.6. Material of Investigation

2.7.

In this, greenhouse is usually a covered structure of plastic film, which is transparent to short wavelength radiation and opaque to long wavelength radiation. The solar radiation, S(t), is incident on the canopy of the greenhouse. A fraction of the solar energy $\{\gamma S(t)\}$, is reflected back from the canopy and a part of the remaining 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 the incident solar radiation, $\alpha_n F_n (1-\gamma_n)\tau S(t)$, is absorbed and the rest is conducted. There are convective and radiative losses from the surface to the room air. An amount given by $\{\alpha_g (1-F_n)(1-\gamma)\tau S(t)\}$ is reflected from the floor and $\{ \alpha_g (1-\gamma_g)(1-F_p)(1-F_n)(1-\gamma)\tau S(t) \}$ is absorbed by the floor.

Figure 3(a) shows a cross-sectional view of a passive thermal heating of an even span greenhouse. Solar radiation, after reflection from greenhouse cover, is transmitted inside the greenhouse. The solar radiation falling on north wall may be reflected, conducted or transmitted depending upon the material of north wall. The radiation falling on the floor of the greenhouse and reflected radiation from north wall may be utilized to heat the greenhouse air temperature. The distribution of solar radiation on north partition wall and floor also depends upon the width and the height of the greenhouse. The transmitted solar radiation through north canopy cover is generally significant during the winter month. This can be retained inside the greenhouse by providing brick north wall and more energy can be stored using phase change material with this wall (Tiwari, 2002).

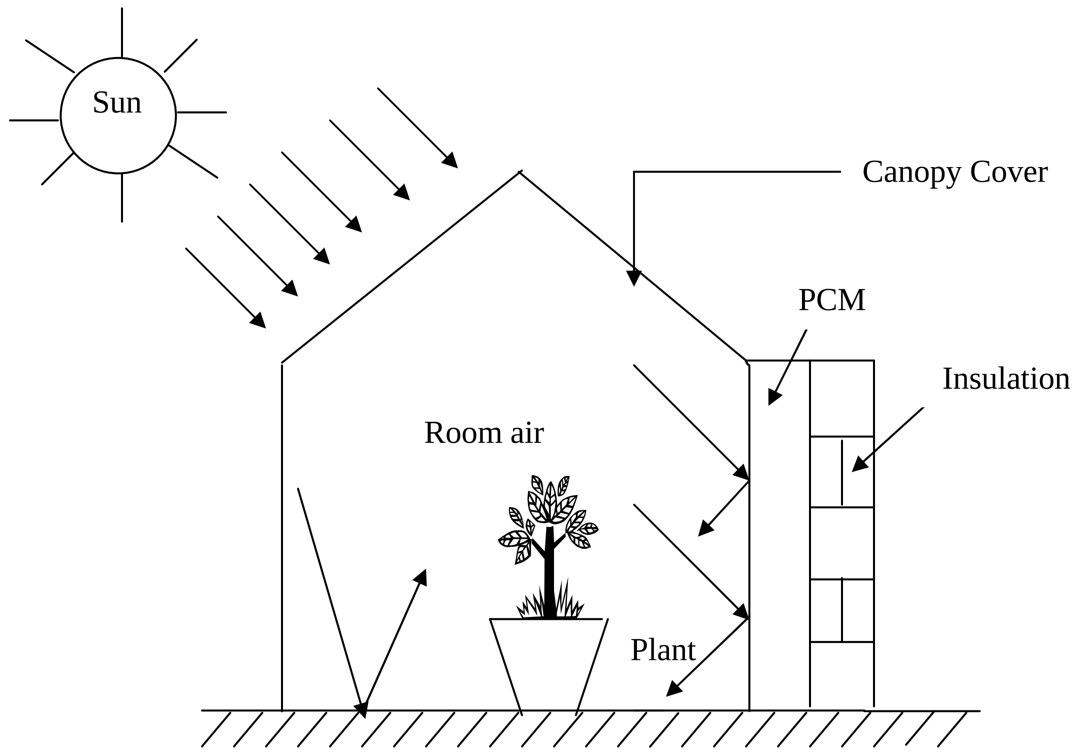

Figure 3(a). Schematic view of greenhouse with insulated PCM north wall.

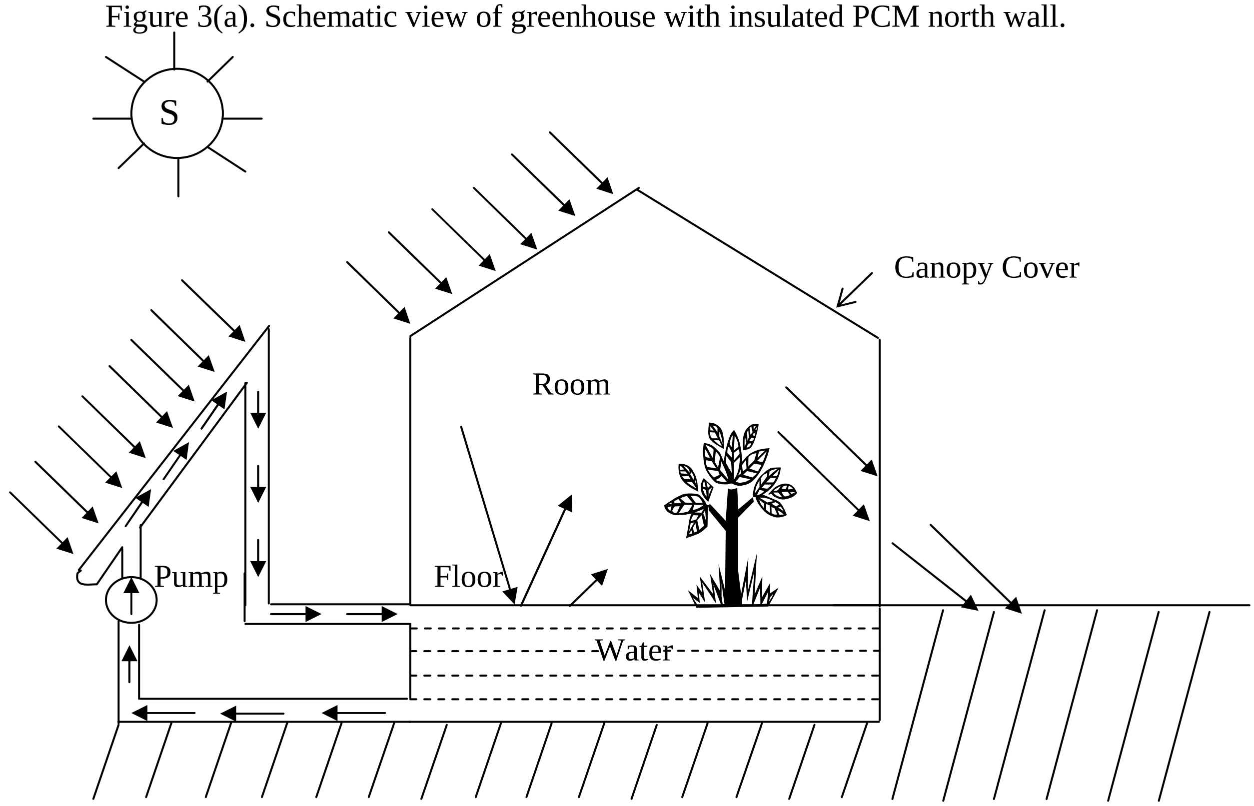

Figure 3(b). Schematic view of greenhouse with flat plate collector.

In figure 3(b) the absorbed energy is transferred to room air and water below the floor. The function of flat plate collector (FPC) is to absorb maximum possible solar radiation incident on it through the glazing, to emit minimum heat, to the atmosphere and downward, through the back of casing, and to transfer the retained heat to the fluid. 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 28.53^0 for New Delhi to receive maximum solar radiation (Tiwari, 2002). This angle is different for each location as it depends on the location.

The passive and active modes used in the even span greenhouses, shown in figures 3(a) and 3(b), have been analysed earlier for the composite climate of Delhi (Kumari et al., 2006 c, 2006 b). In this paper, thermal modeling for three shapes of greenhouse, shown in figure 1, with PCM north wall (fig. 3 (a)) is presented for cold and cloudy climatic conditions of Srinagar. Greenhouse integrated with a solar water heater (fig. 3 (b)) is modeled for all three shapes of the greenhouse for five different climatic zones of India.

3. THEORY

3.1. Definition of Thermal Load Leveling (TLL)

Due to time dependent nature of the room temperature (T_r), the fluctuation in room temperature plays a vital role.

The thermal load leveling can be defined as follows:

$$\text{TLL} = \frac{Q_{\max} - Q_{\min}}{Q_{\max} + Q_{\min}} \tag{6}$$

where,

$Q = M_a C_a (T_r - T_0)$

Q is the heat content in the greenhouse (J)

T_0 is the reference temperature at 0C

T_r is the room temperature (C)

Substituting the value of Q in Equation 6, the expression for TLL becomes,

$$\text{TLL} = \frac{M_a C_a (T_r - T_0) - M_a C_a (T_r - T_0)}{M_a C_a (T_r - T_0) + M_a C_a (T_r - T_0)}$$

or

$$\text{TLL} = \frac{T_{r,\max} - T_{r,\min}}{T_{r,\max} + T_{r,\min}} \tag{7}$$

The thermal load leveling (TLL) is a relative index to represent the fluctuation of room air temperature inside the greenhouse. For thermal heating of the greenhouse with minimum fluctuations the TLL should be minimum, i.e. the value of numerator, (Tr, max-Tr, min), should be minimum and for the denominator, (Tr, max+Tr, min), the value should be maximum in the Equation (7).

4. RESULTS AND DISCUSSION

The hourly variation of plant (T_p), room (T_r) and ambient air (T_a) temperature for even span, uneven span and modified IARI shapes of greenhouse with PCM north wall for a very cold climate of Srinagar has been shown in figures 4(a) and 4(b) respectively. Computations have been made from heating point of view to find best suited shape and methods which includes PCM north wall and flat plate collector. Total solar radiation is calculated theoretically by Liu and Jordan method for a clear day in the month of January.

Figures 4 show the hourly variation of plant and room air temperature for three different shape with PCM north wall (fig. 3(a)).It is evident from the figure 4 that uneven span greenhouse with PCM north wall gives highest hourly variation of plant and room temperature for Srinagar. One can observe that there is a significant rise in the plant temperature for all three shapes due to PCM north wall as shown in figure 4(a) in comparison to ambient air temperature. It is due to minimum heat loss from north wall/roof of the greenhouse, as PCM is used with north wall.

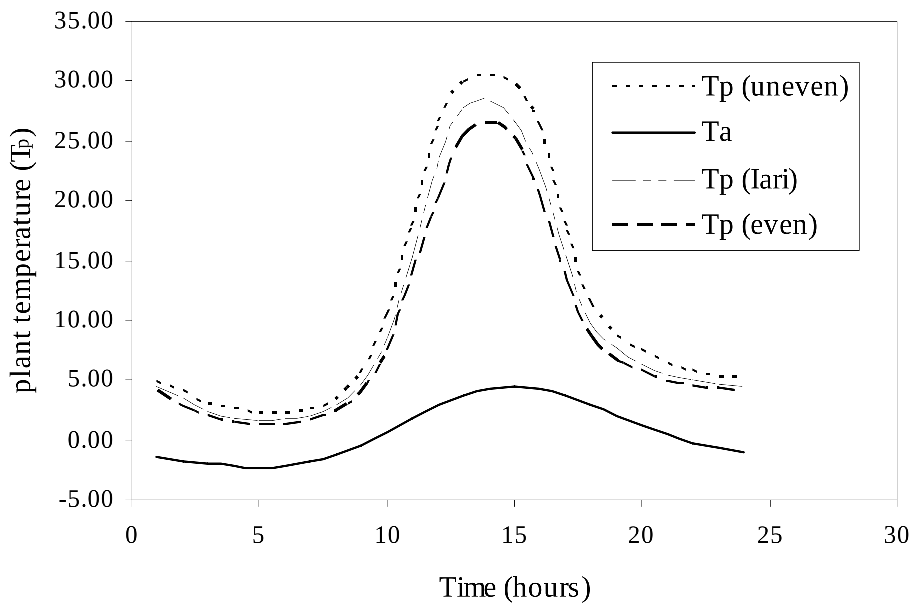

Figure 4 (a). Hourly variation of plant temperature in different shapes of greenhouse (with PCM North wall) at Srinagar.

It is clear that the plant temperature (T_p) is higher than room temperature during sunny hours as expected. It is due to the fact that the plant receives direct as well indirect thermal energy. The result is reverse in the night.

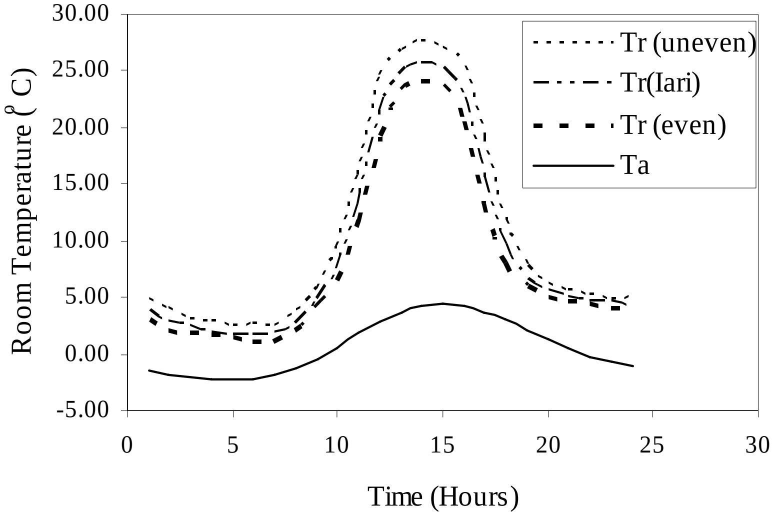

Figure 4 (b). Hourly variation of room air temperature in different shapes of greenhouse (with PCM North wall) at Srinagar.

The hourly variation of plant and room air temperature for three shapes of greenhouse integrated with flat plate collector (fig. 3(b)) has been shown in figures 5(a) and 5(b) respectively. The hourly variation of water temperature below greenhouse floor has been shown in figure 5(c). It shows that uneven span greenhouse has higher temperature than the other two greenhouses. Plant temperature goes to 27^0 C in winter season whereas room air temperature for uneven span greenhouse in figure 5(b) is nearly 25^0 C. It is important to note that the plant and room air temperature is significantly reduced. It is due to fact that the heat loss from canopy cover with PCM north wall is more in the case of active heating (fig. 3(b)). However, the water temperature becomes stagnant during off sunshine hours which can be used for space heating during night hours through a heat exchanger. Since, Srinagar requires heating for the maximum period of the year, hence the uneven span shape of greenhouse should be chosen from heating point of view.

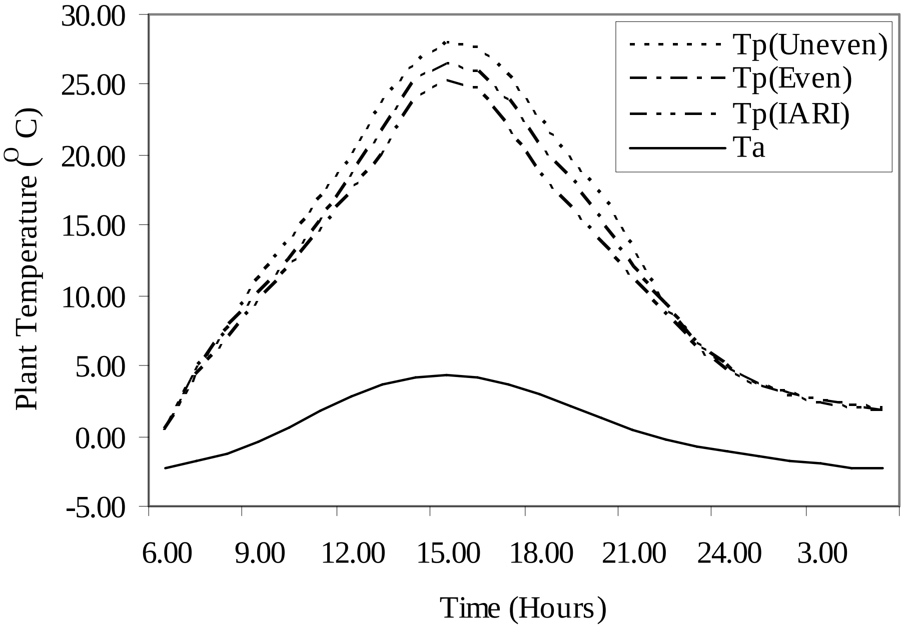

Figure 5 (a). Hourly variation of plant temperature in different shapes of greenhouse (with collector) at Srinagar.

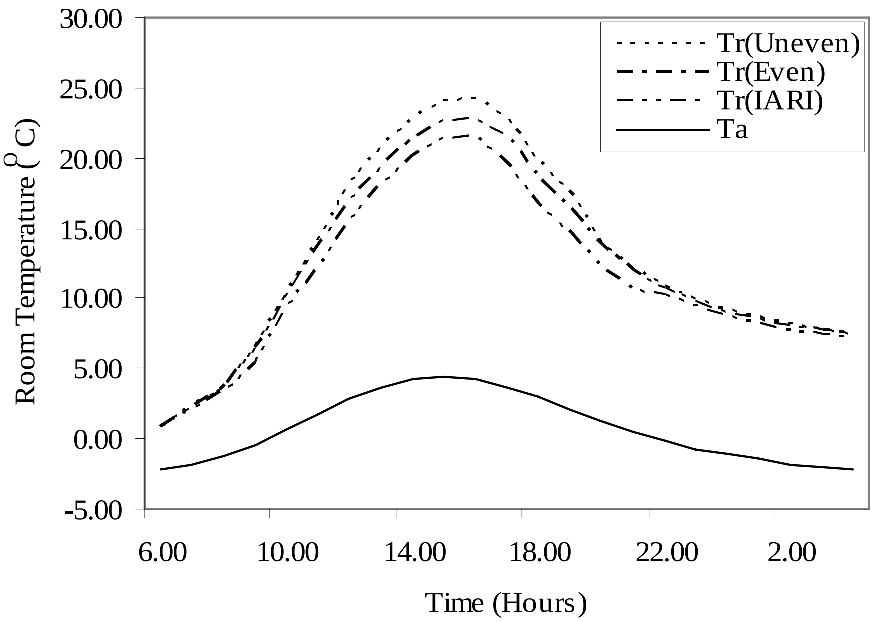

Figure 5 (b). Hourly variation of room air temperature in different shapes of greenhouse (with collector) at Srinagar.

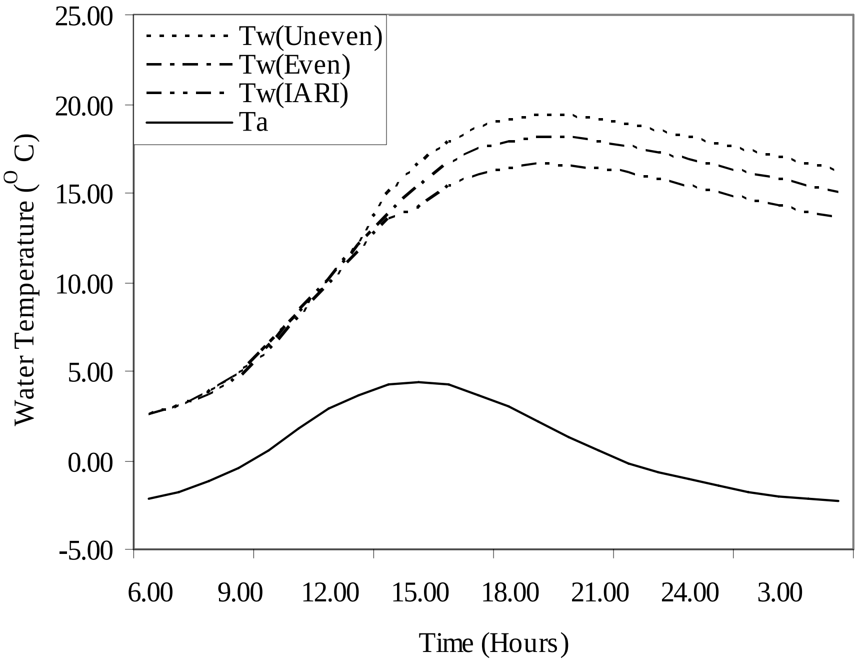

Figure 5 (c). Hourly variation of water temperature in different shapes of greenhouse (with collector) at Srinagar.

Figures 6 show the hourly variations of plant, room air and water temperature with collector area for different shapes of greenhouses for a typical winter day of Kolkata. The annual mean temperature for Kolkata is 26.8^0 C; monthly mean temperatures range from 19 °C to 30 °C (67 °F to 86 °F). Summers are hot and humid and maximum temperatures often exceed 40 °C (104 °F) during May and June. Winter tends to last for only about two and a half months, with seasonal lows dipping to the 12 °C – 14 °C between December and January. In figure 6 plant, room air and water temperature goes higher nearly 50^0 C, 40^0 C and 35^0 C respctively with collector area.

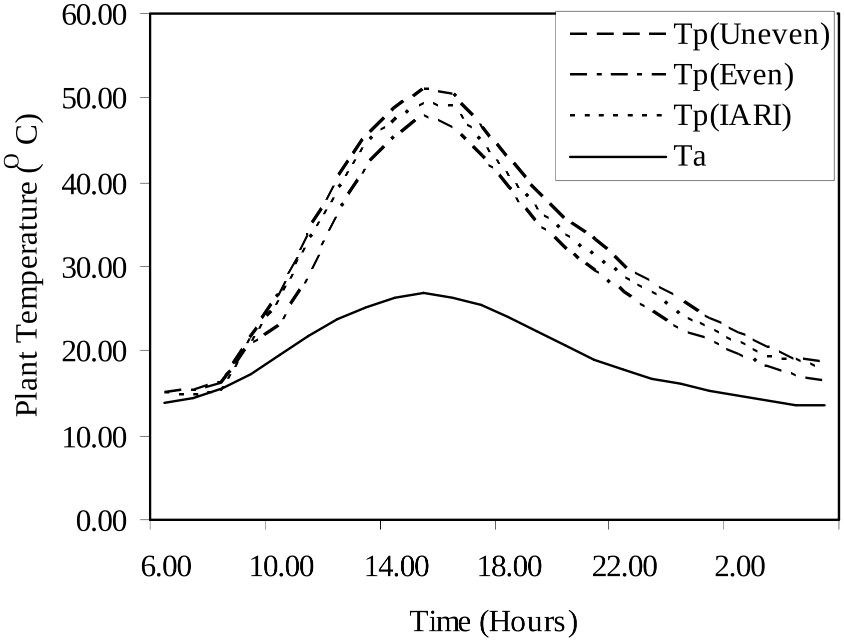

Figure 6 (a). Hourly variation of plant temperature in different shapes of greenhouse (with collector) at Kolkata.

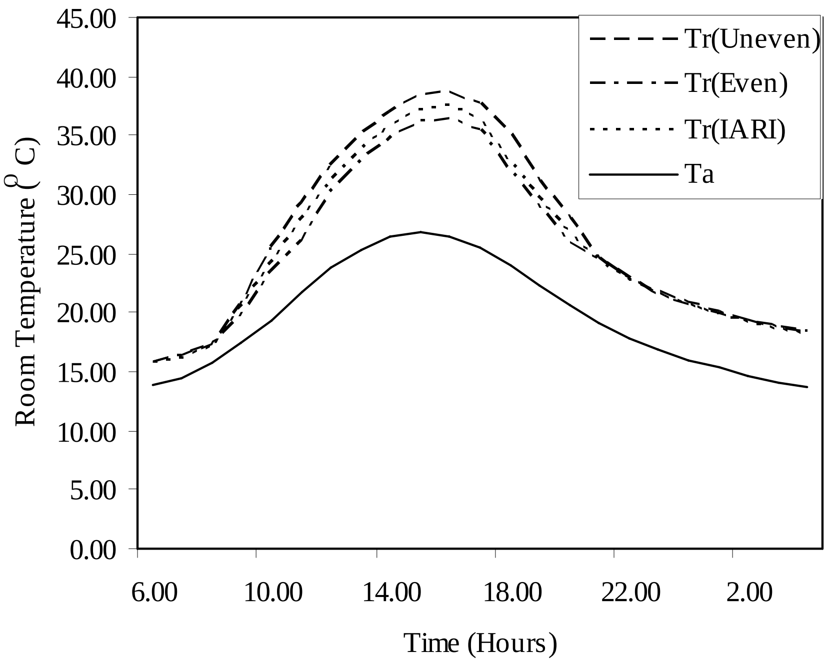

Figure 6 (b). Hourly variation of room air temperature in different shapes of greenhouse (with collector) at Kolkata.

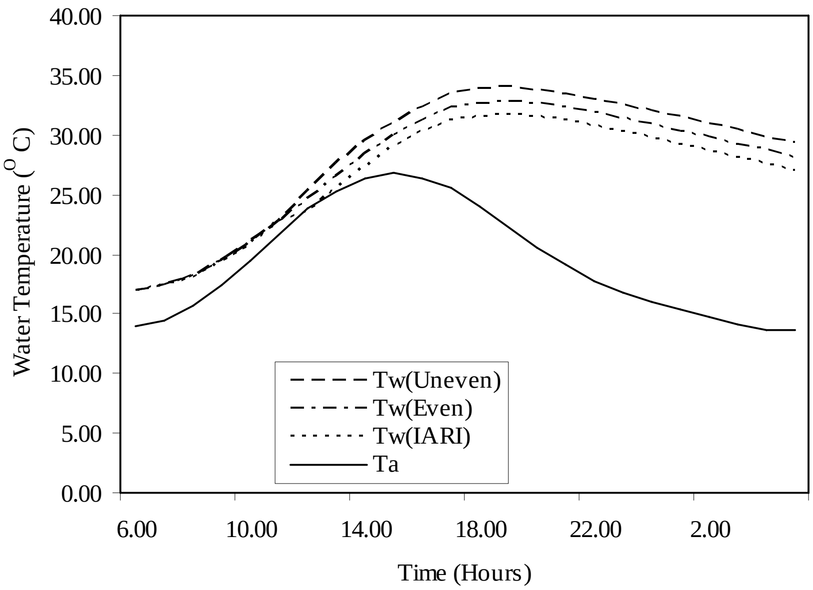

Figure 6 (c). Hourly variation of room air temperature in different shapes of greenhouse (with collector) at Kolkata.

For winter day the maximum and minimum room air temperatures evaluated for different climatic conditions and were used to calculate the thermal load leveling (TLL) using its expression. The results for TLL for the uneven span, even span and IARI type greenhouses are shown in Figures 7 to 9 respectively for different climatic zones. From these figures it is inferred that the TLL is maximum for Srinagar climatic conditions for all shapes of greenhouse. Further it was noted that the TLL for New Delhi and Jodhpur are nearly the same. This indicates that the active thermal heating by the present method is the most suitable for Srinagar in comparison to Kolkata, Delhi, Jodhpur and Chennai.

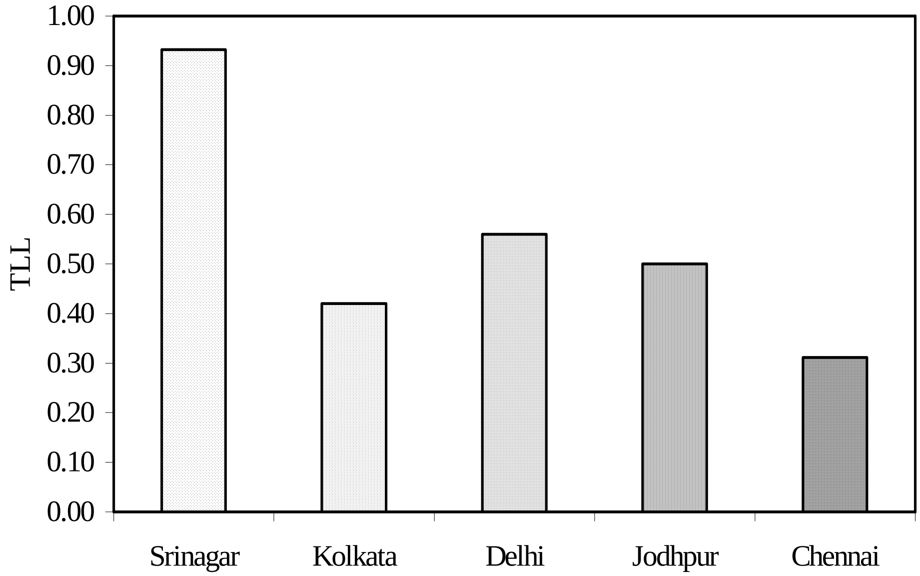

Figure 7. Variation of thermal load leveling (TLL) in uneven span greenhouse for different cities.

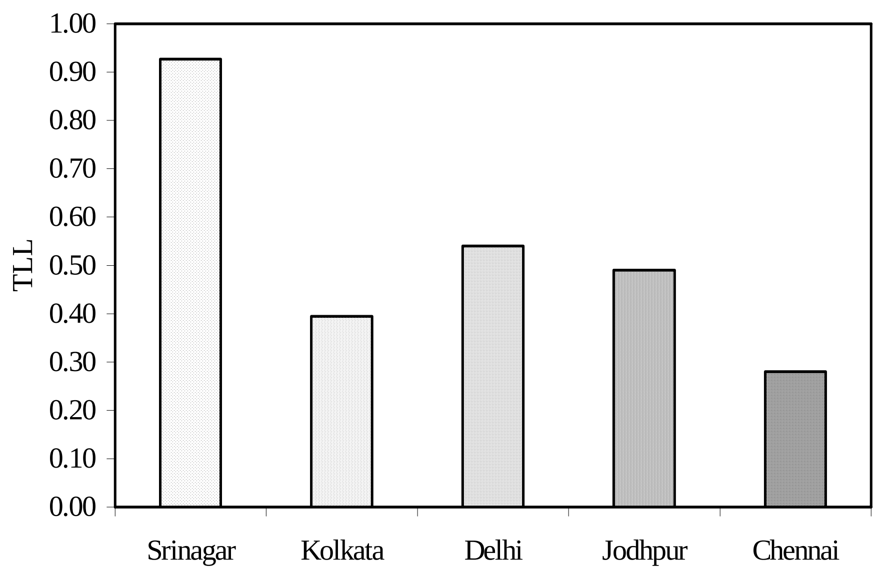

Figure 8. Variation of thermal load leveling (TLL) in even span greenhouse for different cities.

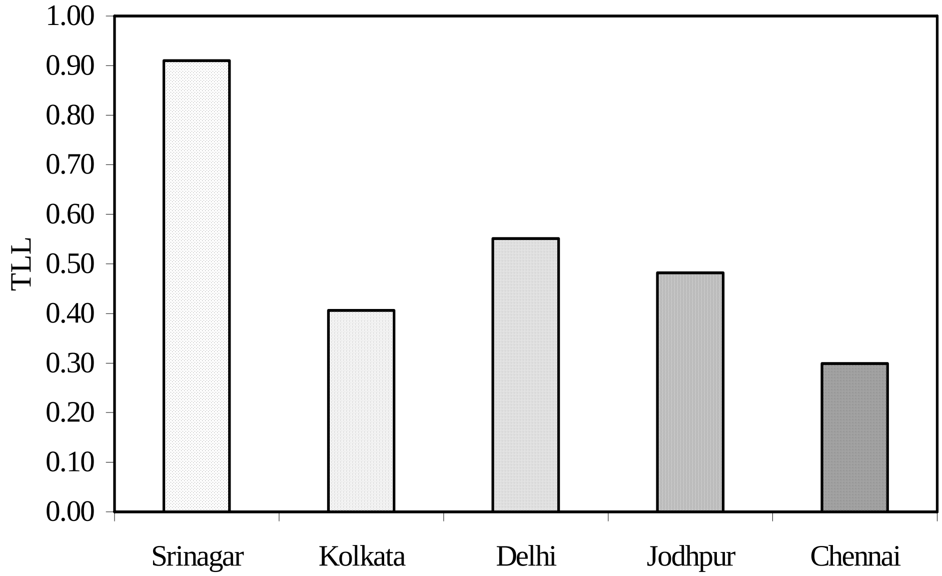

Figure 9. Variation of thermal load leveling (TLL) in IARI greenhouse for different cities.

5. CONCLUSION

For different climatic zones of India, the requirement of heating and cooling load varies with shape. A particular shape may be recommended for each zone, accordingly. For cold and cloudy zone (Srinagar) where heating is the requirement, Uneven span shape greenhouse for both cases i.e. greenhouse with PCM north wall and greenhouse with collector is recommended.

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