On the selection of shape and orientation of a greenhouse for composite climates

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**ABSTRACT**

Five most commonly used single span shapes of greenhouses viz. even-span, uneven-span, vinery, modified arch and quonset type have been selected for comparison. The length, width and height (at the center) are kept same for all the shapes. Total solar radiation input (beam, diffused and ground reflected) to each shape (through each wall, inclined surfaces and roofs) is theoretically computed for east-west and north-south orientations and compared for each month of the year at 31 °N latitude. The total solar radiation available for each shape is then introduced in a developed transient thermal model to compute hourly inside room air temperature for the selected day of the year. Experimental validation is carried out for measured air temperature data for an even-span greenhouse (in which capsicum is grown) at Ludhiana (31 °N and 77 °E), Punjab, India. The predicted and measured values are in close agreement. Even-span or quonset shape in east-west orientation is the best suited for year round applications. Variation in greenhouse shape can cause change up to 3.5-5.5 °C in the inside air temperature during different hours of the day at 31°N latitude.

1. **INTRODUCTION**

In cold climates, higher inside air temperature is required at all the times for maximum plant growth. However, in composite climates, winters are short and mild but summers are long and harsh. Greenhouse effect is desired for only a brief winter period and for rest of the period, excess heat from the greenhouse should be removed by using various cooling technologies (Sethi and Sharma 2007). Total solar radiation received by a greenhouse at a particular time and location depends upon its shape as well as orientation, which ultimately determines the inside air temperature. Various researchers have used different greenhouse shapes along E-W and N-S orientations for raising off-season vegetable or ornamental plants. Modified arch, E-W orientation commercial greenhouse of 179m² area was used (Gauthier et al. 1997) for raising vegetables. Quonset type, E-W orientation greenhouse of 79m² located in Quebec, Canada was used (Bernier et al. 1991) for raising tomatoes. An even span, E-W orientation greenhouse of 24 m² situated at Chandigarh, India was used for raising capsicum (Sethi and Sharma 2007). Quonset shape, N-S orientation greenhouse of 100m² floor area situated at Ludhiana, India (Sethi and Gupta 2004) was used for raising roses. An uneven-span winter greenhouse of 20 m² floor area of E-W orientation situated at Delhi, India (Dutt et al. 1987) was used for growing pot plants. A vinery type high tunnel greenhouse (E-W orientation) located at Israel was used for raising winter vegetables (Albright et al. 1985). A big 1000 m² even-span (E-W orientation) greenhouse located at Agrinion, Greece was used (Santamouris et al. 1994) for the growing roses.

It is observed that five most common shapes of greenhouses have been used for agricultural purposes such as even-span, uneven span, vinery, modified arch and quonset type in both E-W and N-S orientations. These greenhouses were equipped with either heating or a cooling system. In general, a greenhouse receives most of the beam radiation at its floor, which is responsible for the increase in inside room air temperature. Apart from this, greenhouse also receives diffuse and ground reflected radiation from each wall and roof, thus the shape and the orientation of the greenhouse also has some bearing on the greenhouse room air temperature. The selection of optimum shape and orientation of a greenhouse can cause some reduction in the heating and cooling loads of the installed systems thereby saving a lot of cost. In this study, an attempt has been made to select the most suitable shape and orientation of a greenhouse for composite climates on the basis of total solar radiation availability and its effect on the greenhouse room air temperature.

2. **ANALYTICAL APPROACH**

For a realistic comparison, length, width and height of each shape is kept as same viz. 6 m, 4 m and 3m. Each shape is divided into various sections along E-W and N-S orientation.

2.1. **Solar radiation availability on each shape and orientation**

An expression for computing total solar radiation on an inclined surface was given by Liu and Jordon (1960)
Using Eq. 1, $I_i$ has been computed for each section of the selected shape and orientation for each month of a typical day. Beam and diffuse radiation on a horizontal surface is computed for a typical day in each month as discussed by Duffie and Beckman (1991). Hence the total solar radiation on greenhouse canopy cover is

$$S_t = \sum_{i=1}^{n} A_i I_i$$

Where $A_i$ and $I_i$ are the area of $i^{th}$ section and total solar radiation available on $i^{th}$ section. The $S_t$ value thus obtained is then substituted in a thermal model for computing the hourly inside room air temperature for each shape.

3. THERMAL MODELING

$S_t$ after transmission through each wall and roof is received inside the greenhouse at the floor and the plants. Radiation absorbed by the plants is convected and evaporated to the room air, whereas radiation absorbed by the floor is either convected to the room air or lost to the ground by conduction through the floor. The inside room air temperature is raised and various thermal losses occur through the canopy cover, the door and ventilators etc.

3.1 Energy balance equations

Basic energy balance equations for different components of the greenhouse as given by Sethi and Sharma (2007) are as follow

3.1.1 Greenhouse plants

$$a_g \tau S_t = M_c C_p \frac{dT_p}{dt} + h_{pr} A_p (T_p - T_R)$$

The expression for $h_{pr}$ is given in Appendix A Eq A3.

3.1.2 Greenhouse floor

$$a_f (l - a_g) \frac{dT}{dt} = -k A_s \frac{dT}{dx_0} + h_z A_z (T_{x=0} - T_R)$$

The rate of thermal energy conducted in the ground is expressed in a steady state condition as

$$-k A_s \frac{dT}{dx_0} = h_z A_z (T_{x=0} - T_w)$$

Temperature inside the ground after a certain depth ($T_w$) becomes constant and is considered equal to the underground annual temperature $T_a$ beneath the greenhouse floor as discussed by Tiwari and Goyal, (1998). Therefore, Eq. 4a can be written as

$$a_f (l - a_g) \frac{dT}{dt} = h_z A_z (T_{x=0} - T_a) + h_z A_z (T_{x=0} - T_R)$$

3.1.3 Greenhouse room air

Energy balance of the greenhouse room air is shown as

$$A_p h_{pr} (T_p - T_R) + A_g h_z (T_{x=0} - T_R) = m_a C_a \frac{dT_p}{dt} + U_T A_T (T_p - T_a) + h_z A_z (T_R - T_a) + 0.33 N V_s (T_2 - T_a) + V_o$$

Where $U_i$ is the overall heat transfer coefficient of the greenhouse and is computed as shown by Sethi and Sharma (2007).

An expression for $T_p$ is obtained as

$$T_p = \frac{H G \alpha_{eff} S_t + Z T_a + A_g h_{pr} T_p}{Z + A_g h_{pr}}$$

Where $H_G$ and $Z$ are the constant terms introduced for mathematical simplifications as shown in Appendix A Eq A5 and A9. By substituting the expression for $T_p$ in Eq. 3, a first order differential equation of the following form is obtained

$$\frac{dT_p}{dt} + a T_p = f(t)$$

The values of $a$ and $f(t)$ are shown in Appendix A Eq A1 and A2.

The general solution of Eq. 8 is given as

$$T_p = \frac{\int \overline{f(t)} \left(1 - e^{-at}\right)}{a} + T_p e^{-at}$$

An already developed computer program in C++ is used to compute the hourly room air and plant temperature using Eq. 7 and 9.

4. EXPERIMENTAL DETAILS

An E-W orientation, even-span greenhouse (24 m² floor area) having P E as cover was constructed at Chandigarh (31°N latitude and 78°E longitude), Punjab, India. Central and side height of the greenhouse was 3 m and 2 m respectively. Solar radiation availability (beam and diffuse) at each section of the greenhouse was measured at each section of the greenhouse during the sunshine hours (for a typical summer and a winter day) with the help of SM 201, CEL solarimeter having a measuring range of 0-1200 Wm⁻². Ambient air and greenhouse room air temperature was recorded at each hour using four calibrated LCD display thermometers (least count of 0.1 °C). One sensor was placed outside the greenhouse in shade (at 1 m height) and remaining three sensors are placed inside the greenhouse at 0.3, 1.0 and 1.5 m height at different locations (shaded from direct sunlight). Plant temperature was recorded with the help of 8868 IR non contact gun type infrared thermometer having temperature measuring range of –20 °C to 315
°C (least count of 0.5 °C). Wind speed inside and outside the greenhouse was recorded using vane anemometer. Relative humidity was measured inside as well as outside the greenhouse using LCD display hygrometers (least count 0.1 %). The sensors were hung in the centre of the greenhouse and near the greenhouse under shade at 1 m height.

5. RESULTS AND DISCUSSION

5.1 Effect of shape on solar radiation availability
Total solar radiation availability for each selected shape in each month in E-W orientation is computed and shown in Fig. 1 at 31 °N latitude. It is observed that uneven-span shape greenhouse receives the maximum solar radiation during each month of the year. It is due to the largest south wall (SW), which receives the maximum solar radiation during each month as compared to the SW of other shapes. Although, uneven-span shape has the smallest north roof (NR) but reduction in solar radiation on this roof is not much as compared to the other shapes as north sections do not receive the beam radiation. Computations also show that quonset shape receives the minimum solar radiation during each month of the year. It is observed that all the greenhouse shapes receive lesser amount of solar radiation in winter months but greater in summer months.

The yearly total solar radiation availability for all the shapes in E-W orientation at various latitudes is shown in Fig. 2. The comparison is made (for 31 °N latitude) with reference to the even-span shape greenhouse. Uneven-span shape receives 12.79 % more average radiation as compared to even-span shape. Modified arch shape receives 0.44 % more radiation, whereas vinery and quonset shapes receive 10.42 % and 12.27 % lesser yearly average solar radiation as compared to even-span shape. It can also be considered that although the length, breadth and height for all the greenhouse shapes is same (6m, 4m and 3 m respectively) but due to the difference in the ratio of canopy cover area to the floor area \((A_c/A)\) of each shape, the total amount of solar radiation received on the whole greenhouse would automatically be different for each shape and the solar radiation availability should be a linear function of the canopy area, but this is not true. A comparison between \(A_c/A\) ratio and yearly solar radiation availability for the selected shapes shows that uneven-span greenhouse has 0.88 % more \(A_c/A\) ratio as compared to even-span shape but it receives 12.79 % more radiation. Modified arch has 0.82 % lesser \(A_c/A\) ratio as compared to even-span shape but it receives 0.44 % more radiation. Vinery shape has 15.78 % lesser \(A_c/A\) ratio but it receives 10.42 % lesser solar radiation. Similarly, quonset shape has 16.8 % lesser \(A_c/A\) ratio as compared to even-span shape but it receives 27 % lesser solar radiation. It can thus be concluded that shape of the greenhouse definitely affects the total solar radiation availability on it.

5.2 Effect of orientation on solar radiation availability
A comparison of total solar radiation availability during each month of the year for even-span greenhouse in E-W and N-S orientation is shown in Fig. 3. At 31 °N latitude, N-S orientation of even-span shape receives less solar radiation in winter months (5.39 % lesser in December) but significantly more in summer months (15.88 % more in June) as compared to E-W orientation. This is because in winter the eastern and western side sections in N-S orientation receive less radiation as compared to northern and southern side sections in E-W orientation due to lower altitude angle of the sun. However in summer months, eastern and western side sections in N-S orientation significantly receive more solar radiation as compared to the northern and southern side sections in E-W orientation. Therefore, it can be concluded that E-W orientation should be preferred, as it would provide more radiation in winter but lesser in summer, which is desirable in composite climates. For all other shapes like vinery, modified arch and quonset the trend of solar radiation availability is similar to even-span shape as discussed above.

5.3 Experimental validation
The greenhouse room air and plant temperature is theoretically computed using the design data shown in Appendix A and constants in Table 1 along with the hourly solar radiation availability (for a typical day) and total heat transfer coefficient \((U_c/A)\) for each shape in the model. Computations show that the inside room air temperature for uneven-span shape greenhouse remains about 1.5 to 2.5 °C higher during different hours of the day as compared to the even-span shape as shown in Fig. 4. On the other side, air temperature inside the vinery and quonset shapes is about 2 to 3 °C lower during different hours of a summer day as compared to even-span shape. It can thus be concluded that variation in shape from uneven to quonset can cause 3.5 to 5.5 °C change in the inside air temperature of the greenhouse. Hourly variation in the predicted and measured values of the greenhouse room air temperature along with the ambient air temperature during a typical summer day is shown in Fig. 5. It is observed that the predicted values remain slightly higher than the measured values but are very close to each other showing mean square deviation \((\chi^2)\) of 3.26 percent, which indicates that the developed model is validated for room air temperature.
6. CONCLUSIONS

Based on the results following conclusions can be drawn:

1. Uneven-span shape greenhouse receives the maximum solar radiation during each month of the year. Quonset shape receives the minimum solar radiation during each month of the year at 31°N latitude.

2. Even-span or modified arch shape in East-west orientation should be preferred for year round greenhouse applications at 31°N latitude.

3. Variation in greenhouse shape (from uneven to quonset) can cause up to 3.5 - 5.5 °C drop in the inside air temperature during different hours of the day at 31°N latitude.

APPENDIX A

\[ a = \frac{M}{\varepsilon C_p} \]  

\[ f(t) = H_a \frac{\alpha_p H_p + S_i + U_a T_a}{M H_a} \]  

\[ h_p = h_p + \frac{0.016 \times h_p [p(T_p) - p(T_z)]}{T_p - T_z} \]  

\[ h_a = 2.8 + 3 \nu \]  

\[ H_g = \frac{A_g h_a}{A_g h_a + A_g h_b} \]  

\[ H_p = \frac{A_p h_p + Z}{A_p h_p + Z} \]  

\[ U_p = \left[ \frac{1}{Z} + \frac{1}{A_p h_p} \right]^{-1} \]  

\[ U_g = \frac{A_g h_a + A_g h_b}{A_g h_a} \]  

\[ Z = A_i U_i + h_j A_j + U_i + 0.33 N V \]  

\[ \alpha_r = \alpha_g (1 - \alpha_p) \]

Table 1 Constants used for the validation.

\[ A_i = 1.8 \text{ m}^2 \]  

\[ T_{p_i} = 22^\circ\text{C (summer day)}, 4^\circ\text{C (winter day)} \]  

\[ A = 24 \text{ m}^2 \]  

\[ U = 3.96 \text{ Wm}^{-2}\text{C}^{-1} \]  

\[ A = 100 \text{ m}^2 \]  

\[ \nu = 1 \text{ ms}^{-1} \]  

\[ C = 4190 \text{ J kg}^{-1}\text{C}^{-1} \]  

\[ V = 0 \]  

\[ h_i = 2.8 \text{ Wm}^{-2}\text{C}^{-1} \]  

\[ V = 60 \text{ m} \]  

\[ h_a = 1.0 \text{ Wm}^{-2}\text{C}^{-1} \]  

\[ \alpha_i = 0.30 \]  

\[ \gamma = 0.3, 0.7 \]  

\[ M = 120 \text{ kg} \]  

\[ \epsilon = 0.7 \]  

\[ N = 0 \]  

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Fig. 1 Annual variation of total solar radiation availability for different greenhouse shapes in E-W orientation at 31°N latitude.

Fig. 2 Availability of total solar radiation for all the shapes at different latitudes in E-W orientation.

Fig. 3 A comparison of annual variation in total solar radiation availability for even-span greenhouse in E-W and N-S orientation at 31°N latitude.
Fig. 4. Hourly variation of greenhouse air temperature (during sunshine hours) for different shapes in E-W orientation during a typical summer day (10-06-06) at 31 °N latitude.

Fig. 5. A comparison of measured and predicted values of room air temperatures during different hours of a summer day (10-06-06) at 31°N latitude.

REFERENCES


