Temperature distribution in different zones of the micro-climate of a greenhouse: a dynamic model

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Abstract

This communication presents a dynamic model for determination of plant and the enclosed room air temperature in different zones of the micro-climate of a greenhouse. The numerical analysis and the experimental validation of the model have been done for a typical winter day of the month of December in Delhi, India. The parametric study has been presented for the effects of infiltration (number of air changes/hr), heat capacity of plants (isothermal mass) and greenhouse relative humidity ($\gamma$) on plant and enclosed room air temperatures. It is observed that there is a more significant effect of heat capacity of the plant and the relative humidity on the plant temperature than that on the room air temperature. In addition, there is a marginal temperature difference in different zones of the greenhouse. There is fair agreement between the theoretical and experimental observations of room air temperature.

Keywords: Greenhouse; Solar energy; Micro-climate

Nomenclature

$A_D =$ Area of door (m$^2$)
$A_G =$ Greenhouse floor area (m$^2$)
$A_p =$ Area of foliage (m$^2$)
$A_R =$ Area of roof (m$^2$)
$C_a =$ Specific heat of air (J/kg $^\circ$C)
\( F' \) = Greenhouse efficiency factor
\( h_s \) = Heat transfer coefficient between air and ground \((W/m^2\cdot {}^\circ C)\)
\( h_o \) = Heat transfer coefficient between room air and ambient air through walls \((W/m^2\cdot {}^\circ C)\)
\( h_p \) = Heat transfer coefficient between plant and enclosure air \((W/m^2\cdot {}^\circ C)\)
\( h(t) \) = Overall total heat transfer coefficient from inside room to ambient through walls, floor and canopy cover \((W/m^2\cdot {}^\circ C)\)
\( M_p \) = Heat capacity of plants (mass of plants \times specific heat of plants) \((J/\circ C)\)
\( M_a \) = Heat capacity of enclosed air (mass of air \times specific heat) \((J/\circ C)\)
\( N \) = Number of air changes/h
\( p(T) \) = Partial vapour pressure at temperature \( T \) \((N/m^2)\)
\( S \) = Intensity of solar radiation (hourly average) at time \( t \) \((W/m^2)\)
\( T \) = Greenhouse enclosure room air temperature \((^\circ C)\)
\( T_{lx-o} \) = Temperature of ground at \( x=0 \) (floor) \((^\circ C)\)
\( T_a \) = Ambient temperature \((^\circ C)\)
\( T_p \) = Plant temperature at time \( t \) \((^\circ C)\)
\( T_{po} \) = Plant temperature at time \( t=0 \) \((^\circ C)\)
\( t \) = Time (s)
\( U_b \) = Overall bottom heat transfer coefficient \((W/m^2\cdot {}^\circ C)\)
\( V \) = Volume of greenhouse \((m^3)\)
\( V_i \) = Rate of exchange due to ventilation and infiltration \((W)\)
\( x \) = Position coordinate along depth inside ground \((m)\)

**Greek letters**

\( \alpha_c \) = Absorptivity of greenhouse cover (canopy cover)
\( \alpha_p \) = Absorptivity of plant
\( \tau \) = Transmittivity of canopy cover
\( \gamma \) = Relative humidity

**Suffix**

\( D \) = Door
\( E \) = East
\( G \) = Floor
\( N \) = North
\( p \) = Plant
\( R \) = Room
\( S \) = South
\( W \) = West
\( 1 \) = zone-I
\( 2 \) = zone-II
\( 3 \) = zone-III
\( 4 \) = zone-IV
\( Z \) = zone (I–IV)
1. Introduction

The greenhouse environment is represented by a group of spatial average values of climatic factors, such as radiation, temperature, humidity and CO₂ concentration, which affect plant growth and development. The environment thus described or controlled is referred to as the greenhouse macroclimate [1]. Studies on greenhouse macroclimate have been conducted by several researchers [2–4]. Efforts have been made to predict the greenhouse thermal environment under both steady state and transient conditions [5–8]. A dynamic thermal performance simulation model for a greenhouse was also developed numerically [9]. They have solved the system equations numerically by using a Runge–Kutta predictor–corrector technique for the differential equations and the Newton–Raphson iteration technique for the algebraic equations to determine the various dependent variables.

A mathematical model was further developed to predict the plant and room air temperatures besides other parameters, such as instantaneous thermal efficiency, greenhouse efficiency factor etc. considering the effect of evaporation from the plants, conduction through the ground and ventilation [10]. In this model, to simplify the analysis, the heat capacity of the room air was neglected. However, in the present analysis, the heat capacity of the room air has also been considered and the analysis has been done by using the Runge–Kutta method to determine the different parameters for different zones of a greenhouse.

2. Brief description and working principle of greenhouse

A hut type greenhouse with an effective floor area of 24 m² (6 m × 4 m) has been considered for analysis (Fig. 1a). The height of the greenhouse is 2 m, while it is centrally raised to a height of 3 m. The floor area of the greenhouse has been divided into four parts (zones) (Fig. 1b) in order to determine the difference in temperature between each zone. At the centre of each zone at a height of 2 m off the ground, copper-constantan thermocouples have been placed to measure the temperature of the enclosed room air.

3. Thermal analysis

Energy balance equations for the different components of each zone of the proposed greenhouse have been written with the following assumptions: (i) the properties of the plant mass are considered equivalent to water for all thermal analysis proposed due to the high content of water in the plant; (ii) the relative humidity inside the greenhouse does not vary with height due to wetted floor/watering channel; (iii) the analysis is based on quasi-steady state conditions inside the greenhouse due to transient behaviour for short time intervals (Δt); (iv) no stratification is assumed in the vertical direction; (v) the ground heat loss from the floor to the ground has been considered in a steady state mode; and (vi) the heat transfer between different zones is assumed in the straight line such as from zone I to II, zone II to III, zone III to IV and zone IV to I (Fig. 1b). The resulting energy balances for different components of zone I of the greenhouse (Fig. 1b) are given overleaf.
For the plant surface.

\[ \alpha_{pl}(rS) + h_{pl}A_{pl}(T_{pl} - T_{pl}) + h_{pl}A_{pl}[p(T_{pl}) - \gamma p(T_{pl})]] = M_{pl} \frac{dT_{pl}}{dt} + h_{pl}A_{pl}(T_{pl} - T_{pl}) \\
+ (T_{pl} - T_{pl}) + h_{pl}A_{pl}[p(T_{pl}) - \gamma p(T_{pl})] + (p(T_{pl}) - \gamma p(T_{pl})]] \]  

(1)

For the ground.

\[ \alpha_{g}(1 - \alpha_{p})rS = -K \frac{\delta T}{\delta x}|_{x=0} + h_{g}A_{g}(T_{x=0} - T_{1}) \]

which can be simplified as,

\[ h_{g}A_{g}(T_{x=0} - T_{1}) = h_{g}(1 - \alpha_{p})rS - U_{b}A_{g}(T_{1} - T_{a}) \]  

(2)

For the greenhouse enclosed air.

\[ (1 - \alpha_{g})(1 - \alpha_{p})rS + h_{pl}A_{pl}(T_{pl} - T_{pl}) + h_{pl}A_{pl}(T_{pl} - T_{pl}) + h_{pl}A_{pl}[p(T_{pl}) - \gamma p(T_{pl})]] \]

\[ = M_{pl} \frac{dT_{pl}}{dt} + h(t)_{l}(T_{1} - T_{a}) + \frac{h_{d}A_{d}}{2}(T_{1} - T_{a}) + V_{l}(T_{1} - T_{a}) \]

\[ + h_{pl}A_{pl}(T_{pl} - T_{pl}) + U_{b}A_{g}(T_{pl} - T_{a}) - h_{g}(1 - \alpha_{p})rS \]  

(3)

It is mentioned here that zone I interacts only with zone II and zone IV, respectively, where \( h_{o} = 0.016 \), \( S = A_{b}S_{b} + A_{w}S_{w} + A_{n}s_{n} + A_{s}S_{s} + A_{r}S_{r} \), and \( V_{1} = \frac{ NY }{ NT } \).
The energy balance equations for zone II are:

For the plant surface,

\[ \alpha_p (rS)_2 + h_{p1}A_{p1}(T_{p1} - T_{p2}) + h_o A_{p1}[p(T_{p1}) - \gamma p(T_{p2})] = M_{p2} \frac{dT_{p2}}{dt} + h_{p2}A_{p2}(T_{p2} - T_{r2}) \\
+ (T_{p2} - T_{p3})] + h_o A_{p2}[(p(T_{p2}) - \gamma p(T_{r2})) + (p(T_{p2}) - \gamma p(T_{p3}))] \]

(4)

For the ground,

\[ \alpha_g (1 - \alpha_p) rS_2 = -K \frac{\delta T}{\delta x} \bigr|_{x=0} A_{g2} + h_g A_{g2}(T|_{x=0} - T_{r2}) \]

which can be simplified as,

\[ h_g A_{g2}(T|_{x=0} - T_{r2}) = h\alpha_g (1 - \alpha_p) rS_2 - U_o A_{g2}(T_{r2} - T_o) \]

(5)

Fig. 1b—Caption on page 340.
Fig. 1. (a) Cross-sectional view of a hut type greenhouse. (b) Schematic view of different zones of the greenhouse. (c) Hourly variations of the solar intensity and ambient temperature for a typical day in the month of December in Delhi.

Table 1
Design parameters for a greenhouse

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$q_{\text{net}} = \alpha_{p} T + (h_{\text{air}} + \tau_{\text{eff}}) HPG \frac{T}{U_1}$</td>
</tr>
<tr>
<td>2</td>
<td>$T_{\text{eff}} = (HH T_{Th} + KK - HPGV_1 A_{g}/U_1)U_{\text{eff}}$</td>
</tr>
<tr>
<td>3</td>
<td>$HH = (U_2 + U_{h} A_{g}) HPG/ U_1$</td>
</tr>
<tr>
<td>4</td>
<td>$KK = -HPG K/ U_1 - H_{0} A_{p} R_{d}(1 - \gamma)$</td>
</tr>
<tr>
<td>5</td>
<td>$HPG = A_{p} (h_{0} + h_{w}) R_{d}$</td>
</tr>
<tr>
<td>6</td>
<td>$U_1 = \Sigma A_1 h_{i}(t) + h_{a} A_{d} + V_{i} + h_{p} A_{p} + h_{a} A_{a} R_{d} + U_{i} A_{g}$</td>
</tr>
<tr>
<td>7</td>
<td>$U_2 = \Sigma A_2 h_{i}(t) + h_{a} A_{d} + V_{i}$</td>
</tr>
<tr>
<td>8</td>
<td>$\tau_{\text{eff}} = \alpha_{d}(1 - \alpha_{p})$</td>
</tr>
<tr>
<td>9</td>
<td>$\tau_{\text{eff}} = (1 - \alpha_{d})(1 - \alpha_{p})$</td>
</tr>
<tr>
<td>10</td>
<td>$K = -R_{d}(1 - \gamma) h_{0} A_{p}$</td>
</tr>
</tbody>
</table>
For the greenhouse enclosed air.

\[ (1 - \alpha_g)(1 - \alpha_p)r_S + h_{p1}A_{p1}(T_{r1} - T_c) + h_{p2}A_{p2}(T_{r2} - T_r3) + h_oA_p2[p(T_{p2} - \gamma p(T_{p2}))] \]
\[ = M_{a2} \frac{dT_{r2}}{dt} + h(t)_o(T_{r2} - T_a) + V_1(T_{r2} - T_a) + h_{p2}A_{p2}(T_{r2} - T_r3) \]
\[ + U_bA_{g2}(T_{r2} - T_a) - h \alpha_g(1 - \alpha_p)r_S \]

(6)

The energy balance equations for zone III are:

For the plant surface.

\[ \alpha_p(r_S) + h_{p2}A_{p2}(T_{p2} - T_{p3}) + h_oA_p2[p(T_{p2} - \gamma p(T_{p2}))] = M_{p2} \frac{dT_{p3}}{dt} + h_{p2}A_{p2} \]
\[ [(T_{p3} - T_{r3}) + (T_{p3} - T_{p4})] + h_oA_p3[(p(T_{p3}) - \gamma p(T_{r3})) + (p(T_{p3}) - \gamma p(T_{p4}))] \]

(7)

For the ground.

\[ \alpha_g(1 - \alpha_p)r_S = -K \frac{\partial T}{\partial x}(x=0) + h_2A_{g3}(T|_{x=0} - T_r3) \]

which can be simplified as,

\[ h_2A_{g3}(T|_{x=0} - T_r3) = h \alpha_g(1 - \alpha_p)r_S - U_bA_{g3}(T_r3 - T_a) \]

(8)

For the greenhouse enclosed air.

\[ (1 - \alpha_g)(1 - \alpha_p)r_S + h_{p3}A_{p3}(T_{p3} - T_r3) + h_{p2}A_{p2}(T_{r2} - T_r3) + h_oA_p3[p(T_{p3} - \gamma p(T_{p3}))] \]
\[ = M_{a3} \frac{dT_{r3}}{dt} + h(t)_o(T_{r3} - T_a) + V_1(T_{r3} - T_a) + h_{p3}A_{p3}(T_{r3} - T_r4) \]
\[ + U_bA_{g3}(T_{r3} - T_a) - h \alpha_g(1 - \alpha_p)r_S \]

(9)

The energy balance equations for zone IV are:

For the plant surface.

\[ \alpha_p(r_S) + h_{p4}A_{p4}(T_{p4} - T_{p3}) + h_oA_p4[p(T_{p4} - \gamma p(T_{p4}))] = M_{p4} \frac{dT_{p4}}{dt} + h_{p4}A_{p4} \]
\[ [(T_{p4} - T_{r4}) + (T_{p4} - T_{p1})] + h_oA_p4[(p(T_{p4}) - \gamma p(T_{r4})) + (p(T_{p4}) - \gamma p(T_{p1}))] \]

(10)

For the ground.

\[ \alpha_g(1 - \alpha_p)r_S = -K \frac{\partial T}{\partial x}(x=0) + h_2A_{g2}(T|_{x=0} - T_c2) \]

which can be simplified as,

\[ h_2A_{g2}(T|_{x=0} - T_c2) = h \alpha_g(1 - \alpha_p)r_S - U_bA_{g2}(T_{c2} - T_a) \]

(11)
For the greenhouse enclosed air.

\[(1 - \alpha_2)(1 - \alpha_p)\tau S_4 + h_{p4}A_{p4}(T_{p4} - T_{a}) + h_{p3}A_{p3}(T_{r2} - T_{r1}) + h_0A_{p4}[p(T_{p4} - \gamma p(T_{r4}))]
= M_{d4}\frac{dT_{r4}}{dt} + h(t)_{d}(T_{r4} - T_a) + \frac{h_dA_d}{2}(T_{r4} - T_a) + V_1(T_{r4} - T_a) + h_{p4}A_{p4}(T_{r4} - T_{r1}) + U_bA_{g4}(T_{r4} - T_a) - h\alpha_5(1 - \alpha_p)\tau S_4 \] (12)

In the above equations, the partial vapour pressures of the plant and the room air temperatures have been linearized as follows: \(p(T_p) = R_1T_p + R_2\), and \(p(T_r) = R_1T_r + R_2\), which are the equations of straight lines where \(R_1\) is the slope and \(R_2\) is the intercept of the

![Graphs](Zone-I, Zone-II, Zone-III, Zone-IV)

Fig. 2. Hourly variation of the plant temperature in different zones of a greenhouse.
straight lines. The values of the constants $R_1$ and $R_2$ can be obtained from steam tables for the particular operating temperature of the zones.

Eqs. (1)-(12), after simplification, may be arranged in the following eight first order differential equations of the form,

$$M_{p(z)} \frac{dT_{p(z)}}{dt} + a(A, 1)T_p + a(A, 2)T_{r1} + a(A, 3)T_{p2} + a(A, 4)T_{r2} + a(A, 5)T_{e3} + a(A, 6)T_{e3} + a(A, 7)T_{p4} + a(A, 8)T_{r4} = b_A$$

$$M_{a(z)} \frac{dT_{a(z)}}{dt} + a(B, 1)T_{p1} + a(B, 2)T_{r1} + a(B, 3)T_{p2} + a(B, 4)T_{r2} + a(B, 5)T_{e3} + a(B, 6)T_{e3} + a(B, 7)T_{p4} + a(B, 8)T_{r4} = b_B$$

where $a(A,1)$ to $a(A,8)$ and $a(B,1)$ to $a(B,8)$ are constants. The values of $A$ and $B$ vary from 1, 3, 5, 7 and 2, 4, 6, 8 (one equation each for plant and room air temperatures for each zone), respectively, while the value of $Z$ varies from 1 to 4. The values of $a(1,1)$ to $a(1,8)$ and $a(2,1)$ to $a(2,8)$, along with $b_1$ and $b_2$ for zone I, are mentioned as follows,

$$a(1, 1) = \frac{2(h_{p1}A_{p1} + h_{a0}A_{p1}R_1)}{M_{p1}}, \quad a(1, 2) = -\frac{(h_{p1}A_{p1} + h_{a0}A_{p1}\gamma R_1)}{M_{p1}}, \quad a(1, 3) = -\frac{(h_{p1}A_{p1} + h_{a0}A_{p1}R_1)}{M_{p1}}, \quad a(1, 4) = 0, \quad a(1, 5) = 0, \quad a(1, 6) = 0,$$

$$a(1, 7) = -\frac{(h_{p4}A + h_{a0}A_{p4}R_1)}{M_{p1}}, \quad a(1, 8) = 0, \quad a(2, 1) = -\frac{(h_{p1}A_{p1} + h_{a0}A_{p1}R_1)}{M_{a1}}, \quad a(2, 2) = \frac{\left(2\tau_1 + U_{b1}A_{p1} \gamma R_1\right)}{M_{a1}}, \quad a(2, 3) = 0,$$

$$a(2, 4) = -\frac{h_{p1}A_{p1}}{M_{a1}}, \quad a(2, 5) = 0, \quad a(2, 6) = 0, \quad a(2, 7) = 0, \quad a(2, 8) = -\frac{h_{p1}A_{p1}}{M_{a1}},$$

$$b_1 = 2p(\tau_1) + h_{a0}A_{p1}R_2(1 - \gamma) - 2b_{a0}A_{p1}R_2(1 - \gamma),$$

$$b_2 = \frac{(h\tau_{a1} + \tau_{a2})\tau_1 + (h(t)_1 + \frac{h_{a1}}{2} + V_1 + U_{a2}T_d + h_{a0}A_{p1}R_1(1 - \gamma)}{M_{a1}}$$

Similarly the coefficients can be derived for other zones also.

Eqs. (13) and (14) have been solved numerically by using the fourth order Runge–Kutta method to obtain the values of $T_p$ and $T_r$ at the first four steps. Further, the values of $T_p$ and $T_r$ at the subsequent steps are obtained by the Adam–Moulton's predictor–corrector method.

For numerical analysis, a computer program has been written in FORTRAN 77. The other parameters are given in Table 1.
4. Numerical results and discussion

The hourly variation of the solar intensity (total, beam and diffuse) measured on the horizontal surface and the ambient temperature ($T_a$) for a typical day in December, 1996, are shown in Fig. 1c. These data of solar intensity have been used to calculate the solar intensity on each wall and roof of the greenhouse by the Liu and Jordan formula [11]. These data, along with the ambient temperature and the relative humidity inside the greenhouse and the

![Graphs showing room air temperature variations](image)

Fig. 3. Experimental and theoretical values of the room air temperature in different zones of a greenhouse.
constants given in Table 2, have been used as the input parameters in the dynamic model to predict the plant and room air temperatures for different times of the day for each zone of the greenhouse. The variations of plant temperature for different times of the day for each zone are shown in Fig. 2. The plant temperature is marginally higher in zones III and IV as compared to zones I and II. It may be mentioned here that movable insulation (Jute cloth) has been used over the north and south walls and the roof from 6 pm to 7 am. Fig. 3 shows the hourly variation of the room air temperatures (theoretical and experimental). The results show

Fig. 4. Effect of heat capacity of the plant ($M_p$) on the hourly variation of plant and room air temperatures ($T_F$ and $T_R$).
that there is a fair agreement between the two, and they are in accordance with the results reported by Bourgeois et al. [12].

The parametric studies are presented in Figs. 4–6 for zone II. The effect of the heat capacity of the plants (isothermal mass, \( M_p \)) on the plant and room air temperatures is shown in Fig. 4. The plant temperature decreases with an increase in the isothermal mass (\( M_p \)) due to more evaporation from the plant. However, during off sunshine hours, the plant and room air temperatures increased with the isothermal mass due to the storage effect, as expected. The

![Graph](image)

Fig. 5. Effect of infiltration (\( N \)) on the hourly variation of plant and room air temperatures (\( T_p \) and \( T_r \)).
effect of infiltration (number of air changes/hr) on the plant and room air temperatures is shown in Fig. 5. The plant and room air temperatures decrease with the increase in the rate of infiltration due to more withdrawal of the room air, as expected. However, the rate of decrease beyond 40 air changes is not very significant. Therefore, in order to conserve the heat inside a greenhouse, all of its leaks must be sealed properly.

The effect of relative humidity ($\gamma$) on the plant and room air temperatures is shown in Fig. 6. The plant temperature increases with the relative humidity ($\gamma$) due to low evaporation

![Plant temperature graph](image1)

![Room air temperature graph](image2)

*Fig. 6: Effect of greenhouse relative humidity ($\gamma$) on the hourly variation of plant and room air temperatures ($T_p$ and $T_r$).*
Table 2
Constants used for the experimental study

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>$A_G$</td>
<td>24.0</td>
<td>$\tau$</td>
<td>0.7</td>
</tr>
<tr>
<td>$A_R$</td>
<td>26.4</td>
<td>$\alpha_p$</td>
<td>0.55</td>
</tr>
<tr>
<td>$A_P$</td>
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<td>$\alpha_g$</td>
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</tr>
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<td>$A_p$</td>
<td>40.0</td>
<td>$\gamma$</td>
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</tr>
<tr>
<td>$M_p$</td>
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<td>$h_b$</td>
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</tr>
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<td>$h_z$</td>
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<td>$h_D$</td>
<td>3.99</td>
</tr>
<tr>
<td>$h_p$</td>
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<tr>
<td>$t$</td>
<td>3600</td>
<td>$C_a$</td>
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</tbody>
</table>

from the plant, as expected. However, the effect of $\gamma$ on the room air temperature is not significant.

5. Conclusion

On the basis of the study, it can be concluded that the variations in the plant and room air temperatures in different zones of a greenhouse are marginal. This may be due to the fact that fast heat transfer takes place in the greenhouse, particularly during winter when there is no stratification. Also, there is a more significant effect of the isothermal mass and relative humidity on the plant temperature than that on the room air temperature.

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References