Energy balance for the greenhouse structures

Energy balances for the greenhouse covers, shading materials can be developed for each component under the following assumptions:

1. One dimensional heat transfer was considered.
2. The heat storage capacities of the cover and shade materials were small compared to the existing fluxes, so that a steady state analysis was employed (Kindelan, 1980).
3. Assuming the Biot number being less than 0.1 during convective heat transfer (Kreith, 1973) and assuming no spatial variation existed for inside air temperature, a uniform temperature of the cover was assumed.
4. In dealing with the longwave radiation exchanges between the cover or the shade and the surrounding, it was assumed that they were gray bodies (Arinze et.al.,1984). Also, a resistance associated with the longwave radiation exchanges was considered. It was assumed that the internal cover, the external cover, shades and the plant canopy were all parallel planes as shown in Figure 1. Longwave radiation exchanges between large parallel planes with a radiation shield and a network representation as described by Incropera and DeWitt (1985) are shown in Figures 2. This concept was used in this study when dealing with longwave radiation exchanges between any two planes. The surface area of all planes was A_i. Also, the emissivities and the transmissivities of the covers and shading materials were assumed to be ε_c and $\tau_{tc,}$ respectively .
5. When doing energy balances for the covers, air inside the greenhouse and air in between the covers did not have thermal radiation exchange (Arize et al., 1984).

6. Leaves were assumed to be gray bodies with an emissivity of 0.95 and a reflectivity of 0.05 (Yang, 1988 and Ross, 1981). So, the thermal radiation absorptivity of a leaf was assumed to be equal to its emissivity.

7. The surrounding sky was at sky temperature (T_{sky}).

8. The inside shading screen was considered very low in terms of its transmissivity of thermal radiation.

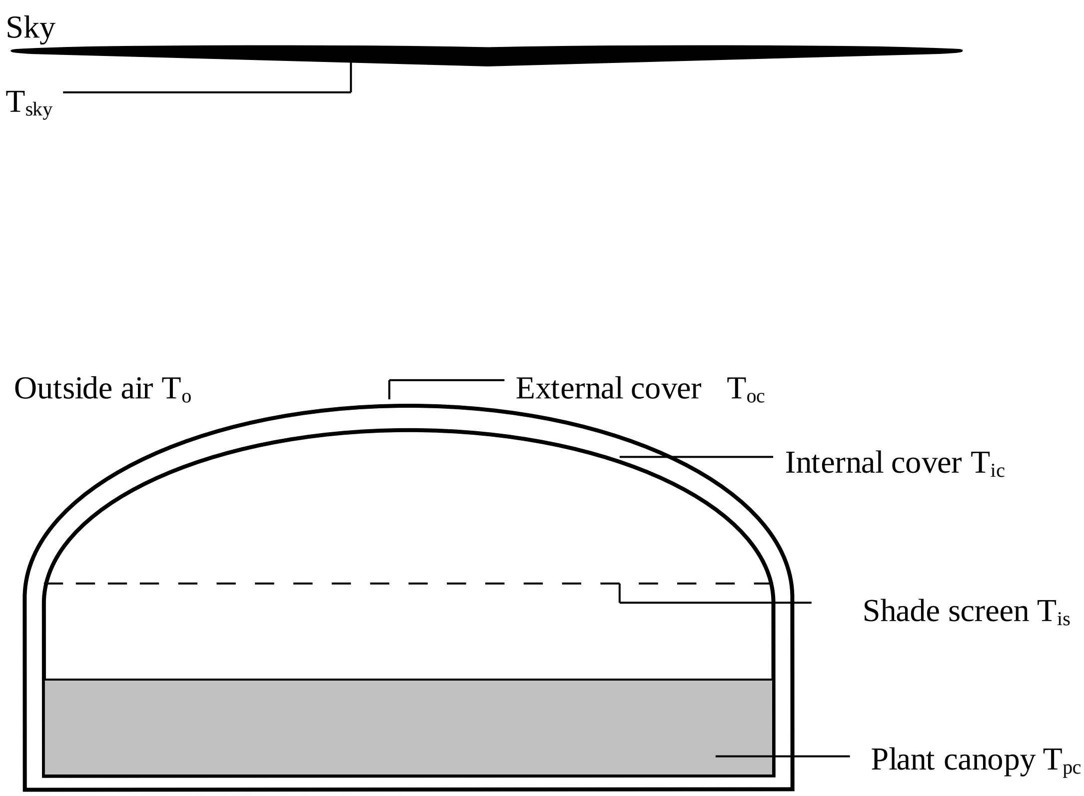

Figure 1: Schematic view of the greenhouse geometry used in longwave radiation exchange among surfaces

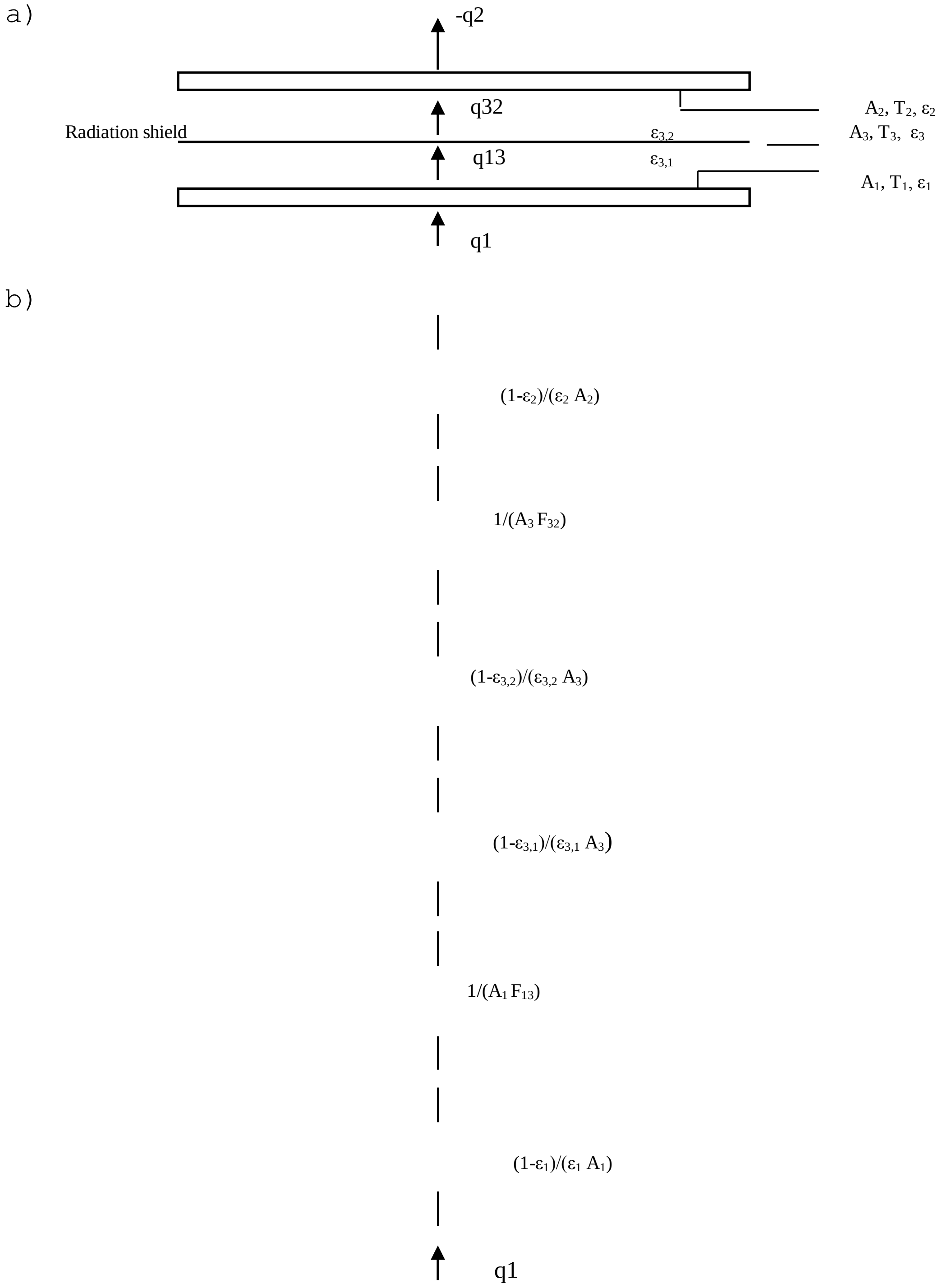

Figure 2: Longwave radiation exchange between large parallel planes with a radiation shield. (a) schematic. (b) Network representation according to Incropera and DeWitt (1985).

External cover

The steady state heat balance for the external cover was written as:

$$0 = Q_{srec} - Q_{cec} - Q_{cab} + Q_{tec} \quad (1)$$

where Q_{srec} was the amount of solar radiation on the external cover (W), Q_{cec} was the wind induced convective heat transfer from the external cover to the outside air (W), Q_{cab} was the convective heat transfer from the external cover to the air in between the covers (W), and Q_{toc} was the net longwave (thermal) radiation on the external cover (W).

The amount of solar radiation on the external cover was defined as:

$$Q_{srec} = \alpha_c \; A_i \; I_{sr} \quad (2)$$

where α_c was the external cover absorbsivity of solar radiation, A_i was the surface area of the cover (m^2), and I_{sr} was the amount of solar radiation at a horizontal surface (W/m^2).

The convective heat transfer between the external cover and the outside air was expressed as:

$$Q_{cec} = h_{ec} \; A_i \; (T_{ec} - T_o) \quad (3)$$

where h_{ec} was the convective heat transfer coefficient for the outside surface of the cover ($W/m^2 \, {}^oC$), and T_{ec} was the external cover temperature (${}^oC$).

$$Q_{cab} = h_{ab} \; A_i \; (T_{ec} - T_{ab}) \quad (4)$$

where h_{ab} was the convective heat transfer coefficient between the covers ($W/m^2 \, {}^oC$), and T_{ab} was the air temperature between the covers (${}^oC$).

The net longwave radiation on the external cover (Q_{tec}) was defined as the following:

$$Q_{tec} = Q_{t(is,ec)} + Q_{t(ic,ec)} - Q_{t(ec,\, sky)} \quad (5)$$

where $Q_{t(is,ec)}$ was the exchange of longwave radiation between the inside shading screen and the external cover (W), $Q_{t(ic,ec)}$ was the longwave radiation exchange between the internal and external covers (W), and $Q_{t(ec,sky)}$ was the exchange of thermal radiation between the external cover and sky (W).

In equation $Q_{t(is,ec)}$, $Q_{t(ic,ec)}$ and $Q_{t(ec, sky)}$ terms were expressed as:

$$Q_{t(is,ec)} = A_i \tau_{tc} \sigma (T_{is}^4 - T_{ec}^4) / r_{t(is,ec)} \quad (6)$$

$$r_{t(is,ec)} = [2 + 4 (1-\varepsilon_c) / \varepsilon_c] \quad (7)$$

$$Q_{t(ic,ec)} = A_i \sigma (T_{ic}^4 - T_{ec}^4) / r_{t(ic,ec)} \quad (8)$$

$$r_{t(ic,ec)} = (2 / \varepsilon_c) - 1 \quad (9)$$

$$Q_{t(ec, sky)} = A_i \varepsilon_c \sigma (T_{ec}^4 - T_{sky}^4) \quad (10)$$

where τ_{tc} was the internal cover transmissivity for longwave radiation, T_{is} was the temperature of the inside shading screen (°K), $r_{t(is,ec)}$ was the corresponding resistance for longwave radiation exchange, ε_c was the cover (shade) emissivity for longwave radiation, T_{ic} was the inside cover temperature (°K), $r_{t(ic,ec)}$ was the corresponding resistance for longwave radiation exchange, and T_{sky} was the sky temperature (°K).

The external cover temperature with inside shade was written by substituting Equations (2-4) into Equation (1) as following:

$$T_{ec} = (\alpha_c I_{sr} + h_{ec} T_o + h_{ab} T_{ab} + Q_{tec} / A_i) / (h_{ec} + h_{ab}) \quad (11)$$

Internal cover

The steady state heat balance for the internal cover was written as:

$$0 = Q_{sric} - Q_{cic} - Q_{cab} + Q_{tic} \tag{12}$$

where Q_{sric} was the amount of solar radiation on the internal cover (W), Q_{cic} was the convective heat transfer from the internal cover to the inside air (W), Q_{cab} was the convective heat transfer from the internal cover to the air in between the covers (W), and Q_{tic} was the net longwave radiation on the internal cover (W).

The amount of solar radiation on the internal cover was written as:

$$Q_{sric} = \tau_c \, \alpha_c \, A_i \, I_{sr} \tag{13}$$

where τ_c was solar radiation transmissivity of the external cover and α_c was the internal cover absorbsivity of the solar radiation.

The convective heat transfer from the internal cover to the inside air was defined as follows:

$$Q_{cic} = h_{ic} \, A_i \, (T_{ic} - T_i) \tag{14}$$

where h_{ic} was the corresponding heat transfer coefficient (W/m^2 ^{o}C) and T_{ic} was the temperature of the internal cover (^{o}C).

The heat transfer by convection from the internal cover to the air in between the covers was written as:

$$Q_{cab} = h_{ab} \, A_i \, (T_{ic} - T_{ab}) \tag{15}$$

The net longwave radiation on the internal cover was expresses as:

$$Q_{tic} = Q_{t(is,ic)} - Q_{t(ic,oc)} - Q_{t(ic, sky)} \tag{16}$$

where $Q_{t(is,ic)}$ was the exchange of longwave radiation between the inside shading screen and the internal cover (W), and $Q_{t(ic,sky)}$ was the exchange of thermal radiation between the internal cover and sky (W).

In equation (16), $Q_{t(is,ic)}$ and $Q_{t(ic, sky)}$ terms were expressed as:

$$Q_{t(is,ic)} = A_i \sigma (T_{is}^4 - T_{ic}^4) / r_{t(is,ic)} \quad (17)$$

$$r_{t(is,ic)} = (2 / \varepsilon_c) - 1 \quad (18)$$

$$Q_{t(ic, sky)} = A_i \tau_{tc} \varepsilon_c \sigma (T_{ic}^4 - T_{sky}^4) \quad (19)$$

where $r_{t(is,ic)}$ was the corresponding resistance for longwave radiation exchange.

Substituting Equations (13-15) into Equation (12), an expression for the internal cover temperature was derived as:

$$T_{ic} = (\tau_c \alpha_c I_{sr} + h_{ic} T_i + h_{ab} T_{ab} + Q_{tic} / A_i) / (h_{ic} + h_{ab}) \quad (20)$$

Inside shade

The steady state heat balance for the inside shade screen was written as:

$$0 = Q_{sris} - Q_{cis} + Q_{tis} \quad (5.50)$$

where Q_{sris} was the amount of solar radiation on the shading screen (W), Q_{cis} was the convective heat transfer from the screen to the inside air (W), and Q_{tis} was the net longwave radiation on the shading screen (W).

The amount of solar radiation on the shading screen was expressed as:

$$Q_{sris} = \alpha_{is} \tau_c^2 A_i I_{sr} \quad (5.51)$$

where α_{is} was the shading screen absorbsivity of the solar radiation and A_{is} was the surface area of the screen (m^2).

The convective heat transfer from the screen to the inside air was defined as:

$$Q_{cis} = 2 h_{is} A_i (T_{is} - T_i) \quad (5.52)$$

where h_{is} was the convective heat transfer coefficient for the screen ($W/m^2\ {}^oC$). The 2 in Equation (5.51) was the coefficient to take both sides of the inside shade into account.

The net longwave radiation on the shading screen was defined as:

$$Q_{tis} = Q_{t(pc,is)} - Q_{t(is,ic)} - Q_{t(is,ec)} - Q_{t(is,sky)} \quad (5.53)$$

$$Q_{t(pc,is)} = A_i \sigma (T_{pc}^4 - T_{is}^4) / r_{t(pc,is)} \quad (5.54)$$

$$r_{t(pc,is)} = (1/\varepsilon_{pc}) - 1 + (1/\varepsilon_c) \quad (5.55)$$

$$Q_{t(is,sky)} = A_i \tau_{tc}^2 \varepsilon_c (T_{is}^4 - T_{sky}^4)$$

(5.56)

where $Q_{t(pc,is)}$ was the exchange of longwave radiation between the plant canopy and inside shading screen, $Q_{t(is,sky)}$ was longwave radiation exchange between the screen and the sky, $r_{t(pc,is)}$ was the corresponding resistance for longwave radiation.

Using Equation (5.51), (5.52) and (5.50), an expression for the internal cover temperature was derived as:

$$T_{is} = (\alpha_{is}\, \tau_c^2\, I_{sr} + 2h_{is}\, T_i + Q_{tis} / A_i) / (2h_{is}) \tag{5.57}$$

5.3.1.4 Plant canopy temperature

The plant canopy temperature was evaluated by Equation (5.28) described in section (5.2). The net radiation (Q^*) in equation (5.28) was defined as:

$$Q^* = 0.5\, \tau_c^2\, \alpha_{pc}\, I_{sr} + Q_{tpc} \tag{5.58}$$

where 0.5 was the level of shading for the inside shade screen, α_{pc} was the absorbsivity of the plant canopy of solar radiation and Q_{tpc} was the net longwave radiation on the plant canopy (W/m^2).

When the inside shade was used, an assumption was made that the plant canopy exchanged longwave radiation with only the shade screen because the transmissivity of the screen for longwave radiation was a small value. In equation (5.58), the Q_{tpc} term was expressed as:

$$Q_{t(pc,is)} = -\, A_i\, \sigma\, (T_{pc}^4 - T_{is}^4) / r_{t(pc,is)} \tag{5.59}$$

5.3.2 Temperatures of the greenhouse structures with outside shade

5.3.2.1 Outside shade temperature

The steady state heat balance for the outside shade was written as:

$$0 = Q_{sros} - Q_{cos} + Q_{tos} \tag{5.60}$$

where Q_{sros} was the amount of solar radiation on the outside shading (W), Q_{cos} was the wind induced convective heat transfer from the outside shading to the outside air (W), and Q_{tos} was the net longwave radiation on the outside shading (W).

The amount of solar radiation on the outside shading was expressed as:

$$Q_{sros} = \alpha_{os} A_i I_{sr} \quad (5.61)$$

where α_{os} was the outside shading absorbsivity of the solar radiation.

The heat transfer from the outside shading by convection was expressed as:

$$Q_{cos} = 2\, h_{os} A_i (T_{os} - T_o) \quad (5.62)$$

where the 2 in equation (5.62) was the coefficient to take both sides of the outside shade into account, h_{os} was the convective heat transfer coefficient for the outside and inside surfaces of the shade (W/m^2 ^{o}C), and T_{os} was the outside shading material temperature (^{o}C).

The net longwave radiation on the outside shading was defined as follows:

$$Q_{tos} = Q_{t(ec,os)} + Q_{t(ic,os)} + Q_{t(pc,os)} - Q_{t(os,sky)} \quad (5.63)$$

$$Q_{t(ec,os)} = A_i\ \sigma (T_{oc}^4 - T_{os}^4) / r_{t(oc,os)} \quad (5.64)$$

$$r_{t(ec,os)} = (2/\varepsilon_c) - 1 \quad (5.65)$$

$$Q_{t(ic,os)} = A_i\ \tau_{tc}\, \sigma (T_{ic}^4 - T_{os}^4) / r_{t(ic,os)} \quad (5.66)$$

$$r_{t(ic,os)} = 2 + 4\,(1-\varepsilon_c) / \varepsilon_c$$

(5.67)

$$Q_{t(pc,os)} = A_i\, \sigma (T_{pc}^4 - T_{os}^4) / r_{t(pc,os)} \quad (5.68)$$

$$r_{t(pc,os)} = 3 + 5\,(1-\varepsilon_c) / \varepsilon_c + (1-\varepsilon_{pc}) / \varepsilon_{pc} \quad (5.69)$$

$$Q_{t(os,sky)} = A_i\, \varepsilon_c\, \sigma (T_{os}^4 - T_{sky}^4) \quad (5.70)$$

where $Q_{t(ec,os)}$ was the exchange of longwave radiation between the external cover and the outside shading (W), $Q_{t(ic,os)}$ was the longwave radiation exchange between the internal cover and outside shading (W), $Q_{t(pc,os)}$ was the exchange of thermal radiation between the plant canopy and outside shading (W), and $Q_{t(os,sky)}$ was the longwave exchange between the outside shading and sky (W).

Substituting Equation (5.61) and (5.62) into Equation (5.60), an expression for the outside shade temperature was derived by substitution with the steady-state heat balance equation as following:

$$T_{os} = (\alpha_{os} I_{sr} + 2 h_{os} T_o + Q_{tos} / A_i) / (2 h_{os}) \qquad (5.71)$$

<u>5.3.2.2 External cover temperature</u>

The steady state heat balance for the external cover was written as:

$$0 = Q_{srec} - Q_{cec} - Q_{cab} + Q_{tec} \qquad (5.72)$$

where Q_{srec} was the amount of solar radiation on the external cover (W), Q_{cec} was the convective heat transfer from the external cover to the outside air (W), Q_{cab} was the convective heat transfer from the external cover to the air in between the covers (W), and Q_{tec} was the net longwave radiation on the external cover (W).

The amount of solar radiation on the external cover was written as:

$$Q_{srec} = \alpha_c \tau_{os} A_i I_{sr} \qquad (5.73)$$

The convective heat transfer from the external cover to the outside air was expressed as:

$$Q_{cec} = h_{ec} A_i (T_{ec} - T_o) \quad (5.74)$$

The convective heat transfer from the external cover to the air between the covers was defined as:

$$Q_{cab} = h_{ab} A_i (T_{ec} - T_{ab})$$

(5.75)

The net longwave radiation on the external cover was written as:

$$Q_{tec} = Q_{t(ic,ec)} + Q_{t(pc,ec)} - Q_{t(ec,os)} - Q_{t(ec,sky)}$$

(5.76)

$$Q_{t(pc,ec)} = A_i \tau_{tc} \sigma (T_{pc}^4 - T_{ec}^4)/r_{t(pc,ec)} \quad (5.77)$$

$$r_{t(pc,ec)} = (1-\varepsilon_{pc}) /\varepsilon_{pc} + 2 + 3 (1-\varepsilon_c) /\varepsilon_c \quad (5.78)$$

$$Q_{t(ec,sky)} = A_i \tau_{tc} \varepsilon_c \sigma (T_{ec}^4 - T_{sky}^4) \quad (5.79)$$

where $Q_{t(pc,oc)}$ was the longwave radiation exchange between the plant canopy and the external cover (W), and τ_{tos} was the outside shading transmissivity for longwave radiation.

Using Equations (72-75), an expression for the external cover temperature was derived as:

$$T_{ec} = (\alpha_c \tau_{os} I_{sr} + h_{ec} T_o + h_{ab} T_{ab} + Q_{tec}/ A_i) / (h_{ec} + h_{ab}) \quad (5.80)$$

5.3.2.3 Internal cover temperature

The steady state heat balance for the internal cover was written as:

$$0 = Q_{sric} - Q_{cic} - Q_{ciab} + Q_{tic} \quad (5.81)$$

where Q_{sric} was the amount of solar radiation on the internal cover (W), Q_{cic} was the convective heat transfer from the internal cover to the inside air (W), Q_{ciab} was the convective heat transfer from the internal cover to the air in between the covers (W), and Q_{tic} was the net longwave radiation on the internal cover (W).

The terms Q_{sric}, Q_{cic}, Q_{ciab}, and Q_{tic} in Equation (5.83) were expressed as:

$$Q_{sric} = \alpha_c \tau_{os} \tau_c A_i I_{sr} \quad (5.82)$$

$$Q_{cic} = h_{ic} A_i (T_{ic} - T_i) \quad (5.83)$$

$$Q_{icab} = h_{ab} A_i (T_{ic} - T_{ab}) \quad (5.84)$$

$$Q_{tic} = Q_{t(pc,ic)} - Q_{t(ic,ec)} - Q_{t(ic,os)} - Q_{t(ic,sky)} \quad (5.85)$$

where $Q_{t(pc,ic)}$ was the longwave radiation exchange between the plant canopy and the internal cover, $r_{t(pc,ic)}$ was the corresponding resistance and $Q_{t(ic,sky)}$ was the longwave radiation exchange between the internal cover and the sky.

The terms $Q_{t(pc,ic)}$, $Q_{t(ic,ec)}$, $Q_{t(ic,os)}$ and $Q_{t(ic,sky)}$ in Equation (5.85) were defined as:

$$Q_{t(pc,ic)} = A_i \sigma (T_{pc}^4 - T_{ic}^4)/r_{t(pc,ic)}$$

(5.86)

$$r_{t(pc,ic)} = (1/\varepsilon_{pc}) + (1/\varepsilon_c) - 1 \quad (5.87)$$

$$Q_{t(ic,sky)} = A_i \tau_{tc}^2 \sigma (T_{ic}^4 - T_{sky}^4)$$

(5.88)

Using Equations (81-84), an expression for the internal cover temperature was derived as:

$$T_{ic} = (\alpha_c \tau_{os} \tau_c I_{sr} + h_{ic} T_i + h_{ab} T_{ab} + Q_{tic}/ A_i) / (h_{ic} + h_{ab}) \quad (5.89)$$

5.3.2.4 Plant canopy temperature

The net radiation (Q^*) in Equation (5.28) was defined as:

$$Q^{*} = 0.5\ \tau_c^2\ \alpha_{pc}\ I_{sr} + Q_{tpc} \qquad (5.90)$$

where 0.5 was the shade factor of the inside shade screen, α_{pc} was the absorbsivity of the plant canopy of solar radiation and Q_{tpc} was the net longwave radiation on the plant canopy (W/m^2).

With the outside shade was being used, the plant canopy exchanged longwave radiation with covers, the outside shade, and the sky. For this case, the following analysis was performed:

$$Q_{tpc} = -\ Q_{t(pc,os)} - Q_{t(pc,ec)} - Q_{t(pc,ic)} - Q_{t(pc,sky)} \qquad (5.91)$$

The term $Q_{t(pc,sky)}$ was defined as:

$$Q_{t(pc,sky)} = A_i\ \tau_{tc}^3\ \sigma\ (T_{pc}^4 - T_{sky}^4) \qquad (5.92)$$

where $Q_{t(pc,sky)}$ was the longwave radiation exchange between the plant canopy and the sky (W/m^2).