

## Greenhouse Steady State Energy Balance Model

The energy balance for the greenhouse was obtained by applying energy conservation to the greenhouse system as a control volume and identifying the energy terms. In this study, the energy storage term in the greenhouse was ignored since the heat capacity of internal air and plants was small compared to the existing fluxes (Walker, 1965 and Kindelan, 1980). The air in each defined zone in the greenhouse was assumed to be well mixed resulting in no spatial variation in temperature. The greenhouse surface and the surrounding were assumed gray bodies and the sky was at sky temperature. Also, it was assumed that the greenhouse ground was completely covered with plants. During the periods of high solar radiation when ventilation was required, the heat loss to ground, the heat of respiration and heat utilized in photosynthesis were assumed to be very small compared to other fluxes and were neglected (Walker, 1965). The cover was assumed to be double layer polyethylene. Neglecting the rate of change of energy stored in the greenhouse and other small fluxes, the energy balance equation for the greenhouse was written as:

$$0 = Q_{sr} - Q_e - Q_{cd} - Q_v - Q_t \quad (1)$$

where  $Q_{sr}$  was the amount of direct and diffuse shortwave solar radiation in the greenhouse (W),  $Q_e$  was the latent heat energy flux due to plant transpiration (W),  $Q_{cd}$  was the conduction heat transfer through the greenhouse covering material (W),  $Q_v$  was the energy removed by ventilation air (W), and  $Q_t$  was the net thermal radiation through the

greenhouse covers to the atmosphere (W). Each term was defined by a relationship.

The variable  $Q_{sr}$  was expressed as:

$$Q_{sr} = \tau_c S_l I_{sr} A_f \quad (2)$$

where  $\tau_c$  was the transmissivity of the greenhouse covering materials for solar radiation,  $S_l$  was the shading level,  $I_{sr}$  was the amount of solar radiation energy received per unit area and per unit time on a horizontal surface outside the greenhouse ( $W/m^2$ ), and  $A_f$  was the floor area of the greenhouse ( $m^2$ ).

The variable  $Q_e$  in equation (1) was expressed as:

$$Q_e = ET L_v A_f \quad (3)$$

Where  $ET$  was rate of transpiration ( $Kg_{H_2O}/sec.m^2$ ) and  $L_v$  was latent heat of vaporization of water ( $J/Kg_{H_2O}$ ).

The variable  $Q_{cd}$  in equation (1) was defined by the following relationship:

$$Q_{cd} = U A_c (T_i - T_o) \quad (4)$$

where  $U$  was the heat transfer coefficient ( $W/m^2 \text{ } ^\circ C$ ),  $A_c$  was area of the greenhouse covers ( $m^2$ ),  $T_i$  was the inside air temperature ( $^\circ C$ ), and  $T_o$  was the outside air temperature ( $^\circ C$ ).

Since the transmitted thermal radiation loss was considered separately and not included as a part of the  $U$  value for conduction heat loss,  $U$  was given the value of  $2.73 \text{ } W/m^2 \text{ } ^\circ C$  (ASHRAE guide and data book fundamentals, 1981)

The variable  $Q_v$  in equation (1) was expressed as:

$$Q_v = V_{va} (1/v) C_p (T_i - T_o) \quad (5)$$

where  $V_{va}$  was the volumetric ventilation rate ( $m^3/s$ ),  $v$  was the specific volume of air

(m<sup>3</sup>/kg), and C<sub>p</sub> was the specific heat of air (J/Kg °C). When the evaporative cooling system was used, T<sub>o</sub> in equation (5) was the temperature of the air leaving the cooling system. It was expressed as:

$$T_e = T_o - \eta(T_o - T_{wb}) \quad (6)$$

The variable Q<sub>t</sub> was the difference between the thermal radiation emitted from the surface and the thermal radiation gained from the atmosphere such that:

$$Q_t = \sigma A_f \tau_{tc} \tau_{os} (\epsilon_i T_i^4 - \epsilon_{sky} T_{sky}^4) \quad (7)$$

where  $\sigma$  was the Stefan-Boltzmann's constant ( $5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ ),  $\tau_{tc}$  and  $\tau_{os}$  were the transmissivities of the thermal radiation for the double layer polyethylene and the shading material, respectively,  $\epsilon_i$  was the average emissivity of the interior surface, and  $\epsilon_{sky}$  was the apparent emissivity of the sky. The emissivity of the sky was evaluated by the following equation (Idso, 1981):

$$\epsilon_{sky} = 0.70 + 5.95E-7 * e_0 * \exp(1500/T_o) \quad (8)$$

where  $e(T_o)$  and  $T_o$  were ambient vapor pressure and temperature at a standard height in Pa. and K, respectively.

The sky temperature was approximated by the Swinbank model (1963) as a function of outside air temperature (T<sub>o</sub> in unit of Kelvin):

$$T_{sky} = 0.0552 * (T_o)^{1.5} \quad (9)$$

Substituting equations (2-5) into equation (1), and expressing each term per unit floor area yielded:

$$I_{sri} = ET L_v + a (T_i - T_o) + V_{va} b (T_i - T_e) + Q_t/A_f \quad (10)$$

where  $V_{va}$  was the volumetric ventilation rate (m<sup>3</sup>/s.m<sup>2</sup> of floor area),  $a = UA_c/A_f$ ,  $b =$

$(1/v)C_p$ ,  $T_e = T_o$  when the natural or fan ventilation was used without evaporative cooling, and  $I_{sri} = \tau_c S_l I_{sr}$ .

Then, an expression for the interior temperature was derived as:

$$T_i = [I_{sri} - Q_t/A_f + (a T_o + b V_{va} T_e) - ET L_v] / (a + b V_{av}) \quad (11)$$

It is clear from equation (11) that the variables affecting inside greenhouse temperature ( $T_i$ ) were the inside solar radiation ( $I_{sri}$ ), outside temperature ( $T_o$ ), transpiration rate (ET), and ventilation rate ( $V_{va}$ ).

### **Greenhouse Steady State Mass Balance Model**

To evaluate the inside relative humidity for a given ventilation rate and a rate of moisture production, a mass balance calculation was performed. In this study, it was assumed that moisture loss from the air by condensation on the surfaces was small and was neglected. Also, the plant transpiration was assumed to be the only source of moisture production in naturally and fan ventilated greenhouses. When the evaporative cooling system was used, additional moisture was added to the greenhouse environment by the cooling system. The overall mass balance was:

$$M_v = M_{et} \quad (12)$$

where  $M_v$  was the amount of moisture transferred from the inside air to the outside air via ventilation ( $\text{Kg H}_2\text{O /s}$ ), which was expressed as:

$$M_v = (1/v) V_a (w_i - w_o) \quad (13)$$

where  $w_i$  and  $w_o$  were the humidity ratios of the inside and outside air, respectively, in  $\text{Kg}_{\text{H}_2\text{O}}/\text{Kg}_{\text{dry air}}$ .

The variable  $M_{\text{et}}$  in equation (13) was the amount of moisture added by transpiration ( $\text{Kg}_{\text{H}_2\text{O}}/\text{s}$ ).

The relationship for relative humidity (RH) expressed as a percent was given by the equation:

$$\text{RH} = [e(T) / e^*(T)] * 100 \quad (14)$$

where  $e(T)$  was the partial pressure of the water vapor in moist air (Pa) and  $e^*(T)$  was the saturation vapor pressure (Pa). The partial pressure of water vapor was defined by:

$$e(T) = (w + P_{\text{atm}})/(w + 0.622) \quad (15)$$

where  $P_{\text{atm}}$  was the atmospheric pressure (Pa).

The saturation vapor pressure for a given temperature was computed with the equation given by ASHRAE Handbook of Fundamentals, (1993):

$$\begin{aligned} e^*(T) = \exp [ & -5800.2206/T + 1.3914993 - 0.04860239 T \\ & + 0.41764768E-4 T^2 - 0.14452093E-7 T^3 \\ & + 6.5459673 \ln (T) ] \end{aligned} \quad (16)$$

where  $T$  was in K and  $e(T)$  was in Pa.

Water use during the mass transfer process between the air and water for the evaporative cooler was evaluated by the steady flow mass balance equation:

$$m_a w_o + m_w = m_a w_e \quad (17)$$

where  $m_w$  was the evaporative cooling system water intake ( $\text{Kg}_{\text{H}_2\text{O}}/\text{s}$ ),  $m_a$  was the mass flow rate of the outside air through the cooling system ( $\text{Kg}_{\text{dry air}}/\text{s}$ ), and  $w_e$  was the

humidity ratio of the leaving air passed through the cooling system ( $\text{Kg H}_2\text{O/Kg dry air}$ ).

Therefore,

$$m_w = m_a (w_e - w_o) \quad (18)$$

or

$$m_w = (1/v) V_{av} (w_e - w_o) \quad (19)$$

Equation (19) can be used to evaluate the water evaporation rate in the evaporative cooling system for a given air flow rate through the greenhouse. However, a general formula for water intake for the cooling system as a function of outside conditions needed to be evaluated. Cooling load of the evaporative cooling system of a greenhouse was expressed as:

$$Q_v = Q_{sr} - Q_e - Q_{cd} - Q_t \quad (20)$$

The volumetric ventilation rate with an average inside design temperature was defined as:

$$V_{va} = [I_{sri} - Q_t/A_f - a(T_i - T_o) - ET L_v] / b(T_i - T_e) \quad (21)$$

where a and b were described in equation (10).

Since the evaporative cooling process is an adiabatic exchange of heat, the amount of sensible heat removed from the air equals the amount of heat absorbed by the water evaporated as latent heat of vaporization. Therefore, the difference ( $w_e - w_o$ ) was expressed as:

$$(w_e - w_o) = C_p/L_v (T_o - T_e) \quad (22)$$

Substituting equations (22) and (21) in equation (19) yielded:

$$m_w = \{ [I_{sri} - Q_t - a(T_i - T_o) - ET L_v] / (T_i - T_e) \} d(T_o - T_e) \quad (23)$$

where  $d=1/L_v$ .

In Equation (23), water intake by the evaporative cooling system was a function of solar radiation, ambient and inside temperatures.

## **LIST OF REFERENCES**

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