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Energy Balance Equation for Natural Ventilation of Greenhouses under Unsteady-State Conditions

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Abstract: The design formula currently used to estimate the natural ventilation rate ($\dot{m}_a$) for greenhouses is a fundamental energy balance equation applied to the greenhouse under the steady-state conditions, in which the cover overall heat transmission coefficient (*U*) and its transmittance to solar radiation ($\bar{\tau}_c$) are considered as constant values for the greenhouse. This equation always gives negative values of $\dot{m}_a$ at low solar radiation levels due mainly to: (i) the large spatial variation of $\bar{\tau}_c$ in the greenhouse, (ii) depending of the *U* parameter on the environmental conditions inside and outside the greenhouse and the physical properties of covering material and (iii) neglecting of the heat capacity of the greenhouse components and the soil heat flux. The purpose of this study was to modify the formula to be capable to predict the value of $\dot{m}_a$ precisely under any environmental conditions. Therefore, the *U* parameter was expressed as a function of the temperature difference between inside and outside the greenhouse and the wind speed outside the greenhouse; the transmitted solar radiation was estimated based on the spatial variation of $\bar{\tau}_c$ in the greenhouse; the soil heat flux and the heat capacity of the greenhouse components were included. Results showed that values of $\dot{m}_a$ estimated using the modified formula are more realistic and in accord with measured and simulated results reported in the literature. The negative values of $\dot{m}_a$ resulted from the original formula at low solar radiation levels could be avoided. It was concluded that the thermal masses of the greenhouse components are essential to be considered in the greenhouse energy balance.

Nomenclature

A_c	Surface area of the greenhouse cover (m^2)
A_f	Surface area of the greenhouse floor (m^2)
A_L	Effective area around the location L in the greenhouse (m^2)
C_p	Specific heat at constant pressure ($J\ kg^{-1}\ °C^{-1}$)
h_i	Specific enthalpy of moist air inside the greenhouse ($J\ kg^{-1}$)
h_o	Specific enthalpy of moist air outside the greenhouse ($J\ kg^{-1}$)
k_s	Equivalent thermal conductivity of the greenhouse soil ($W\ m^{-1}\ °C^{-1}$)
m	Mass of the cover, air, plants, external and internal structures (kg)
$\dot{m}_a$	Ventilation rate of the greenhouse air ($kg\ s^{-1}$)
r^2	Coefficient of determination
S_i	Global solar radiation flux transmitted into the greenhouse ($W\ m^{-2}$)
S_o	Global solar radiation flux outside the greenhouse ($W\ m^{-2}$)
T_c	Cover outer surface temperature (°C)
T_i	Mean dry bulb temperature of air inside the greenhouse (°C)
T_o	Dry bulb temperature of air outside the greenhouse (°C)
T_f	Floor surface temperature (°C)
T_∞	soil temperature at a certain depth (°C)
U	Overall heat transmission coefficient of the greenhouse cover ($W\ m^{-2}\ °C^{-1}$)
V	Wind speed outside the greenhouse ($m\ s^{-1}$)
z	Vertical depth in the greenhouse soil, measured from the floor surface (m)

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Greek symbols

$\bar{\tau}_c$ Average transmittance of the greenhouse cover to global solar radiation (-)

ψ Cover to floor surface area ratio (A_c/A_f)

$\tau_{c,L}$ Local transmittance of the cover at a location L in the greenhouse (-)

ω Absolute humidity (kg of water vapor/ kg of dry air)

Key words: Greenhouse · Ventilation · Sensible Heat Balance · Modified Formula

INTRODUCTION

Adjusting the amount of ventilation per unit time is seriously important for suitable environment for plant growth in the greenhouse. The ventilation rate can be estimated by applying the energy balance to the greenhouse air [1-5]. However, this method requires a determination of the fraction of solar energy used for evapo-transpiration in the greenhouse. This fraction depends on the plant and soil characteristics and needs to be determined separately when the greenhouse includes an evaporative cooling system in summer. Therefore, a design tool, such as a mathematical formula, that can be used on-line to calculate the ventilation rate ($\dot{m}_a$) is desirable. The most popular formula used to estimate the ventilation rate is based on a fundamental energy balance applied to the greenhouse air under the steady-state condition. In many areas of the world, the greenhouse vents are usually closed during nighttime because the greenhouse air temperature drops below the set point temperature (25-28°C). During the daytime, the energy balance equation of the greenhouse air is given by Mihara [6] as:

$$\dot{m}_a = S_o\bar{\tau}_c - \psi U(T_i - T_o)/(h_i - h_o) \qquad (1)$$

Where $\dot{m}_a$ is the ventilation rate of moist air (kg s^{-1} m^{-2} [floor area]); S_o is the outside solar radiation flux (W m^{-2}); $\bar{\tau}_c$ is the average cover transmittance to global solar radiation (constant value); ψ is the cover to floor area ratio (A_c/A_f); U is the cover over all heat loss coefficient (W m^{-2} °C^{-1}); T_i is the mean dry bulb temperature inside the greenhouse (°C); T_o is the dry bulb temperature of the outside air (°C) and (h_i-h_o) is the specific enthalpy difference of the moist air between inside and outside the greenhouse (J kg^{-1}). Limitations of using Eq. (1) as reported by Mihara [6] are: $S_o > 230$ W m^{-2}; $(h_i-h_o) > 8.368$ kJ kg^{-1} and the time interval should be higher than 20 min. Reasons of these limitations may attribute to: (i). The effects of the soil heat flux (q_s) and the heat capacity of the greenhouse components (i.e., plants, internal structures, etc) are neglected. (ii) Constant values of $\bar{\tau}_c$ and U are used in Eq. (1). However, the soil heat flux has significant effects if the plant canopy density is low. On the other hand, if dense plants exist in the greenhouse, the heat capacity of the plants can not be neglected whereas the soil heat flux can be neglected. Spatial variations of $\bar{\tau}_c$ (i.e., the highest minus the lowest value) was found to be 0.4 [7] and 0.8 [8]. The value of U strongly depends on the environmental conditions inside and outside the greenhouse and the physical properties of covering materials. Accordingly, substituting constant values of $\bar{\tau}_c$ and U may result in a large error in $\dot{m}_a$ from Eq. (1) Furthermore, when S_o is low in the morning and afternoon, Eq. (1) results in negative values of $\dot{m}_a$. To this end, conclusions can be drawn as follows: *a*) Total energy (sensible and latent heat) balance is adequate method to estimate $\dot{m}_a$ rather than the sensible heat balance. *b*) The un-steady state analysis is necessary to estimate $\dot{m}_a$ because the natural ventilation in the greenhouses is a transient phenomenon. *c*) Including the soil heat flux (q_s) and the heat capacity of the greenhouse components is essential to avoid the negative values of $\dot{m}_a$ in the morning and afternoon.

The objective of this study was to make Eq. (1) applicable to estimate $\dot{m}_a$ precisely for any greenhouse at any location and under any environmental conditions inside and outside the greenhouse by: (I) estimating the transmitted solar radiation into the greenhouse more accurately by considering the spatial variation of $\bar{\tau}_c$ in the greenhouse, (ii) expressing the parameter U as a function of the environmental conditions inside and outside the greenhouse and (iii) considering the heat capacities of the greenhouse components and the soil heat flux.

ENERGY BALANCE OF THE GREENHOUSE

In Fig. 1, the greenhouse is considered as a controlled volume (*cv*) surrounded by a control surface. The control surface of this volume was chosen to pass through the middle of the cover thickness and at very thin layer below the floor surface. Accordingly, the heat capacity of the greenhouse soil can be excluded.

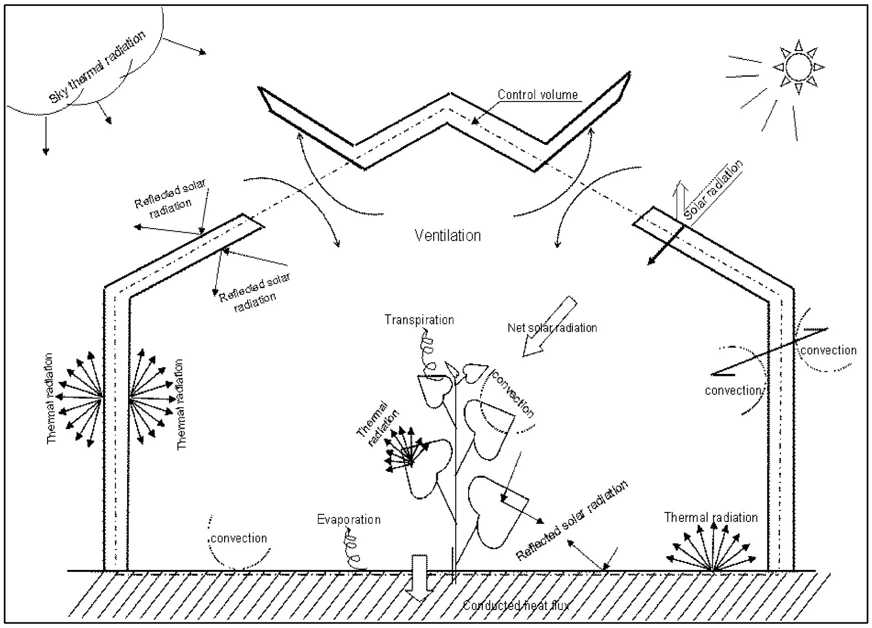

Fig. 1: Schematic diagram of the greenhouse and its control volume (cv) and the different modes of energy exchange

The convection exchanges between the inside greenhouse air and the surface of the floor and the inner surface of the cover; and between the outside ambient air and the outer surface of the cover can be excluded. The greenhouse cover was assumed opaque to thermal radiation. Thermal radiation exchanges among the floor surface, plants and the inner surface of the cover are remaining inside the control surface. Therefore there is no thermal radiation crosses the greenhouse cover.

The different modes of energy exchange between inside and outside the control volume (*cv*) crossing the control surface are: (i) The global (direct plus diffuse) solar radiation transmitted into the greenhouse ($S_o \bar{\tau}_c$). (ii) The energy (sensible and latent heat) associated with the ventilated air ($\dot{m}_a h_o$ and $\dot{m}_a h_i$ in W). (iii) The heat flux conducted in the soil upward or downward (q_s). (iv). The sensible heat exchanges between inside and outside the greenhouse cover [$UA_c(T_i - T_o)$ in W], A_c is the surface area of the greenhouse cover (m^2). An energy balance under the un-steady state condition was applied to the greenhouse *cv* in Fig. 1, based on the unit area of floor leads to the following equation:

$$\dot{m}_a = S_o\bar{\tau}_c - U\psi(T_i - T_o) - q_s - \sum_{cv}\left(mC_p\frac{dT}{dt}\right)\Big/(h_i - h_o) \qquad (2)$$

Eq. (2) is the modified form of Eq. (1), in which the new and modified terms are as follows:

The Overall Heat Transmission Coefficient (*U*): Detailed analysis of the parameter *U* for a naturally ventilated, fog-cooled glass- house under unsteady-state conditions was reported by Abdel-Ghany and Kozai [9]. The *U* parameter was estimated based on different environmental conditions inside and outside the greenhouse. The effects of the radiative properties of the covering material on the value of *U* were included. The convective and radiative resistances on the inner and outer surfaces of the cover were also included. Value of *U* was found to strongly depend on the wind speed outside the greenhouse (*V*) and the temperature difference between inside and outside (T_i-T_o). However, the relative humidity of air in the greenhouse had no significant effect on the *U* parameter [9]. A parametric study was conducted to investigate the effects of different environmental parameters on the value of *U*. Based on this study, Fig. 2(a) illustrates the *U* parameter as affected by *V* in m s^{-1} and (T_i-T_o) in °C for an incident solar radiation flux (S_o) equals to 900 W m^{-2} and a relative humidity in the greenhouse equals to 90%. Three-dimensional analysis was applied to the results using Table Curve-3D software package (Ver-4.0, SYSTAT). The *U* parameter could be plotted as a function of *V* in m s^{-1} and (T_i-T_o) in °C [Fig. 2(b)] and a correlation with coefficient of determination (r^2) of 0.92 could be obtained in the form:

$$U = \mathrm{Exp}\Big(1.108 - V^{0.5}\left[0.0895\times\ln(V) - 0.359\right] + 753\times10^{-6}(T_i - T_o)^2\Big) \qquad (3)$$

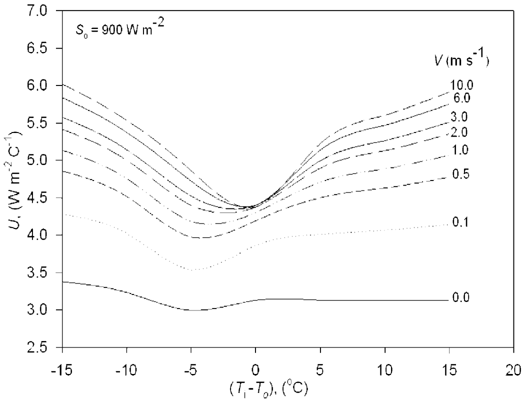

Fig. 2(a): The overall heat transmission coefficient (U) as affected by the wind speed (V) outside the greenhouse and the inside-outside greenhouse air temperature difference (T_i-T_o).

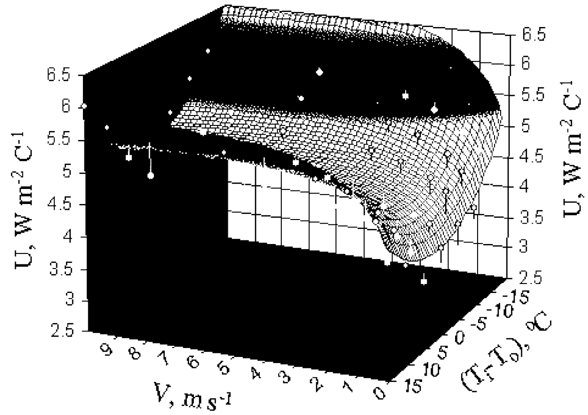

Fig. 2(b): Three-dimensional plot and the fitting surface represents for the parameter U as a function of (V) and (Ti-To).

The Soil Heat Flux (q_s): Value of q_s can be measured or approximately calculated assuming: the floor soil is a homogeneous layer having a depth z (m), an equivalent thermal conductivity k_s (in W m^{-1} °C^{-1}), an upper surface temperature T_f (i.e. floor surface temperature in °C) and a lower constant subsoil temperature T_∞ in °C (i.e. unaffected by the diurnal variations of T_f and S_i). For a small time interval, the quasi-steady state condition, one dimensional conduction can be applied. Within a time interval of 5 seconds, q_s (in W m^{-2}) can be approximated as:

$$q_s = k_s(T_f - T_\infty)/z \tag{4}$$

Where value of k_s was taken to be 2.0 W m^{-1} °C^{-1} [10] and values of z and T_∞ were taken to be 0.5 m and 20 °C, respectively [2-4].

Greenhouse Transmittance to Solar Radiation ($\bar{\tau}_c$): The greenhouse local transmittance ($\tau_{c,L}$) was measured at different locations L, (L= 1, 2, 3, ...n) in the greenhouse. The spatial distribution of these locations in the greenhouse is illustrated in Fig. 3 and value of $\bar{\tau}_c$ in Eq. (2) was estimated as:

$$\bar{\tau}_c = \sum_{L=1}^{n} A_L \tau_{c,L} \Big/ \sum_{L=1}^{n} A_L \tag{5}$$

Where n is the number of locations and A_L is the effective area for $\tau_{c,L}$ around the location L (in m^2)

The Heat Capacities of Masses in the Greenhouse Control Volume $\sum_{cv}(mC_p dT/dt)$: This summation is the rate of change of stored energy of the masses enclosed in the cv of the greenhouse, in which the mass m (in kg), the specific heat C_p (in J kg^{-1} °C^{-1}) and the change of temperature with time dT/dt (in °C s^{-1}) were estimated for half of the covering material, half of the aluminum frame constructing the greenhouse envelope, plants, greenhouse air and the internal structure. This can be expressed as:

$$\sum_{cv}(mC_p dT/dt) = 0.5\left(mC_p dT/dt\right)_{\text{cover}} + 0.5\left(mC_p dT/dt\right)_{\text{aluminum frame}} + \left(mC_p dT/dt\right)_{\text{internal structure}} + \left(mC_p dT/dt\right)_{\text{plants}} + \left(mC_p dT/dt\right)_{\text{inside air}} \tag{6}$$

In the present study, the greenhouse was without plants, so that the term $(mC_p\ dT/\ dt)_{\text{plants}}$ in Eq. (6) was excluded in the calculation. In the descript numerical solution, $dT/\ dt$ will be replaced by $\Delta T/\Delta t$ for small time intervals (5 seconds). Including the heat capacity of the greenhouse cv in addition to q_s in Eq. (2) makes this equation valid to estimate $\dot{m}_a$ more correctly at low or even at zero solar radiation flux and the negative results from Eq. (1) can be avoided in the early morning and late afternoon.

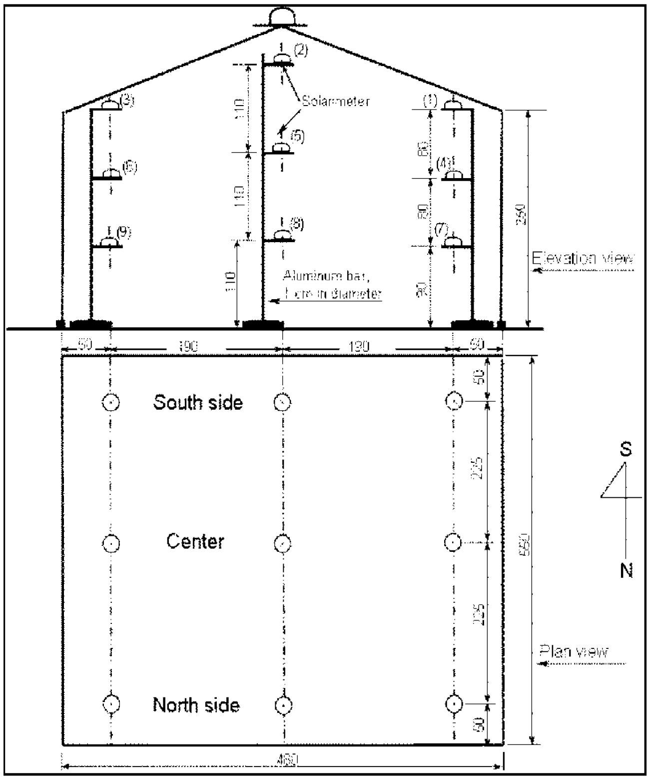

Fig. 3: Outline of the experimental greenhouse and the locations of the sensors used to measure solar radiation inside and outside the greenhouse, (dimensions in cm, not to scale)

EXPERIMENTAL MEASUREMENTS

The experiment was conducted in a 26 m^2 glass-covered, single-span greenhouse without plants (Fig. 3). The greenhouse was oriented in a N-S direction on the Matsudo campus, Chiba University (Tokyo area, Japan, 139.46°E, longitude and 35.41°N, latitude). The greenhouse was naturally ventilated using two roof ventilators (0.6 m x 5 m) that are automatically full opened for $T_i \geq 28°C$. The floor soil was covered with a black PVC plastic sheet. The measurements were carried out on sunny day (Oct 14, 2005) from 6:00 to 18:00. Required parameters were measured at 5-sec intervals and averaged over 30-min and recorded in the data logger (CR23X Micrologger, Campbell Scientific Inc). These parameters were: (i). The dry and wet bulb temperatures inside and outside the greenhouse. (ii) The outside wind speed (V). (iii) Temperatures of the floor surface (T_f) at different locations on the floor; the inner surface of the greenhouse cover (T_c) and the aluminum frame at different locations on the cover and on the frame using bare thermocouple junctions (0.3 mm in diameter) and the average value for each were considered. The effect of radiation on these junctions was excluded by using a correction factor suggested by Abdel-Ghany *et al.* [11] in the form:

$$\Delta T_R = -0.22 + 5.11\left(1.0 - e^{-.0024 S_i}\right) \quad r^2 = 0.94 \tag{7}$$

In Eq. (7) ΔT_R is the value of temperature in degree °C that should be subtracted from the measured value by the thermocouple and S_i is the transmitted solar radiation flux into the greenhouse. (iv) The global solar radiation flux outside the greenhouse (S_o) and at 27 locations spatially distributed inside the greenhouse (S_i) using MS-100 solarmeters (EKO-Instruments Trading Co. Ltd., Japan). The spatial distribution of the solarmeters at the north, center and south side in the greenhouse is illustrated in Fig. 3. Value of the local cover transmittance to global solar radiation ($\tau_{c,L}$) and the effective area (A_L), $L = 1, 2\ldots 27$ were estimated at each location to be used in Eq. (5). The specific enthalpy h_o, h_i in J kg^{-1} was estimated as a function of the dry bulb temperature (T) and the absolute humidity of the air (ω) using a correlation reported by Abdel-Ghany *et al.* [12] as:

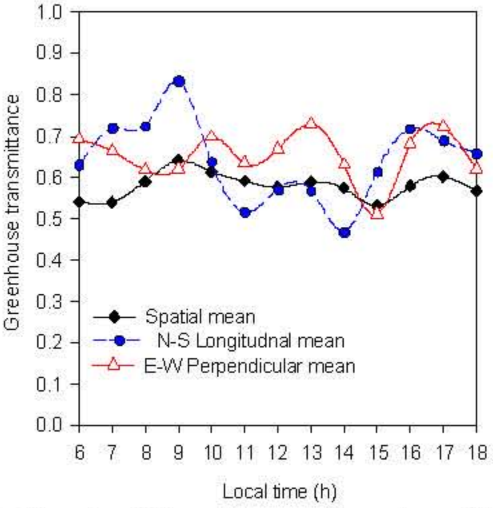

Fig. 4: Diurnal variation of the greenhouse transmittance ($\bar{\tau}_c$) estimated using three different methods.

$$h = (1.007T - 0.026) + \omega(250 + 1.84T),\ T \text{ in } ^\circ\text{C} \quad (8)$$

RESULTS AND DISCUSSION

During the day of measurements the apparent low value of $\tau_{c,L}$ at a certain time that was occurred by the shading effect of the inside greenhouse solid structure was replaced by the arithmetic mean of $\tau_{c,L}$ values before and after this time. Maximum difference of $\tau_{c,L}$ was observed in the greenhouse to be 0.6 between the locations 2 and 4 at the south side; 0.5 between the locations 3 and 7 at the center; and 0.5 between the locations 3 and 8 at the north side (Fig. 3). These differences showed the need of considering the spatial variation of $\tau_{c,L}$ when calculating the greenhouse transmittance ($\bar{\tau}_c$). Fig. 4 illustrates the time courses of $\bar{\tau}_c$ estimated from Eq. (5) (i.e., spatial mean) compared with $\bar{\tau}_c$ estimated using two other methods (i.e., N-S longitudinal mean and E-W perpendicular mean). The N-S longitudinal mean is the arithmetic mean of $\tau_{c,L}$ values located on a vertical plan located longitudinally in the N-S direction, at the middle of the greenhouse (L = 2, 5, 8 at north, center and south locations in Fig. 3). The E-W perpendicular mean is arithmetic mean of $\tau_{c,L}$ values, L = 1,2,3,...9 at the center of the greenhouse (Fig. 3). In Fig. 4, both methods give higher or lower values of $\bar{\tau}_c$ than the spatial mean through all the daytime. Therefore, considering the spatial distribution of $\tau_{c,L}$ when calculating the value of $\bar{\tau}_c$ is necessary because it is more representative for the greenhouse transmittance.

During the period when the ventilators are opened, values of $\dot{m}_a$ estimated by using three methods and presented in Fig. 5. These methods are: (i) The un-steady state condition using Eq. (2), (the heat capacities of the greenhouse components and the soil heat flux were considered). (ii) The steady state condition using Eq. (2), (the heat capacities of the greenhouse components were neglected and the soil heat flux was considered). (iii). The steady state condition using Eq. (1), (the heat capacities and the soil heat flux were neglected). Fig. 5 showed that values of $\dot{m}_a$ estimated from Eq. (2) are more realistic specially in the after noon. The results in Fig. 5 emphasize the necessity of considering the heat capacities of the greenhouse components and the soil heat flux in the energy balance equation for calculating $\dot{m}_a$ in order to avoid the negative or zero values of $\dot{m}_a$ at low solar radiation levels. The zero or negative values of $\dot{m}_a$ from Eq. (1) are attributed to the fact that in the late afternoon the warm air in the greenhouse is cooling down and the heat loss from the greenhouse is higher than the input solar energy to the greenhouse. At that time, the soil and the greenhouse components release a sensible heat to the greenhouse air which was neglected in Eq. (1).

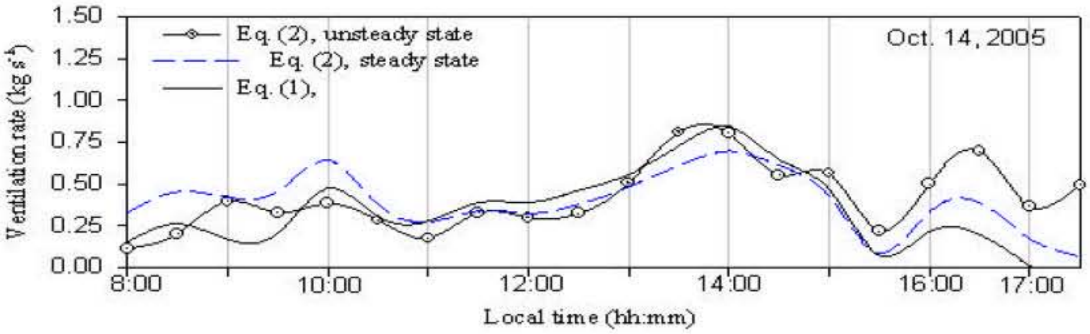

Fig. 5: Time courses of the natural ventilation rate ($\dot{m}_a$) estimated by using the modified formula [Eq. (2)] in the steady and the unsteady state conditions and Eq. (1)

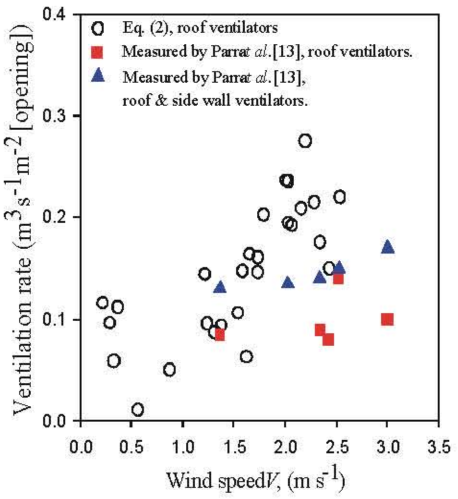

Fig. 6: Ventilation rate ($\dot{m}_a$) per unit area of vent opening estimated by using the modified formula in comparison with the measured values of Parra *et al.*, [13] as affected by the wind speed (V) outside the greenhouse.

Ventilation rate depends on the design configuration and the environmental conditions inside and outside the greenhouse. Therefore, it was not possible to directly compare the results of the present study with those measured in different greenhouses under different conditions. However, to show the order of magnitude, values of $\dot{m}_a$ (from Eq. (2) per unit area of vent opening) are plotted in Fig. 6 against the wind speed *V* outside the greenhouse. In addition, values of $\dot{m}_a$ measured by Parra *et al.* [13] in two cases (i.e., roof & roof and side wall ventilators in multi-span greenhouse) are also presented. Values of $\dot{m}_a$ measured by Parra *et al.* [13] are lower than those estimated using Eq. (2) because the greenhouse used in the present study was small ($A_f = 26\ m^2$) with two roof ventilators compared with the multi-span greenhouse of Parra *et al* [13], ($A_f = 882\ m^2$) that had one roof ventilator per span. Moreover, the two side wall ventilators in the large, multi-span greenhouse did not significantly enhance the ventilation rate that depends mainly on the roof ventilators.

CONCLUSION

The modified formula presented in this study (Eq. 2) was based on an energy balance applied to greenhouse under the unsteady state condition. This formula is a design tool that can be used on-line to estimate the natural ventilation rate more accurately at any environmental conditions. Temperatures of the greenhouse components and the floor surface in addition to the heat capacities of these components are needed. However, applying an energy balance under the steady state condition and neglecting the soil heat flux as in Eq. (1) results an error in the natural ventilation rate, especially at low solar radiation flux. The calculated results using the modified formula in the current paper were realistic and in accord with those measured and reported in the literature.

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