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Modified thermal model to predict the natural ventilation of greenhouses

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ABSTRACT

Most of thermal models used to estimate the natural ventilation of greenhouses ($\dot{m}_a$) use an average value for the cover transmittance (τ_c) to estimate the input solar energy to the greenhouse. These models failed to predict $\dot{m}_a$ at low solar radiation flux due to the spatial variation of τ_c in the greenhouse and the thermal inertia of soil. This study is to develop and validate a thermal model predict $\dot{m}_a$ precisely. All modes of energy were treated, under the unsteady state conditions, at the outer surface of the cover to avoid the sources of error. The required parameters were measured for a naturally ventilated glasshouse. The predicted values of $\dot{m}_a$ were in the range between 0.36 kg s^{-1} and 1.65 kg s^{-1} and showed good accordance with measured and simulated values in the literature. The results also confirmed that outside wind at a speed <2.5 m s^{-1} has no significant effect on the value of $\dot{m}_a$ and the temperature difference of air between inside and outside the greenhouse (ΔT) is the main driving force of ventilation. A correlation between $\dot{m}_a$ and ΔT was provided, it can be used to estimate $\dot{m}_a$ that required to maintain the air temperature in the greenhouse at a desired level.

1. Introduction

Ventilation of greenhouses plays a major role in providing a suitable environment for plant growth. In summer, ventilation is for cooling the greenhouse air, and in winter ventilation can remove excess humidity from the greenhouse. Recently, most greenhouse ventilation studies have been focusing on the use of natural ventilation to reduce electric energy consumption by greenhouses. Although investigation of natural ventilation in the greenhouses started since 50 years ago, there is still no adequate method to precisely predict the amount of natural ventilation [1]. Based on the survey of the previous researches performed in this area, the main methods that have been used to estimate the natural ventilation rate of greenhouses and the problems associated with each method can be summarized as follows:

(i) Measuring methods, in which, a tracer gas such as N_2O or CO_2 is injected in the greenhouse and the decay rate of the gas concentration is measured [2–8]. These methods can measure the ventilation rates during the time of experiments only. However, the ventilation rate strongly depends on the environmental conditions and on the greenhouse design parameters. Therefore, developing theoretical models to estimate the ventilation rate of greenhouses was essential need.
(ii) Air dynamic models, in which, ventilation was assumed to be driven by two forces, namely, the wind force and the buoyancy force and such models is used only for greenhouses with roof vents [9]. The resulted ventilation rate from these models depends on two critical dimensionless coefficients, (i.e., the discharge coefficient and the wind coefficient). However, these coefficients are usually determined by in situ measurements and differ from greenhouse to greenhouse, and depend on the design configuration of the vents, greenhouse location, orientation and environmental conditions. Several values for the wind coefficient (0.006–0.28) and for the discharge coefficient (0.4–0.848) were reported in the literature [9–11].
(iii) Energy balance models, in which, energy balances are applied to the greenhouse air. A simple design formula was suggested by [12] to estimate $\dot{m}_a$ based on the fundamental heat balance of the greenhouse. This formula assumed the air is completely mixed in the greenhouse and is given by:

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Nomenclatures

A_c surface area of the greenhouse cover (m^2)
A_f surface area of the greenhouse floor (m^2)
C_{pa} specific heat of air at constant pressure (J kg^{-1} °C^{-1})
d greenhouse cover thickness (m)
f_d ratio of diffuse to global solar radiation (–)
h_{c-o} convective heat transfer coefficient between the cover surface and the outside ambient air (W m^{-2} °C^{-1})
I_i specific enthalpy of moist air inside the greenhouse (J kg^{-1})
I_o specific enthalpy of moist air outside the greenhouse (J kg^{-1})
j surface number of the greenhouse cover (1,2,. . ., 6)
k_f equivalent thermal conductivity of the greenhouse soil (W m^{-1} °C^{-1})
$\dot{m}_a$ ventilation rate of the greenhouse (kg s^{-1})
N_a number of air exchange per hour (h^{-1})
n refractive index of the covering material (–)
Q_{c-o} convection heat rate between the cover surface and outside ambient (W)
q_o heat rate conducted into the greenhouse soil surface (W)
R_n net thermal radiation exchange between the cover and sky (W)
r_b ratio of beam irradiance received by a tilted surface to that received by a horizontal surface (–)
S_i global solar radiation flux transmitted into the greenhouse (W m^{-2})
S_L solar radiation loss to outside the greenhouse (W m^{-2})
S_n net global solar energy crossing the control volume of the greenhouse (W)
S_o global solar radiation flux at the greenhouse outer surface (W m^{-2})
T_c cover outer surface temperature (°C)
T_i air temperature inside the greenhouse (°C)
T_o air temperature outside the greenhouse (°C)
T_f floor surface temperature (°C)
T_{sky} equivalent temperature of sky (°C)
U overall heat loss coefficient of the greenhouse cover (W m^{-2} °C^{-1})
V wind speed outside the greenhouse (m s^{-1})
V_g volume of the greenhouse air (m^3)
z vertical depth under the greenhouse measured from the soil surface (m)

Greek symbols
α_c absorptance of the cover to global solar radiation (–)
β slope angle of the cover surface (degree)
ΔI specific enthalpy difference (I_i–I_o) (J kg^{-1})
ΔT temperature difference (T_i–T_o) (°C)
δ evaporation efficiency (–)
γ_s surface azimuth angle (degree)
η solar radiation heating efficiency (–)
κ absorption coefficient of the cover material (m^{-1})
θ incidence angle of direct solar radiation (degree)
θ_r angle of refraction (degree)
θ_z solar zenith angle (degree)
ρ_a ensity of moist air (kg m^{-3})
$\rho_{c,j}$ directional reflectance of the cover surface j to direct beam solar radiation (–)
$\bar{\rho}_{c,j}$ directional reflectance of the cover surface j to global solar radiation (–)
$\hat{\rho}$ nterface reflectance between the cover surface and air (–)
ρ_f reflectance of the floor surface to global solar radiation (–)
τ_c average transmittance of the greenhouse cover to global solar radiation (–)
$\tau_{c,j}$ directional transmittance of the cover surface j to direct solar radiation (–)
$\hat{\tau}$ transmittance due to absorption of solar radiation in the cover material (–)
ω absolute humidity (kg of water vapor/kg of dry air)

$$\dot{m}_a = \frac{S_o \tau_c A_f - U A_c \Delta T}{\Delta I}, \qquad (\Delta I > 0.0) \tag{1}$$

This equation has been modified, based on the sensible heat balance of the greenhouse air and used as ASAE-STD and reported in [9] in the form:

$$\dot{m}_a = \frac{(1-\delta)\tau_c S_o A_f - U A_c \Delta T}{C_{pa} \Delta T} \tag{2}$$

In Eqs. (1) and (2), S_o is the global solar radiation flux on a horizontal surface outside the greenhouse; τ_c is the average transmittance of the greenhouse cover to solar radiation; A_f and A_c are the surface areas of the greenhouse floor and cover; U is the overall heat loss coefficient of the cover; ΔI is the moist air specific enthalpy difference between inside and outside the greenhouse (I_i–I_o); C_{pa} is the specific heat of air at constant pressure and δ is an "evaporation coefficient", which estimates the fraction of total solar radiation load taken up by evaporation in the greenhouse. No details are given in the literature for the proper selection of δ, and standard examples often use $\delta = 0.5$. The term $(1-\delta)\tau_c$ in Eq. (2) is also defined as the solar radiation heating factor η, (i.e. the fraction of S_o that was converted into sensible heat and used to warm up the greenhouse air). Several values of η are reported in the range between 0.3 and 0.7 [13–15]. Determination of δ as well as η value is quite difficult, especially if the greenhouse includes a crop canopy and associated with an evaporative cooling in summer. Limitations of using Eq. (1) as reported in [12] are: $S_o > 230$ W m^{-2}; $\Delta I > 8.368$ kJ kg^{-1} and the time interval should be higher than 20 min. In summer, values of ΔI and ΔT in Eqs. (1) and (2) are always positive during the daytime, even though, these equations resulted in negative values of $\dot{m}_a$ at low solar radiation levels.

Several previous studies estimated the natural ventilation rate of greenhouses by using energy balance methods. All of these studies assumed that solar radiation transmitted into the greenhouse was the only input energy and used an average value of the cover transmittance (τ_c). However, τ_c depends on the spatial location within the greenhouse and on the altitude of the greenhouse. The maximum longitudinal variation of τ_c over the floor surface in a venlo-type N–S glasshouse (4 mm thick of cover) was measured by [16] at the location 52°20′N to be 0.4. In addition, the maximum spatial variation of τ_c was measured by [17] in a scale model of a glasshouse (4 mm thick of cover) at the location 37°58′N to be 0.8. Accordingly, using an average value of τ_c will cause a large error in the estimation of the transmitted solar radiation into the greenhouse and in the estimation of $\dot{m}_a$ as well. This error is expected to be high in small greenhouses because the cover to floor surface area ratio is usually high (e.g., 3–5), and unfortunately most of the ventilation studies using an energy balance method or any other method were based on experimental greenhouses.