INFLUENCE OF AN INSECT SCREEN ON GREENHOUSE VENTILATION

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ABSTRACT. *The influence of an insect screen on ventilation rate was experimentally investigated in a multispan glass–covered greenhouse equipped with a continuous roof vent, located at the University of Thessaly near Volos in the coastal area of eastern Greece. Microclimate variables as well as the ventilation rate were measured during summer. Two measuring techniques were used for the determination of ventilation rate: (1) the decay rate tracer gas technique, using* N_2O *as tracer gas, and (2) the water vapor balance technique. The influence of the insect screen on ventilation rate was studied using a wind–related coefficient identified by fitting a simple linear model to the experimental values. The two measuring techniques gave similar results, but the water vapor balance technique provided a better fit to the experimental data. The wind–related coefficient significantly decreased when an insect screen covered the vent. Finally, the influence of the insect screen on the discharge coefficient was investigated. The discharge coefficient was correlated to the aerodynamic properties of the screen using porous media flow analysis.*

Keywords. *Natural ventilation, Screened openings, Ventilation rate, Tracer gas, Discharge coefficient.*

Greenhouse ventilation induced by wind and temperature effects directly affects greenhouse environmental conditions such as temperature, humidity, and carbon dioxide concentration, and thus it is the main mechanism for greenhouse climate control. Under Mediterranean climate conditions (with high radiation loads), a good air temperature and humidity control is crucial (Boulard and Baille, 1993). Over the last two decades, several studies have dealt with the determination of the ventilation rate. Different techniques have been used to determine ventilation rate, with tracer gas (Bot, 1983; de Jong, 1990; Fernandez and Bailey, 1992; Boulard and Draoui, 1995; Kittas et al., 1995) and energy balance (Deltour et al., 1985; Boulard and Baille, 1993; Wang, 1998) the most widely used ones.

In order to prevent insect intrusion and to decrease insecticide use, many growers have recently adopted the use of insect screens in ventilation openings. The use of screens in ventilation openings has a considerable effect on greenhouse microclimate by affecting the ventilation rate. Several studies were initiated to analyze the influence of insect screens on natural ventilation. Miguel (1998) used the porous media flow approach to characterize the aerodynamic properties of a screen (i.e., permeability and inertia factors). Other authors used the discharge coefficient to evaluate the influence of screens on greenhouse natural ventilation (Sase and Christianson, 1990; Kosmos et al., 1993). Munoz et al. (1999) studied the influence of screens on ventilation rate and on the wind–effect coefficient. They found a reduction of both wind–effect coefficient and overall ventilation rate.

The aim of this study was to increase the available information concerning the influence of insect screens in vent openings on the ventilation rate of a full–scale greenhouse. For this purpose, we measured the ventilation rate in a greenhouse equipped with insect screens in the vent openings using two different measurement techniques: (1) the decay rate tracer gas method, using N_2O as a tracer gas, and (2) the water vapor balance technique. The results allowed us to:

- Compare the two measuring methods.
- Determine the effect of insect screens on wind–driven ventilation.
- Present, discuss, and calibrate a simple formula for the prediction of ventilation rate.
- Present information about the ventilation discharge coefficient.

MATERIAL AND METHODS

GREENHOUSE FACILITIES AND PLANT MATERIAL

The experiments were carried out during June 1999 in an experimental bi–span glass–covered greenhouse, with the gutters oriented north–south, located at the University of Thessaly near Volos (latitude 39° 44', longitude 22° 79') in the coastal area of eastern Greece. The geometrical characteristics of the greenhouse were: eave height = 2.9 m, and ridge height = 3.95 m. Each span was isolated from the other by an internal glass wall. The span characteristics were: width = 6.5 m, length = 31 m, floor area (A_f) = 200 m^2, and volume (V) = 690 m^3 (including the volume above the

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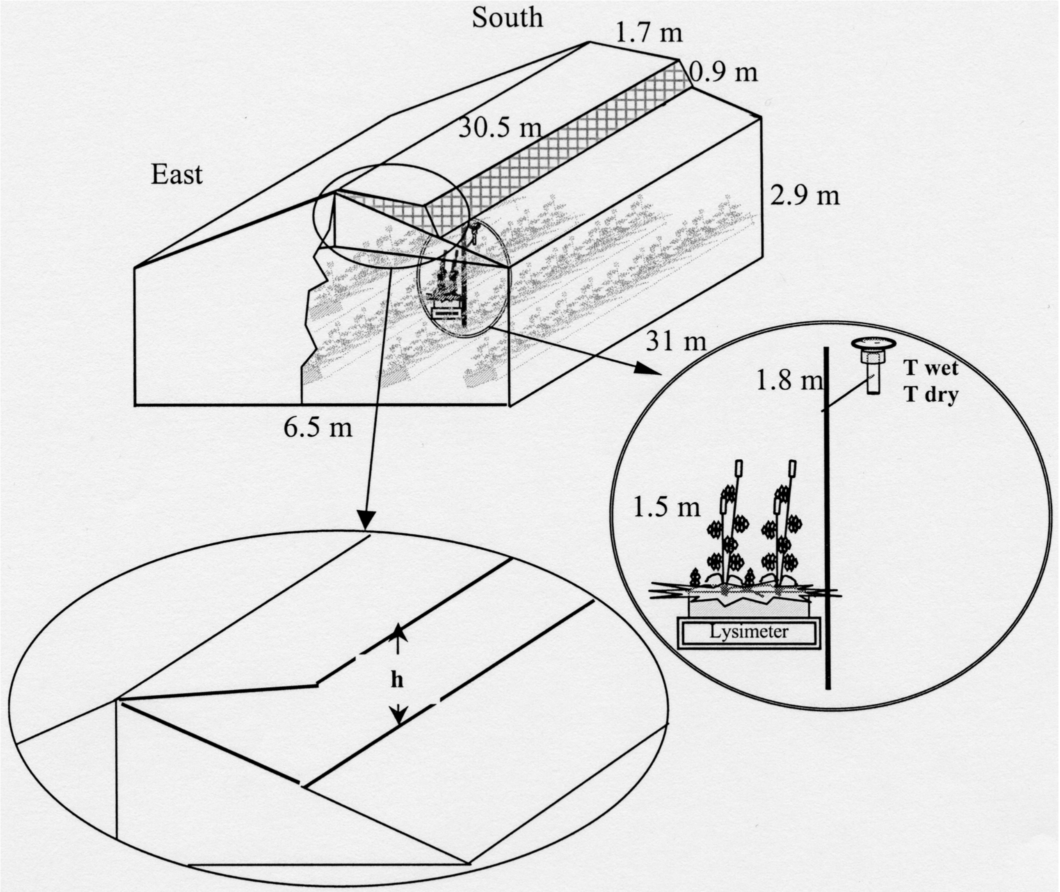
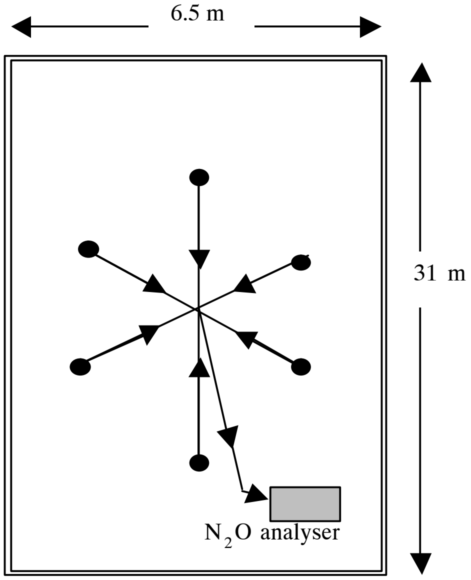


(a)



(b)

Figure 1. (a) Experimental greenhouse and meteorological instruments, and (b) distribution of pipes used for air sampling in the greenhouse.

gutters). Each span was equipped with a single continuous roof vent located at the west side (fig. 1a). The prevailing wind of the region has a north–south direction. The vent was 30.5 m long and 1.70 m wide. Two different cases were examined: (1) a span without screen, and (2) a span with an insect screen installed in the ventilation opening.

Screen porosity (ε) can be defined as the fraction of the total volume of a screen occupied by void space. Since insect screens are usually made of thin materials, their porosity can be calculated as the fraction of the total area of the screen occupied by air space. For this study, the porosity of the screen used in the greenhouse opening was 0.6 m^2/m^2.

Both spans were occupied by a rose crop (*Rosa hybrida*, cv. First Red) planted on March 1997 in containers filled with perlite, with a plant density of 6 plants m^{-2}. Water and fertilizers were supplied every hour from 6:00 to 21:00 via a drip system, which was automatically controlled by a fertigation computer. During the period of measurements, the plant height was about 1.5 m.

CLIMATE MEASUREMENTS

Inside and outside wet and dry bulb temperatures were recorded using aspirated psychrometers located at a height of 1.80 m in the middle and outside of the greenhouse. Wind speed, wind direction, and solar radiation were measured using a cup anemometer (model AN1–UM–3, Delta–T devices, Cambridge, U.K.), a wind vane (model WD1–UM–3, Delta–T devices, Cambridge, U.K.), and a pyranometer (model CM–6, Kipp and Zonen, Delft, The Netherlands), respectively, located on a mast 4 m above the ground at a distance of 15 m from the greenhouse. Transpiration rate (Tr) was measured every 10 minutes by means of a weighing lysimeter located in a central row of the greenhouse compartment. The device includes: an electronic balance (scale capacity of 12.1 kg, resolution of ±0.1 g) equipped with a tray carrying three plants. The mean value (period 9:00 to 19:00 h) of the latent heat used for Tr was about 208 W m^{-2}. All the above measurements were recorded with a data logger (model DL3000, Delta–T devices, Cambridge, U.K.) with a 1 Hz measuring frequency.

VENTILATION RATES MEASUREMENTS

Two different measuring techniques were used in order to estimate the effect of the insect screen on ventilation rate: (1) the decay rate tracer gas technique (Nederhoff et al., 1983), and (2) the water vapor balance technique (Boulard and Draoui, 1995).

The ventilation measurements were based on the mass balance of natural (H_2O) or artificial (N_2O) components of the greenhouse air. Assuming homogeneity of the gas (H_2O or N_2O) within the air, the following relation holds:

$$V\frac{dC_i}{dt} = Q(t)\left[C_i(t) - C_o(t)\right] \pm F_i(t) \qquad (1)$$

where

Q = ventilation rate (m^3 s^{-1})
V = greenhouse volume (m^3)
C_i and C_o = inside and outside concentration of tracer gas (kg m^{-3})
$F_i(t)$ = rate of supply or removal of tracer gas within the greenhouse (kg s^{-1}).

Knowing the inside and outside concentration of the tracer gas and the $F_i(t)$ values, we can calculate ventilation rate (Q).

The Decay Rate Tracer Gas Technique

The decay rate tracer gas technique is based on the mass balance of greenhouse air. With this technique, the tracer gas (N_2O) is injected in the greenhouse up to the full scale of the analyzer. If the decrease of gas internal concentration is measured over time, $C_i(t)$ and $F_i(t)$ and $C_o(t)$ are equal to zero, then the ventilation rate (Q) can be deduced using the following relation:

$$C_i(t) = C_i(t_0)\,e^{-[(Q/V)(t-t_0)]} \qquad (2)$$

or:

$$Q = -\frac{V}{(t - t_0)}\ln\left(\frac{C_i(t)}{C_i(t_0)}\right) \qquad (3)$$

where $C_i(t_0)$ is the initial concentration of the tracer gas, and t is the time. The ventilation rate (Q) can be calculated from the slope of the regression line obtained by plotting $\ln\left(\frac{C_i(t)}{C_i(t_0)}\right)$ versus t.

The tracer gas was distributed up to 200 ppm while the vent openings were closed. During gas injection, the fans of the fog system were used for uniform gas distribution. After that, the fans were stopped and the vent was opened to the desired opening. Air samples were continuously taken at six points in the greenhouse, by means of six equally distributed plastic pipes of the same length, located at a height of approximately 1.8 m from the ground (fig. 1b). The air from the six positions was then mixed and pumped to an infrared gas analyzer (model 7000 ADC gas analyzer, analysis up to 200 ppm, accuracy at ±5 ppm, Analytical Development Company, Hoddesdon, U.K.). The duration of each experiment varied between 5 and 20 minutes, depending on environmental conditions and on the ventilation opening. During the experiments, wind speeds varied between 1 and 4 m s^{-1} and the ventilation opening ranged from 0 to 83 cm. The concentration of N_2O was also measured and stored in the data logger system once per second.

The Water Vapor Balance Technique

The water vapor balance technique uses water vapor as the tracer gas. Thus, values of inside $w_i(t)$ and outside $w_o(t)$ greenhouse air specific humidity (kg kg^{-1}) and the greenhouse crop transpiration rate Tr(t) were used to calculate the greenhouse ventilation rate. The specific humidity of the inside and outside air was calculated using the wet and dry bulb temperature measurements. Assuming uniform humidity conditions in the greenhouse volume, and considering that evaporation from the growing substrate was negligible, equation 1 can be rewritten as follows:

$$\rho V\frac{dw_i}{dt} = \rho Q(t)\left[w_o(t) - w_i(t)\right] + Tr(t) \qquad (4)$$

where ρ is the air density(kg m^{-3}). Equation 4 can be rewritten as:

$$Q(t) = \frac{\left(\rho V\frac{dw_i}{dt}\right) - Tr(t)}{\rho[w_o(t) - w_i(t)]} \qquad (5)$$

A SIMPLE FORMULA FOR THE PREDICTION OF VENTILATION RATE

Assuming that, for wind speeds higher than 1 to 1.5 m s^{-1}, the thermal buoyancy effect is small (de Jong, 1990), then the ventilation rate can be considered as a function of wind speed (u) and ventilation rate (Q) and can be given by (Kittas et al., 1996):

$$Q = \frac{A_v}{2}C_d(C_w)^{0.5}u \qquad (6)$$

where

A_v = effective opening area
C_d = vent opening discharge coefficient
C_w = global wind effect coefficient of ventilation.

This formula can be used for statistical identification of the wind–related parameter $C_d(C_w)^{0.5}$ using measurements of Q, A_v, and u.

RESULTS

The results presented in this study refer to measurements performed during periods with the same wind direction (±15°), parallel to the greenhouse ridge (i.e., north–south). The mean values (period 9:00 to 19:00 h) of the outside climate characteristics during the period of measurements are presented in table 1.

Table 1. Average values (period 9:00 to 19:00 h) of outside climate parameters during the period of measurements.

Air Temperature (°C)	Relative Humidity (%)	Solar Radiation (W m^{-2})	Wind Speed (m s^{-1})
29.1	35	608	2.7

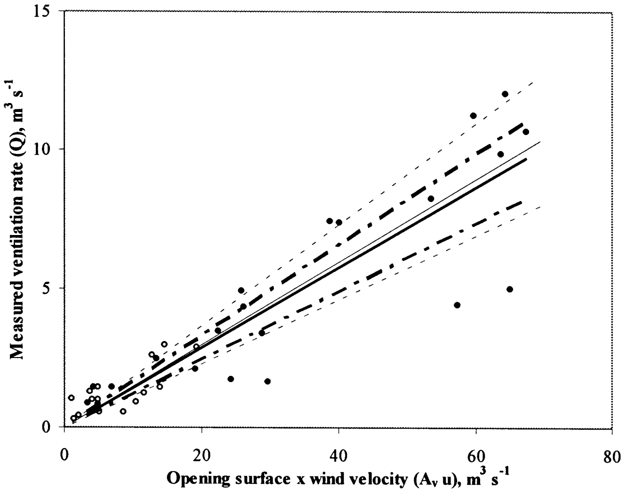


Figure 2. Measured ventilation rate (Q) versus the product of opening surface and wind velocity (A_v u) in the greenhouse without screen. Different symbols refer to different ventilation rate measurement techniques: ○ (open circle) = decay rate; ● (closed circle) = water vapor balance. The solid straight lines were obtained by linear regression, and the dashed lines represent 95% confidence limits about the regression lines: thin line = decay rate regression line; thick line = water vapor balance regression line; thin dashed lines = decay rate confidence limits; thick dashed lines = water vapor balance confidence limits.

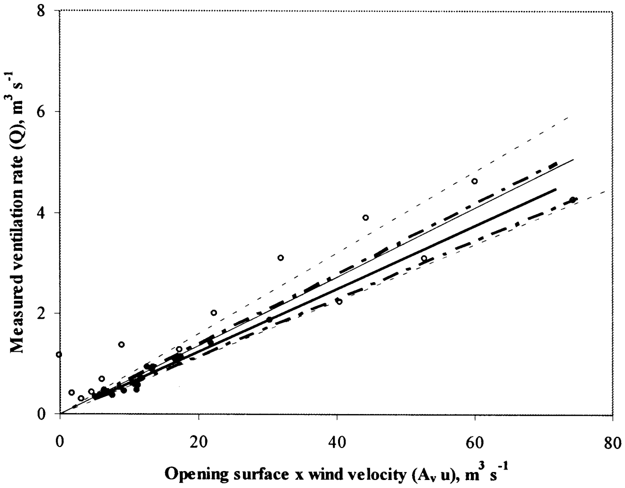


Figure 3. Measured ventilation rate (Q) versus the product of opening surface and wind velocity (A_v u) in the greenhouse with screen. Different symbols refer to different ventilation rate measurement techniques: ○ (open circle) = decay rate; ● (closed circle) = water vapor balance. The solid straight lines were obtained by linear regression, and the dashed lines represent 95% confidence limits about the regression lines: thin line = decay rate regression line; thick line = water vapor balance regression line; thin dashed lines = decay rate confidence limits; thick dashed lines = water vapor balance confidence limits.

Table 2. Regression coefficients (95% confidence) for the groups of data (Q, A_v, and u) and wind–related coefficient, $C_d(C_w)^{0.5}$, for different measurement techniques, with and without screen.

Ventilation Rate Measurement Technique	Openings	Number of Measurements	Slope	$C_d(C_w)^{0.5}$	R^2
Decay rate method (N_2O)	Without screen	15	0.149 ±0.016	0.298	0.53
	With screen	11	0.068 ±0.005	0.136	0.66
Water vapor balance method	Without screen	21	0.144 ±0.010	0.288	0.74
	With screen	18	0.064 ±0.003	0.128	0.80

CALIBRATION OF MODEL'S PARAMETERS

In figures 2 and 3, the ventilation rate (Q) measured by the two techniques (decay rate tracer gas and water vapor balance) is plotted as a function of the product of effective opening area and wind velocity (A_v u) for the case of a greenhouse without screen and a greenhouse with screen, respectively. The experimental data were fitted to equation 6 using Marquardt's algorithm (Marquardt, 1963), and a regression, which is represented by straight lines in figures 2 and 3, was obtained. According to equation 6, the slope of the regression line is equal to 0.5 $C_d(C_w)^{0.5}$. Regression coefficients and calculated wind–related coefficients, $C_d(C_w)^{0.5}$, are shown for each case in table 2. The dashed lines in figures 2 and 3 represent 95% confidence limits about the regression lines. Because the confidence limits of the regression lines are very similar, we can conclude that the two different measuring techniques supply similar coefficient values for each case (greenhouse with or without screen). Accordingly, we can pool the data of the two methods, and in order to determine the influence of the insect screen on the wind–related coefficient $C_d(C_w)^{0.5}$, we can calculate a unique coefficient $C_d(C_w)^{0.5}$ for each case.

In figure 4, the airflow rate measured for the two cases (pooled data) is plotted versus the product of effective opening area and by wind velocity (A_v u). The straight lines were obtained by linear regression, and regression results are presented in table 3. According to equation 6, the calculated coefficient $C_d(C_w)^{0.5}$ is equal to 0.289 and 0.136 for the greenhouse without and with screen, respectively.

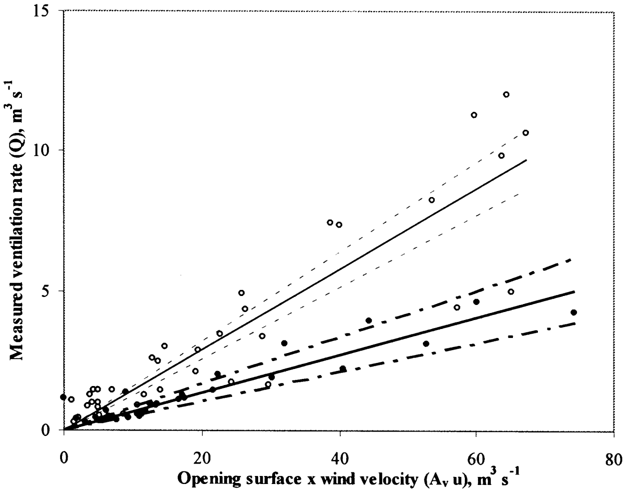


Figure 4. Measured ventilation rate (Q) versus the product of opening surface and wind velocity (A_v u): ○ (open circle) = greenhouse without screen; ● (closed circle) = greenhouse with screen. The solid straight lines were obtained by linear regression, and the dashed lines represent 95% confidence limits about the regression lines: thin line = regression line for greenhouse without screen; thick line = regression line for greenhouse with screen; thin dashed lines = confidence limits for greenhouse without screen; thick dashed lines = confidence limits for greenhouse with screen.

Table 3. Regression coefficients (95% confidence) for the groups of data (Q, A_v, and u) and wind–related coefficient, $C_d(C_w)^{0.5}$, with and without screen (pooled data, obtained with the two measurement techniques).

Openings	Number of Measurements	Slope	$C_d(C_w)^{0.5}$	R^2
Without screen	36	0.144 ±0.008	0.288	0.80
With screen	29	0.068 ±0.003	0.136	0.87

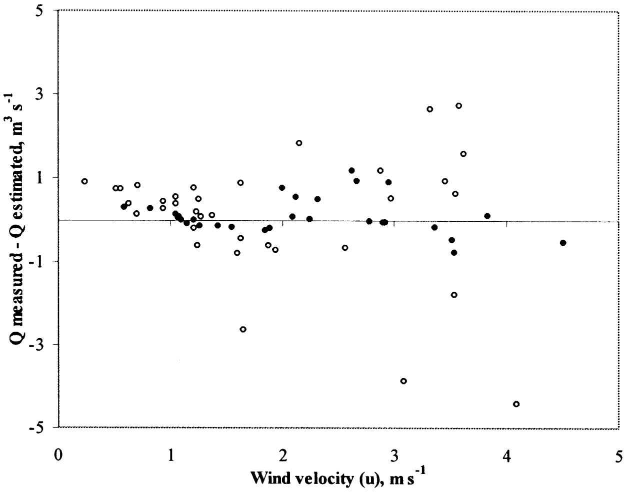


Figure 5. Residuals of measured and estimated ventilation rates (Q measured – Q estimated) versus wind velocity (u): ○ (open circle) = greenhouse without screen; ● (closed circle) = greenhouse with screen.

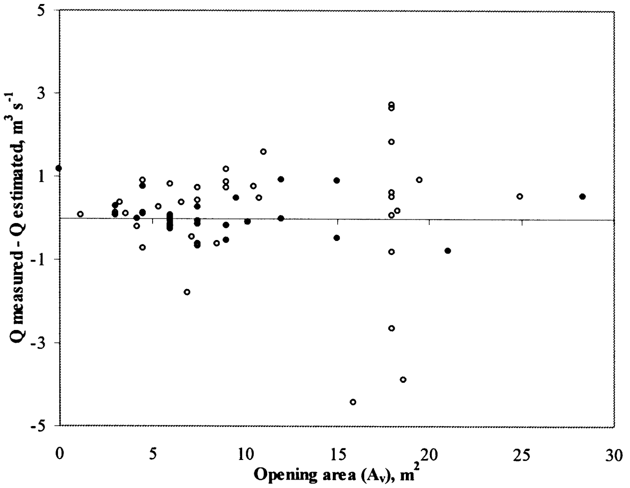


Figure 6. Residuals of measured and estimated ventilation rates (Q measured – Q estimated) versus opening area (A_v): ○ (open circle) = greenhouse without screen; ● (closed circle) = greenhouse with screen.

Figures 5 and 6 present the residuals (Q measured – Q estimated) against the wind velocity and the effective opening area, respectively. The randomly scattered residuals, supported by the low value of the coefficient of determination between the residuals and u (R^2 = approximately 0.02 for both greenhouse with screen and greenhouse without screen) and A_v (R^2 = approximately 0 for both cases), indicate that the wind velocity and the opening area have been correctly taken into account by the model (eq. 6). However, a careful examination of the residuals shows that the values vary in the range ±2 m^3 s^{-1}, except some that are beyond these limits. From figures 5 and 6, we can see that these extreme values occur during the experiments with the water vapor balance method and only for the case without screen. These errors can be attributed to possible errors in transpiration rate measurements, either from direct solar radiation penetration to the lysimeter by the window opening, or from temporary shading of the lysimeter by the greenhouse frame.

DISCUSSION

EFFECTS OF INSECT SCREENS ON VENTILATION RATES

Although two different techniques were used to evaluate the effect of insect screens on greenhouse ventilation rate, the calculated values of coefficient $C_d(C_w)^{0.5}$ were rather similar for both techniques. In addition, the value of coefficient $C_d(C_w)^{0.5}$ for the greenhouse without screen was very close to values (0.256) given in the literature for a similar greenhouse type (Boulard and Baille, 1995).

The results also showed that the ventilation rate significantly decreased as a result of adding an insect screen in the ventilation openings. Using the identified value of coefficient $C_d(C_w)^{0.5}$ (table 3) and the theoretical model for the prediction of ventilation rate (eq. 6), we can calculate the ventilation rate (Q). For example, for a wind speed (u) of 3 m s^{-1}, Q is equal to 11.1 m^3 s^{-1} (0.9 air changes/min) for a greenhouse without screen and only 5.2 m^3 s^{-1} (0.45 air changes/min) for a greenhouse with screen. In the latter case, an optimum ventilation rate (0.75 to 1 air changes/min, or 8.63 to 11.5 m^3 s^{-1} based on the volume of our greenhouse), as recommended by *ASAEStandards* (1999), requires an outside wind speed higher than 6 m s^{-1}. Such climate conditions are rare in the region where the present study was carried out. Recommended ventilation rates, with the often–encountered outside wind speed of 3 m s^{-1}, can be achieved by doubling the vent opening surface.

EFFECT OF THE DISCHARGE COEFFICIENT

Airflow through an opening is caused by pressure difference. Bernoulli's equation is generally used to describe the relationship between pressure drop (Δp, Pa) and air velocity through the opening:

$$\Delta p = 0.5\, \zeta_{tot}\, \rho\, v^2 \tag{7}$$

where ζ_{TOT} is the Euler number, which represents the pressure drop coefficient, and v is the average air velocity across the opening.

When a screen is installed in an opening, the above coefficient can be considered as:

$$\zeta_{tot} = \zeta_s + \zeta_{ns} \tag{8}$$

where the subscripts s and ns indicate the pressure drop across the screen and across the inlet opening, respectively. From equation 8 and by generally defining the Euler number as $\zeta = 1/C_d^2$, we have:

$$\zeta_{tot} = \zeta_s + \zeta_{ns} = \frac{1}{C_{d,s}^2} + \frac{1}{C_{d,ns}^2} = \frac{1}{C_{d,tot}^2} \tag{9}$$

or:

$$C_{d,tot} = \frac{C_{d,s}\, C_{d,ns}}{\sqrt{C_{d,s}^2 + C_{d,ns}^2}} \tag{10}$$

From table 3, we found that:

$$C_{d,ns}C_{w,ns}^{0.5} = 0.289 \text{ for a non–screened greenhouse} \quad (11)$$

$$C_{d,tot}C_{w,tot}^{0.5} = 0.136 \text{ for a screened greenhouse} \quad (12)$$

If we accept, for simplicity, that installation of the screen in the greenhouse vent openings has a negligible effect on the wind–effect coefficient C_w ($C_{w,ns} = C_{w,tot}$), then the additional screen resistance to airflow is taken into account and incorporated into discharge coefficient $C_{d,tot}$. Thus, dividing equation 11 by equation 12, we can obtain the following relationship between the discharge coefficient of the greenhouse with screen ($C_{d,tot}$) and the discharge coefficient of the greenhouse without screen ($C_{d,ns}$):

$$C_{d,tot} = C_{d,ns} / 2.125 \quad (13)$$

In the case of a single continuous opening, the value of the discharge coefficient (C_d) is usually close to 0.70 ($C_{d,ns}$ = 0.70) (Boulard and Draoui, 1995). Therefore, equation 13 gives:

$C_{d,tot} = 0.33$ with a corresponding $\zeta_{tot} = 9.21$. Knowing that $\zeta_{ns} = 2$ ($C_{d,ns} = 0.70$) and using equation 9 we find that: ζ_s = 7.16 which gives a corresponding discharge coefficient $C_{d,s}$ = 0.37.

The screen resistance (ζ_s) can also be calculated using porous media flow analysis (Miguel, 1998). The pressure drop across an insect screen can be expressed as (Forchheimer, 1901):

$$\frac{\Delta p}{\Delta x} = \frac{\mu}{K}u + \rho\left(\frac{Y}{K^{0.5}}\right)u^2 \quad (14)$$

where

Δx = screen thickness (m)

μ = dynamic viscosity (kg s^{-1} m^{-1})

K = permeability (m^2), which represents the ability of the material to transmit fluid through itself

Y = inertia factor.

Using equation 14 and knowing the permeability (K) and inertia factor (Y), we can estimate the pressure drop across the screen for different wind speeds. The corresponding Euler number can be deduced by plotting pressure drop (Δp) versus wind speed (u) and finding the slope of the best–fit line. Miguel (1998) tested 14 different porous materials with different porosities. He found an equation that better relates screen permeability (K) to porosity:

$$K = 3.44 \times 10^{-9}\,\varepsilon^{1.6} \quad (15)$$

and an equation that better relates the inertia factor (Y) to porosity:

$$Y = 4.30 \times 10^{-2} / \varepsilon^{2.13} \quad (16)$$

The permeability (K) of the screen used in this study (ε = 0.6) was found to be 1.51×10^{-9} m^2, and the inertial factor (Y) was 0.13. Using the above K and Y values, the corresponding Euler number deduced by plotting pressure drop (Δp) versus wind speed (u) was found to be $\zeta_s = 6.97$, a value that is very close to $\zeta_s = 7.16$.

The same procedure can be used to determine the influence of another type of insect screen on greenhouse ventilation rate. For example, if we use an anti–aphid screen (ε = approximately 0.5) and follow the same procedure described above (determine screen permeability and inertia factor using screen porosity, and then estimate screen total resistance to ventilation), then we can estimate the new discharge coefficient (due to the screen) and thus the possible ventilation reduction (ventilation rate will be decreased to the same extent as discharge coefficient). Using this procedure, we found that anti–aphid screen resulted in a discharge coefficient of $C_{d,aphid} = 0.27$.

A reduction in the discharge coefficient can be correlated to a corresponding reduction on the airflow rate. In the previous paragraph, it was shown experimentally and theoretically that the specific insect screen (ε = 0.6) decreased the discharge coefficient by almost by half (47% reduction), and the ventilation rate also decreased by almost the same amount (53% reduction). Thus, the ventilation rate reduction of a greenhouse with insect screens can be considered proportional to the reduction of the discharge coefficient. Based on this assumption, we can estimate the potential reduction of the ventilation rate for different types of insect screens, knowing only their porosity. For example, an anti–aphid screen ($C_{d,aphid}$ = 0.27) will reduce the ventilation rate by 61%. An increase in the ventilation area of the same proportion (61%) is then necessary to keep the ventilation rate unchanged.

The greenhouse ventilation rate can be given by (ASHRAE, 1993):

$$Q = \frac{H_c A_f}{\rho C_p \Delta T} \quad (17)$$

where

H_c = sensible heat removed by ventilation from the greenhouse (W m^{-2})

C_p = specific heat of air (J kg^{-1} K^{-1})

ΔT = inside–to–outside air temperature difference (° C).

Kittas et al. (2001) have shown that, under high– and low–ventilation regimes in a glass greenhouse during summer conditions, sensible and latent heat were nearly unchanged. This was attributed to the fact that an increase in ventilation rate caused an increase in aerodynamic conductance and a decrease in the canopy stomatal conductance, which finally resulted in similar latent heat exchange rates.

Therefore, considering a greenhouse with two different ventilation regimes (Q_1 and Q_2,) and taking into account that the sensible heat remains unchanged, application of equation 17 supplies:

$$\frac{Q_1}{Q_2} = \frac{\Delta T_2}{\Delta T_1} \quad (18)$$

Accordingly, a 53% reduction in the ventilation rate (ε = 0.6) will increase the inside–to–outside air temperature difference (ΔT) by a factor of about 2, while a 61% reduction (anti–aphid screen) will increase the difference by a factor of about 2.5. These results imply that a more careful consideration of the greenhouse ventilation openings is needed when using screens in order to prevent the greenhouse from overheating.

SUMMARY

Ventilation rate measurements were performed in a naturally ventilated greenhouse equipped with a continuous roof opening covered by an insect screen. Two measuring techniques were used to calculate the ventilation rate, and the

data obtained were applied to evaluate the influence of the insect screen on ventilation rates. Both techniques gave similar values for the statistically identified wind–related coefficient, $C_d(C_w)^{0.5}$. Results confirmed and quantified the major reduction in ventilation due to the insect screen.

In addition, porous media flow analysis was used to correlate the discharge coefficient with the aerodynamic properties of the screen, and relationships found in the literature were used to calculate screen aerodynamic properties from porosity, which is an easily measurable characteristic. The results indicate that screens can reduce the discharge coefficient by 50%, and thus the ventilation rate will be decreased to the same extent. Accordingly, it was possible to quantify the ventilation reduction due to the screen by determining the pressure drop coefficient. Knowing the porosity, which is usually provided by the manufacturer or determined using a microscope, we can deduce the aerodynamic properties of the screen, and thus the pressure drop coefficient.

Using equation 6, we can calculate the increase in the ventilation opening necessary in a greenhouse with screens in order to maintain the same ventilation rate as a greenhouse without screens. On the other hand, for a given screen, we can determine its influence on the discharge coefficient and thus on the ventilation rate. This approach can be exploited further to determine if a given greenhouse ventilation opening design provides enough ventilation when equipped with an insect screen and to propose better vent design in order to improve greenhouse ventilation.

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LIST OF SYMBOLS

A_f = tgreenhouse floor area (m^2)
A_v = effective opening area (m^2)
C_d = discharge coefficient (dimensionless)
C_i = inside concentration of tracer gas (kg m^{-3})
C_o = outside concentration of tracer gas (k m^{-3})
C_p = specific heat of air (J kg^{-1} K^{-1})
C_w = global wind–effect coefficient of ventilation (dimensionless)
$C(t)$ = concentration of tracer gas at time t (ppm)
$C(t_o)$= initial concentration of tracer gas (ppm)
$F_i(t)$ = rate of supply or removal of tracer gas within the greenhouse (kg s^{-1})
H_c = sensible heat removed by ventilation from the greenhouse (W m^{-2})
K = permeability (m^2)
w_i = specific humidity, inside air (kg kg^{-1})
w_o = specific humidity, outside air (kg kg^{-1})
Q = ventilation flow rate (m^3 s^{-1})
Tr = transpiration rate (kg m^{-2} s^{-1})
$t–t_o$ = duration of the measurement set (s)
u = outside wind velocity (m s^{-1})
V = greenhouse volume (m^3)
v = average air velocity across the ventilation opening (m s^{-1})
Y = inertia factor (dimensionless)
Δp = pressure drop (Pa)
ΔT = inside–to–outside air temperature difference (° C)
Δx = screen thickness (m)
ε = screen porosity (m^2 m^{-2})
ζ = Euler number (dimensionless)
μ = dynamic viscosity (kg s^{-1} m^{-1})
ρ = air density (kg m^{-3})

SUBSCRIPTS

f = floor
i = inside
o = outside
ns = without screen
s = with screen
v = ventilation
tot = total
aphid = anti–aphid screen