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MEASUREMENT AND SIMULATION OF THE VENTILATION RATES IN A NATURALLY VENTILATED AZROM-TYPE GREENHOUSE IN ZIMBABWE

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ABSTRACT. *A simple greenhouse ventilation model, based on the stack and wind effects (the main driving forces for natural ventilation) was adapted, calibrated, and validated using measured air renewal rates in a three-span naturally ventilated Azrom-type greenhouse in Zimbabwe. Crop transpiration rates were monitored using stem heat balance sap flow gauges installed on the main stems of rose plants to continuously monitor whole-plant transpiration (WPT). This allowed continuous and automatic determination of full scale air renewal and leakage rates using the water vapor balance method. The model was fitted to experimental data of ventilation rates, and discharge and wind effect coefficients were determined. The results show a good fit between measured and predicted values (*$R^2 = 0.80$ *and 0.82 for winter and summer, respectively), although there is a general over-estimation of the greenhouse air renewal rates, particularly during the night. The model, nevertheless, adequately describes the natural ventilation process in the greenhouse all year round. The model can be used as a design tool to evaluate and optimize the effects of different ventilation configurations and strategies on greenhouse air renewal rates, and as a component in a greenhouse climate model in order to further evaluate the effects of ventilation strategies on the inside greenhouse and crop microclimate, and thus lead to better greenhouse climate control.*

Keywords. *Climate control, Climate model, Greenhouses, Ventilation, Ventilation model, Ventilation rate.*

Control of the environmental conditions inside a greenhouse in the tropics and sub-tropics (for example Zimbabwe) is necessary for cultivation of off-season crops, to extend the growing season, to increase the potential yield, to conserve water, to control conditions for plant growth, and to avoid pests and diseases. In Zimbabwe, where warm and dry daytime conditions prevail all year-round, greenhouse cooling is one of the major challenges faced by greenhouse growers, particularly in summer, when incident solar radiation can be very high. Natural ventilation, effected by allowing exchange of air with the exterior through openings in the greenhouse, is the most widely used practice, as it is cheaper than other methods, and almost all greenhouse designs incorporate fixed or controllable roof and/or side vents. The resulting energy and air exchange between the greenhouse interior and the outside affects the greenhouse microclimate considerably. It affects not only the energy balance of the greenhouse (and therefore the air temperature within the greenhouse), but also the balance of the air components, including the concentrations of water vapor, carbon dioxide, and other gases in the greenhouse (Bakker et al., 1995; Pieters and Deltour, 1997; Hanan, 1998). Ventilation rates in greenhouses have traditionally been measured using the greenhouse energy balance method (Demrati et al., 2001; Dayan et al., 2002; Dayan et al., 2004), tracer techniques (Kittas and Bartzanas, 2007; Teitel et al., 2008; Hong et al., 2008) and the water vapor balance method (Boulard and Draoui, 1995; Wang and Deltour, 1996; Kittas et al., 2002; Harmanto et al., 2006).

Despite the importance of the ventilation process for greenhouse climate control in the tropics and sub-tropics, little research has been conducted on the subject in Africa. This may be due to the high cost and unavailability of the equipment (gas analyzers and tracers for tracer gas techniques, and the sensors and data loggers for the water vapor balance and energy balance methods) in these regions. The problem with ventilation rate measurement using tracer techniques, water vapor balance method, or energy balance method is that the techniques and the equipment for monitoring are usually expensive and require considerable technical expertise. A cheaper alternative is to use models to simulate the air exchange or ventilation in greenhouses. Such a model should be simple and practical, allowing the ventilation caused by both the thermal buoyancy and wind to be described efficiently with the measurement of as few parameters as possible. The main aim of this study was to investigate the possibility of using a simple ventilation model for simulating the air exchange rates under all conditions in a commercial naturally ventilated Azrom-type greenhouse equipped with continuous roof and side vents in Zimbabwe, under subtropical climate conditions.

THEORETICAL BACKGROUND

THE NATURAL VENTILATION PROCESS

In natural ventilation, for air to move into or out of a greenhouse, a pressure difference between the interior and exterior of the greenhouse is required. This pressure difference is caused by wind (wind effect), difference in air density due to temperature difference between the interior and exterior air (stack or chimney effect), or a combination of both wind and stack effects (Boulard and Baille, 1995; ASHRAE, 2005).

Wind Effect

When air flow is due to wind only, a pressure field is created around the greenhouse, causing air to enter the greenhouse through any openings. Wind pressures are generally raised on the windward side of the greenhouse and lowered on the leeward side. The occurrence and change of wind pressures on the greenhouse surfaces depends on wind speed and wind direction relative to the greenhouse, the location and surrounding environment of the greenhouse and the shape of the greenhouse (Monteith and Unsworth, 1990; Boulard and Baille, 1995). The pressure difference across the greenhouse surfaces, ΔP_w (Pa), could be expressed as (Bernoulli):

$$\Delta P_w = \frac{1}{2}\rho C_w u_e^2 \quad (1)$$

where ρ is the density of air (kg m^{-3}), C_w is an average or local wind effect coefficient, and u_e is the mean external wind speed (m s^{-1}).

STACK EFFECT

When the interior temperature is higher than the exterior temperature, a negative interior pressure (relative to the exterior) at the bottom and positive interior pressure on the top is produced, while a neutral pressure level (NPL) exists where the interior and exterior pressures are equal. Warmer air flows out of the greenhouse near the top and is replaced by colder outside air that enters the greenhouse near its base. The reverse occurs when the interior temperature is lower than exterior temperature. At all other levels, the pressure difference between the interior and exterior, ΔP_s (Pa), depends on the distance from the neutral pressure level and can be written as (ASHRAE, 2005):

$$\begin{aligned}\Delta P_s &= (\rho_e - \rho_i)\cdot g\cdot(h - h_{neutral}) \\ &= \rho\, g\,(h - h_{neutral})\cdot\frac{T_i - T_e}{T_i} \qquad (2)\end{aligned}$$

where ρ is the average density of air (kg m^{-3}), g is the gravitational constant (= 9.81 m s^{-2}), h is the height of observation (m), $h_{neutral}$ is the height of the neutral pressure level (m), and T is the absolute temperature (K) (subscripts i = interior and e = exterior).

Equation 2 applies when $T_i > T_e$. If $T_i < T_e$, T_i in the denominator is replaced by T_e and $(T_i - T_e)$ in the numerator is replaced by $(T_e - T_i)$.

Combined Effect of Wind and Temperature Difference

In most cases, natural ventilation depends on the combined force of wind and stack effects. The pressure patterns continually change with the relative magnitude of thermal and wind forces. The total pressure difference can be obtained by superimposing the pressure differences due to the wind and stack effects. Several physical ventilation models have been developed for combined wind and stack effects. Sherman (1992) and Walker and Wilson (1993) compared such models and proposed the following superposition principle for the total effective ventilation rate:

$$G = \sqrt{G_s^2 + G_w^2} \quad (3)$$

where G_s and G_w are the ventilation rates due to the stack effect and wind effect, respectively. Ventilation is usually characterized by the air renewal rate, R_a (in h^{-1}), which is defined as the ratio of the total volume of fresh air supplied in 1 h to the greenhouse volume:

$$R_a = \frac{3600\cdot G}{V} \quad (4)$$

where G is the ventilation rate (m^{3}s^{-1}) and V is the greenhouse volume (m^3).

Leakage Rate

Leakage rate or infiltration is the air renewal rate (in h^{-1}) due to the uncontrolled flow of air when the greenhouse vents are closed. Any air exchange under these conditions is then through cracks and other unintentional openings in the greenhouse. Infiltration occurs because no greenhouse is completely airtight, and the exchange is driven by pressure differences across the greenhouse shell (ASHRAE, 2005). The surface pressure field driving the air flow include wind pressure, pressures arising from temperature differences between the interior and exterior, and pressures resulting from operation of mechanical exhaust systems. The leakage rate, $R_{a,0}$ (in h^{-1}), can be modelled according to an empirical power law relationship between the flow and the pressure difference across cracks the greenhouse envelope (Sherman and Grimsrud, 1980; Fernandez and Bailey, 1992; Papadakis et al., 1996):

$$R_{a,0} = \frac{3600}{V}.C\left(\Delta P\right)^n \quad (5)$$

where V is the greenhouse volume (m^3), ΔP is the pressure difference, and C and n are the flow coefficient and exponent, respectively (which can be determined statistically from a comparison with measured leakage rates).

GREENHOUSE VENTILATION FUNCTION

The air renewal rate, R_a (in h^{-1}), for a greenhouse with continuous roof and side vents and taking both wind and stack effects into account, can be described by an equation proposed by Kittas et al. (1997) and also used by Sbita et al. (1996), Demratti et al. (2001), Roy et al. (2002), and Fatnassi et al. (2003):

$$R_a = \left(\frac{3600}{V}\right) C_D \left[\left(\frac{A_r A_s}{\sqrt{\left(A_r^2 + A_s^2\right)}}\right)^2 2g \cdot h_c \cdot \left(\frac{T_i - T_e}{T_i}\right) + \left(\frac{A_V}{2}\right)^2 C_w u_e^2\right]^{0.5} \quad (6)$$

where V is the greenhouse volume (m^3), C_D is the discharge coefficient, T_i is the internal air temperature (K), T_e is the external air temperature (K), A_r is the total opening area of the roof vents (m^2), A_s is the total opening area of the side vents (m^2), A_V is the total opening area of all the vents (= $A_r + A_s$) (m^2), g is the acceleration due to gravity (= 9.81 m s^{-2}), h_c is the vertical height between the midpoints of the side and roof vents (m), C_w is the wind effect coefficient, and u_e is the external wind speed at a height of 2 m. As mentioned earlier, the equation applies when $T_i > T_e$. If $T_i < T_e$, T_i in the denominator is replaced by T_e and ($T_i - T_e$) in the numerator is replaced by ($T_e - T_i$).

If the greenhouse is closed (so that $A_V = 0$) or if the temperature difference between interior and exterior air is zero and wind speed is zero (as may be the case at night or under an overcast sky) the ventilation rate is replaced by the leakage rate, $R_{a,0}$. In this research, the coefficients C_D and C_w were derived statistically from experimental data fitting.

MATERIALS AND METHODS

DESCRIPTION OF THE SITE AND GREENHOUSE

All experiments were carried out in a 3-span commercial Azrom-type greenhouse (fig. 1) at Floraline (Pvt) Ltd in Harare, Zimbabwe (17.8°S, 31.1°E, altitude 1500 m) between July 2007 and June 2008. Climatologically, the site is characterized by a dry season from May to October and a rainy season from November to April. The winter season (June to August), which overlaps with the dry season, is cold at night and in the early morning, but warm in the middle of the day. Temperatures gradually increase in September (an optimum spring month) with October being the hottest month. The summer season (December to February) overlaps with the rainy season. During the rainy season rain usually comes in the form of afternoon and evening thunderstorms, leaving much of the day clear.

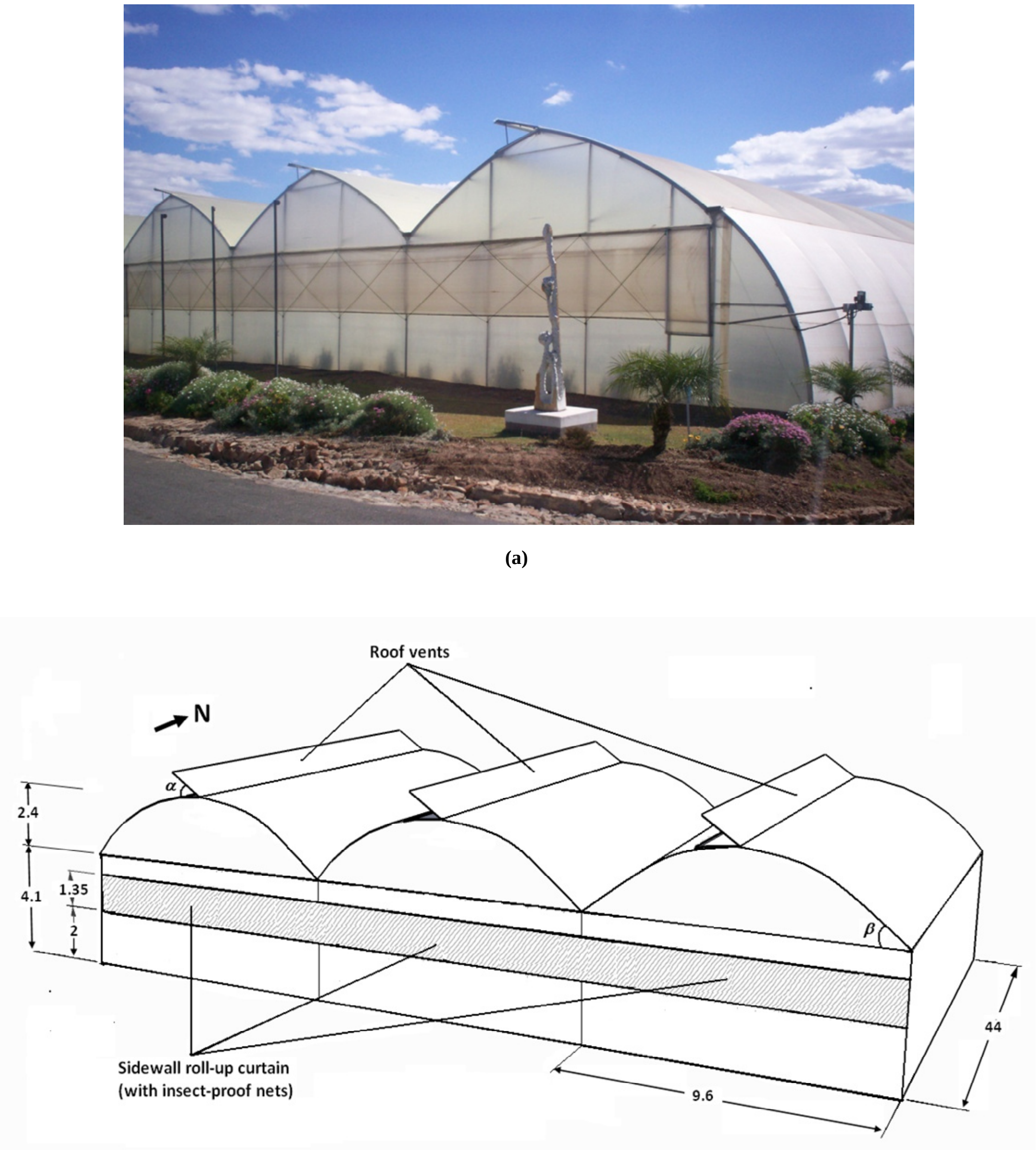

Figure 1. (a) Outside view of the commercial rose cultivated greenhouse in which measurements were taken. (b) The geometrical characteristics of the greenhouse (dimensions in m). α and β are the angles between the roof vent and the greenhouse roof, and the roof and the horizontal, respectively.

Each span of the greenhouse was 9.6 m wide and 44 m long, with ridge and gutter heights of 6.5 and 4.1 m, respectively. The ridges were oriented north-south, the greenhouse total floor area was 1267 m^2, and the roof sloped at about 26° to the horizontal (fig. 1). The cladding material was 200-μm polyethylene film with terrestrial infrared and UV absorbing additives (Ganeigar Co., Israel). Controllable roof vents (one in each span on the west side of the roof) were located along the whole length of the ridge and were 1.4 m wide, with maximum opening angle of about 34° with the roof. The polyethylene side vents could be rolled up from 2 m above the floor to 3.35 m on the south wall and to 3.45 m on the north wall. High Density Polyethylene (HDPE) insect-proof nets covered the openings of the side vents (Ganeigar Co., Israel). The insect-proof nets have openings dimensions of 50 mesh for both warp and weft directions, allowing the passage of 0.35-mm diameter spheres, as specified by the manufacturer. However, other parameters which could affect screen permeability, such as wire diameter, were not specified by the manufacturer. The use of insect-proof nets could alter ventilation performance of the greenhouse, for a detailed discussion on the relationship between screen characteristics and greenhouse ventilation, the reader is referred to Teitel (2007).

The side and roof vents openings were controlled by an automated climate control system (NETAFIM NETAGROW Version 718.3, Priva, Israel) in response to a calculated ventilation temperature (T_{setv}), the temperature above which ventilation is initiated, calculated as a function of time of day on the basis of set ventilation temperatures and a number of influences, including the measured inside air relative humidity, outside conditions, and the ventilation temperature at the previous time step. The vents were controlled by the ventilation temperature to be realized: the climate control system uses the calculated ventilation temperature to calculate the vent position (%) as a function of weather conditions, including the difference between T_{setv} and the outside air temperature, wind speed, the radiation flux density, and set minimum and maximum vent limitations.

Two circulation fans were used for air mixing: these were 0.75 m in diameter with a rated outflow of 16000 m^3/h at zero static pressure, blowing N-S, and installed under each gutter at a height of about 3.5 m and 12 m from the north and south walls, respectively. The crop (average height of about 1.2 m and with a total crop cover representing about 40% of the total greenhouse floor area) included several cultivars of roses, grown in vermiculite in slightly raised (30 cm above the floor) 20- × 0.45- × 0.2-m (length × width × depth) containers laid parallel to the gutters with twelve 20-m rows in each span. The cultivars included commercial ones like Myrthe, Nectarine, Respect, Orchestra, Bonfire, and Romeo and several trial cultivars. All the cultivars were grafted onto Natal Brier rootstocks. Water and fertilizers were supplied by a drip system, which was automatically controlled by a fertigation computer.

CLIMATE AND PHYSIOLOGICAL MEASUREMENTS

The following greenhouse climate data were measured at an automatic weather station (AWS) installed near the center of the greenhouse (see fig. 2):

net radiation at 1.5 m above the greenhouse floor, by means of a net radiometer equipped with Teflon coated sensor surfaces (model NR-LITE, Kipp and Zonen, Delft, Netherlands);

air temperature and relative humidity at 1.5 m above the greenhouse floor, by means of temperature and humidity probes, each equipped with a capacitive relative humidity chip and a platinum resistance thermistor (model RHT2nl, Delta T Devices Cambridge, UK). The probes were shielded from radiation by 12-plate gill radiation shields;

incoming solar radiation above the canopy by means of a tube solarimeter (model TSL, Delta T Devices Cambridge, UK);

photosynthetically active radiation (PAR) above the canopy by means of a PAR sensor (model PAR-LITE, Kipp and Zonen, Delft, Netherlands), respectively. Due to practical limitations the tube solarimeter and PAR sensor were installed at 2 and 2.5 m above the greenhouse floor, respectively.

In order to keep track of possible gradients and variations within the greenhouse air, the air temperature and relative humidity were measured at three other heights of 0.4, 0.8, and 2 m above ground level at the same position as the automatic weather station (fig. 2).

In addition, mixing of the greenhouse air was also tested by measuring the air temperature and relative humidity (at the same height) at four other positions in the greenhouse (fig. 3). The greenhouse air temperature and relative humidity were taken as the average of the sensor readings at the five positions.

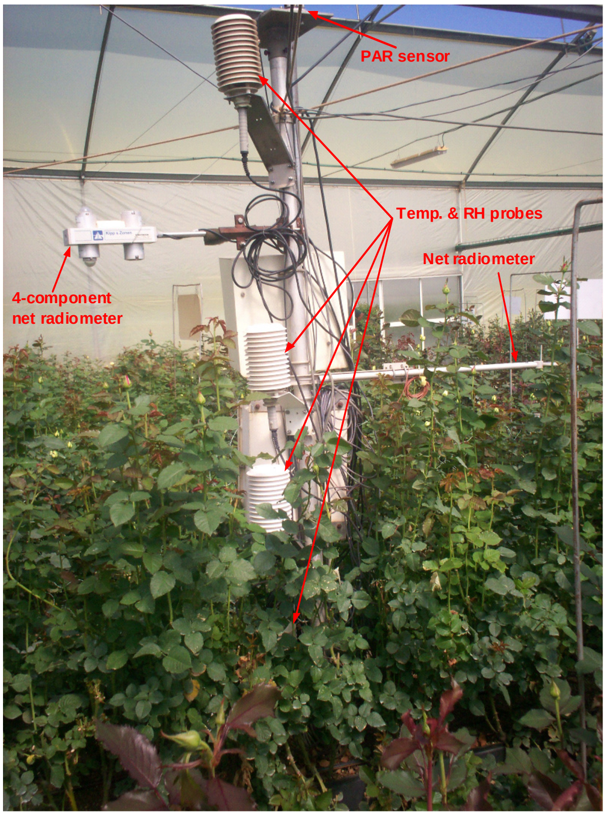

Figure 2. The internal AWS, showing the position of the sensors. Also shown is a four-component net radiometer (model CNR1, Kipp and Zonen, Delft, Netherlands) used for regular calibrations of the tube solarimeter (not shown in the picture) and net radiometer.

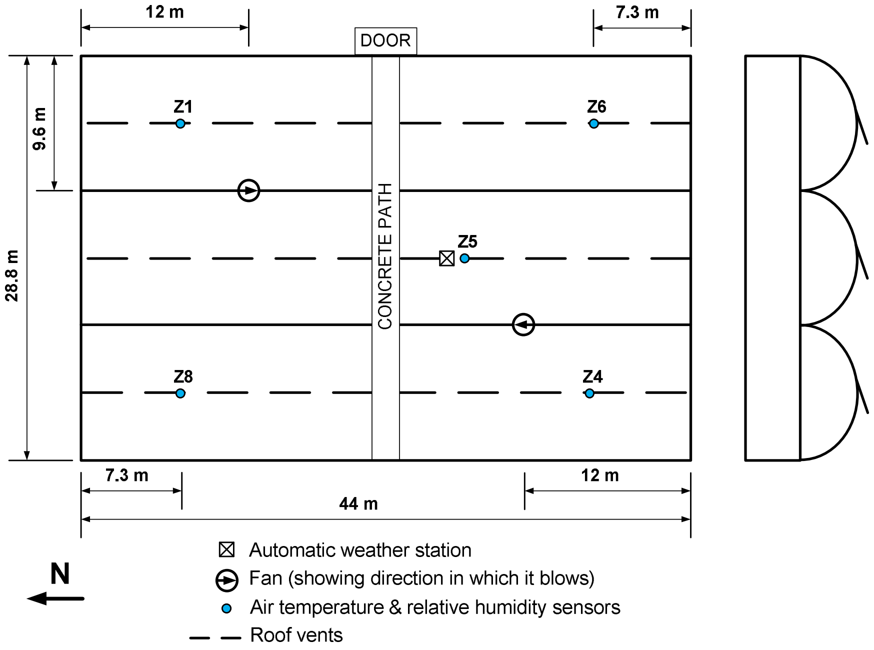

Figure 3. The placement of air temperature and relative humidity sensors within the greenhouse for the investigation of greenhouse mixing.

Simultaneous measurements of the following outside weather parameters were also recorded at an external station that was sited in an open space well clear of buildings and other obstacles:

air temperature and relative humidity at 1.5 m above ground, by means of the same model of temperature and humidity probe as inside the greenhouse;

total solar radiation and PAR at 2 m above the ground, by means of a pyranometer (model CM3, Kipp and Zonen, Delft, Netherlands) and the same type of PAR sensor as before;

wind speed and direction at 2 m above the ground by means of a cup anemometer (model A100L2, Delta T Devices Cambridge, UK) and a wind vane (model WD1, Delta T Devices Cambridge, UK), respectively.

Crop transpiration rates were monitored using stem heat balance sap flow gauges (model SGA10WS, Dynamax, Inc., Houston, Tex.) installed on the main stems of two rose plants to continuously monitor the whole-plant transpiration, WPT per plant (Baker and van Bavel, 1987; Baker and Nieber, 1989; Rose and Rose, 1998). Weekly maintenance in the form of checking for gauge contact with the stem and sap accumulation were performed and the heaters loosened when necessary to account for rapid plant growth. The gauges were changed to other stems if the need arose.

All measurements were automatically recorded by CR10X and CR23X data loggers (Campbell Scientific Ltd., Shepshed, UK) and DL2e data loggers (Delta T Devices Cambridge, UK) every 5 s and averaged over 30 min.

In addition, leaf area index (LAI) was estimated non-destructively using a Sunscan canopy analysis system (model SS1-TM, Delta T Devices, Cambridge, UK) and the total leaf area of the plant on which each gauge was installed was estimated destructively using a WinDIAS color image analysis system (Delta T Devices, Cambridge, UK) every two weeks. The sap flow gauge was then installed on different plants to enable the destructive sampling of the leaf area. The whole plant transpiration rate was scaled up to crop transpiration rates by assuming that the WPT was uniform throughout the crop and using the relation (Ham et al., 1990):

$$T_r(t) = \frac{P_V \cdot A_g \cdot F_s(t) \cdot LAI}{3.6 \cdot 10^6 \cdot A_L} \quad (7)$$

where $T_r(t)$ is the greenhouse crop transpiration rate (kg s^{-1}), P_V is the fraction of the total greenhouse floor area covered by the crop, A_g is the total greenhouse floor area (m^2), $F_s(t)$ is the average WPT or stem sap flow rate (g h^{-1}), A_L is the total leaf area of the plant on which the gauge was installed (m^2) and LAI is the average leaf area index. The leaf area index (LAI) averaged 2.1, with small fluctuations due to the continuous harvesting of the roses.

VENTILATION RATE DETERMINATION

Full scale ventilation rates (ventilators open) and leakage rates (ventilators closed) were measured throughout the day using the water vapor balance method (Boulard and Draoui, 1995; Wang and Deltour, 1996; Kittas et al., 2002; Harmanto et al., 2006) during the periods 5-16 August 2007 and 1-30 June 2008 (winter) and 8-31 December 2007, 1-16 January 2008 and 3-20 February 2008 (summer).

The water vapor balance method is a tracer technique, based on the mass balance of water vapor in the greenhouse and using water vapor as the tracer. Values of outside and inside greenhouse air absolute humidity and the greenhouse crop transpiration rate were used to calculate the greenhouse ventilation rates. The absolute humidities of the outside and inside air were calculated using measured values of air temperature and relative humidity outside and inside the greenhouse, respectively. The crop transpiration rate, $T_r(t)$, was calculated from measurements of the whole plant transpiration (sap flow), leaf area, and the leaf area index. All the measurements were automatically recorded by a data logger (model CR23X, Campbell Scientific Ltd., Shepshed, UK) every 5 s and averaged over 30 min.

The parameters C_D and C_w were then determined statistically using SigmaPlot (Systat Software Inc., San Jose, Calif.) by fitting the experimental data to the ventilation model described earlier (eq. 6) using data from the period 5-16 August 2007 for the winter season and 8-31 December 2007 for the summer season. The ventilation model was validated by comparing the measured ventilation rates for the period 1-16 January 2008 and 3-20 February 2008 (summer) and 1-30 June 2008 (winter) with predicted values calculated for the same periods using equation 6. The areas of the vent openings were calculated by using the control algorithm of the ventilation control system and compared to values measured on selected days and at selected times of the day. Table 1 shows the periods of the data that were used to calibrate and validate the ventilation model.

Table 1. The calibration and validation periods for the ventilation rate model.

Season	Calibration Period	Validation Period
Winter	5-16 Aug. 2007	1-30 June 2008
Summer	8-31 Dec. 2007	1-16 Jan. and 3-20 Feb. 2008

Leakage rates were calculated as the average value of the air renewal rates when the greenhouse was closed. In summer, there were no sufficiently long periods when the greenhouse was fully closed by the system, so the leakage rates were measured on selected days by manually closing the greenhouse (resulting in a rapid build-up of humidity) and then monitoring the rate of change of absolute humidity while the greenhouse was closed. Care was taken to ensure that the circulation fans were operational during the measurement to ensure that the greenhouse air was well mixed in order to minimize errors due to non-uniform water vapor concentration.

Data Analysis

Assuming (i) perfect mixing of water vapor in the volume of the greenhouse, and (ii) that evaporation from the soil and vermiculite is negligible (justified by the presence of a plastic mulch on the soil surface and the cover offered by the crop canopy), the greenhouse ventilation rate was calculated from the mass balance of water vapor of the greenhouse:

$$V\frac{d\chi_i}{dt} = G(t)\cdot[\chi_e(t) - \chi_i(t)] + T_r(t) \quad (8)$$

where $G(t)$ is the ventilation rate (m^3 s^{-1}), V is the greenhouse volume (m^3), χ_i and χ_e are the inside and outside air absolute humidity, respectively (kg m^{-3}), and $T_r(t)$ is the greenhouse crop transpiration rate (kg s^{-1})

For small time steps, Δt, equation 8 can also be expressed as:

$$\begin{aligned} V\frac{\Delta\chi_i}{\Delta t} &= V\frac{\chi_i\left(t+\frac{\Delta t}{2}\right) - \chi_i\left(t-\frac{\Delta t}{2}\right)}{\Delta t} \\ &= G(t)\cdot[\chi_e(t) - \chi_i(t)] + T_r(t) \end{aligned} \quad (9)$$

so that the air renewal rate, R_a (h^{-1}), can be calculated as:

$$R_a(t) = \frac{3600}{V}\cdot\frac{\left[V\frac{\chi_i\left(t+\frac{\Delta t}{2}\right) - \chi_i\left(t-\frac{\Delta t}{2}\right)}{\Delta t}\right] - T_r(t)}{[\chi_e(t) - \chi_i(t)]} \quad (10)$$

Equation 10 was used to calculate the greenhouse air renewal rate as a simple function of χ_i, χ_e and T_r(t).

RESULTS AND DISCUSSION

In this study, greenhouse ventilation and leakage rates were measured using the water vapor balance method from measured parameters of air temperature and relative humidity and crop transpiration rates. This measurement was done for both the winter and summer seasons during the period July 2007 to June 2008. These ventilation rates were then used to calibrate and validate the ventilation model.

EXPERIMENTAL RESULTS

External and Greenhouse Climate Parameters

Figure 4 shows a summary of the prevailing outside weather conditions for the period July 2007 to June 2008, during which the measurements were taken. The prevailing winds were mostly north to north-easterly.

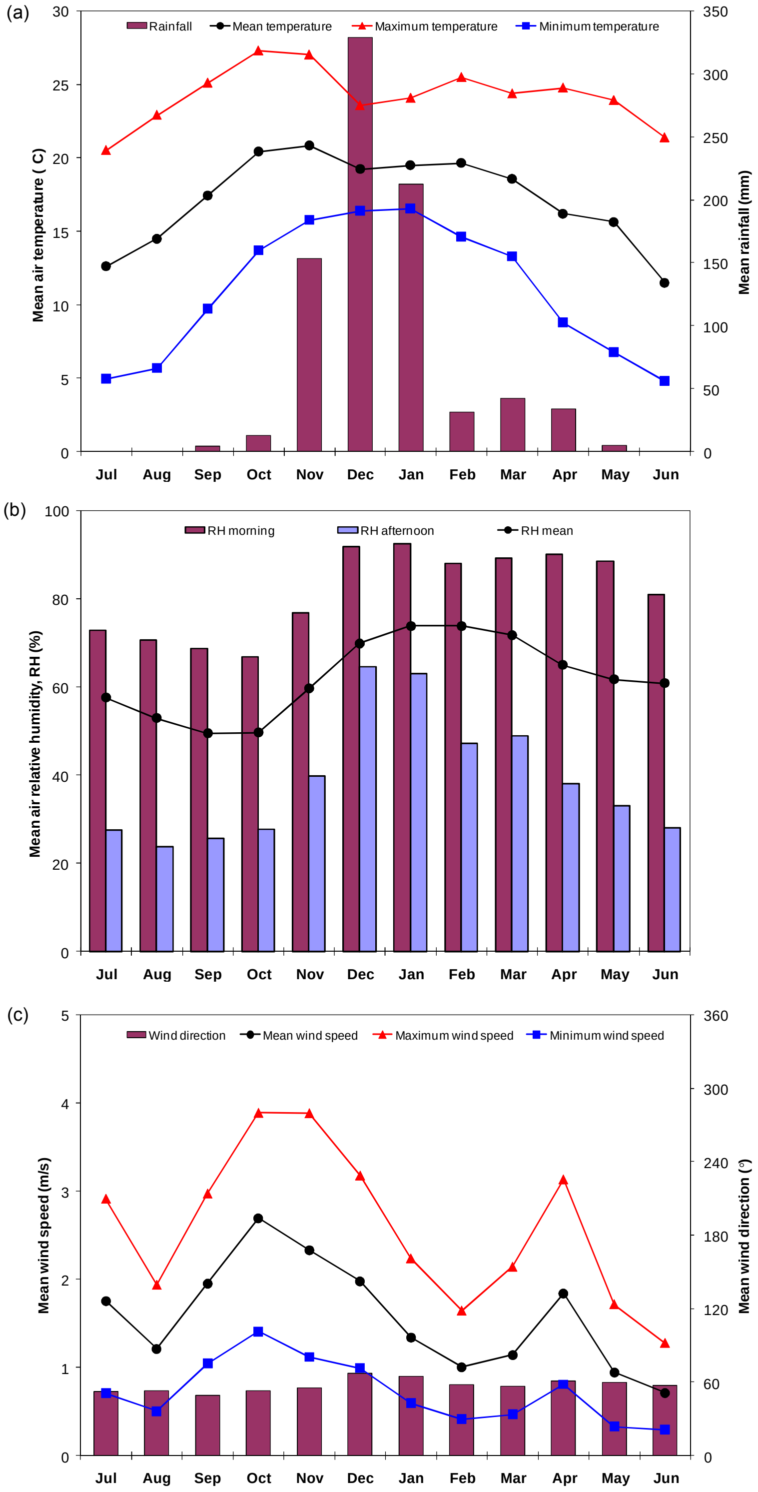

Figure 4. The prevailing external climate at the site for the period July 2007 to June 2008. Maximum and minimum values correspond to the monthly averages of daily minimum and maximum values.

Prior to analyzing the greenhouse ventilation rates using the water vapor balance method, greenhouse climate homogeneity needed to be tested. Air temperature and air humidity was measured at five designated locations in the greenhouse (fig. 3) during a 4-day period (27-31 Oct. 2007), off which a single day is graphically represented in figure 5 and 4-day average values are given in table 2. Figures 5a and 5b show the variations of the 30-min averages of the temperature and relative humidity, respectively.

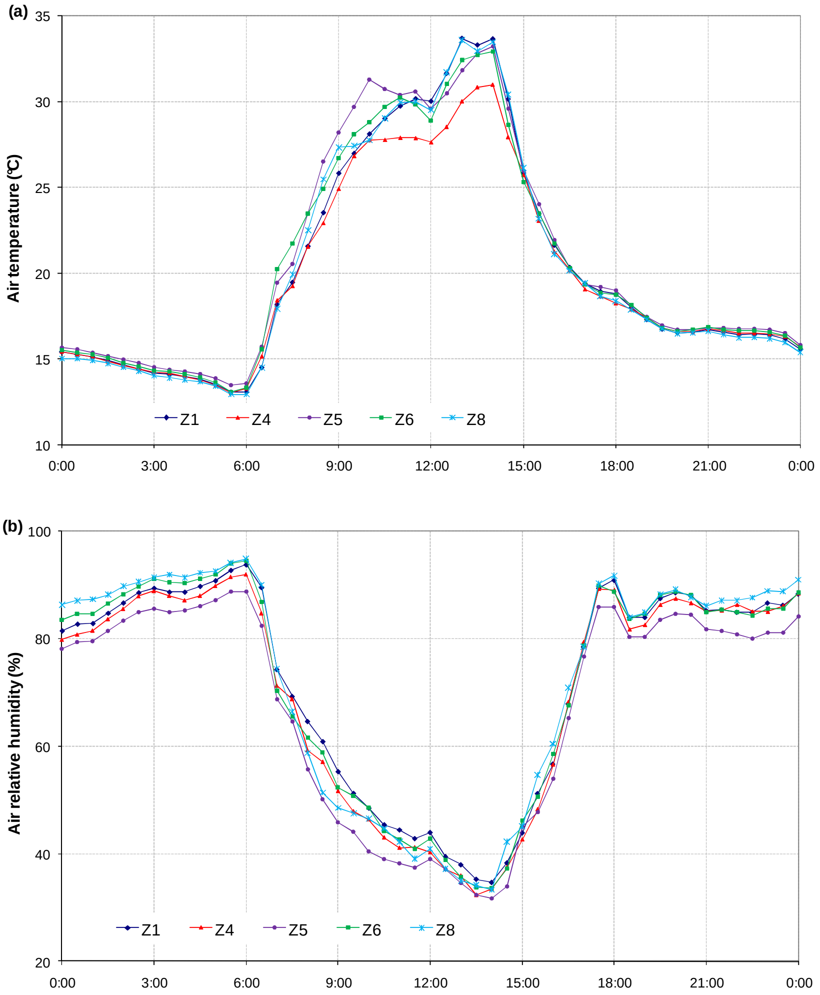

Figure 5. Greenhouse air temperature and relative humidity at five measuring positions during a single measuring day (28 Oct 2007).

The results seem to suggest that there are no appreciable gradients in the temperatures and relative humidity in the greenhouse. Sensor Z4 located to the southwest of the greenhouse, indicated consistently lower daytime temperatures than the other four sensors. There were no significant differences between the night-time temperatures and the daytime relative humidities measured at the five positions. The nighttime humidity measured by sensor Z5, located in the center of the greenhouse and at the point at which all climatic measurements were made earlier, was consistently lower than at the other four positions. However, the results seem to confirm the assumption made earlier that because there are no gradients in the greenhouse, the temperature and relative humidity measured at any point in the greenhouse is representative of the whole greenhouse.

Table 2. Summary of greenhouse air temperature and relative humidity homogeneity test results, measured at five sensor locations during a 4-day period (27-31 Oct. 2007).

Sensor	Z1	Z4	Z5	Z6	Z8
Daytime					
Average temperature (°C)	23.7	22.8	24.1	23.7	23.8
Temperature deviation (°C) from mean value	0.0	-0.8	0.5	0.1	0.2
Average relative humidity (%)	59.6	57.3	54.9	58.9	58.7
Relative humidity deviation (%) from mean value	1.7	-0.6	-3.0	1.0	0.9
Nighttime					
Average temperature (°C)	16.0	16.0	16.4	16.0	15.9
Temperature deviation (°C) from mean value	0.0	0.0	0.3	0.0	-0.2
Average relative humidity (%)	78.6	78.0	75.6	80.2	80.0
Relative humidity deviation (%) from mean value	0.1	-0.5	-2.8	1.7	1.4

Figure 6 shows the typical diurnal evolution of the measured outside total solar radiation, the difference in air temperature, and absolute humidity between the interior and exterior of the greenhouse, external wind speed, whole plant transpiration, and air renewal rates for the summer and winter seasons. These are shown for 29 December 2007 (a cloudy day in summer), 13 February 2008 (a clear summer day), and 30 June 2008 (a typical cold winter day). The ventilation strategy employed was designed to control the quantity of air exchanged with the outside in response to weather conditions. This was achieved by the climate control computer in response to seasonal settings of ventilation temperatures and the influence of outside and inside weather conditions. During the summer, the ventilation control system maintained all vents fully open for most of the day in order to minimize the temperature rise due to the high solar input during daytime and to expel excess humidity during the night and early morning. This maintained air renewal rates above 10 h^{-1} during the day, resulting in no more than a 10°C difference between the inside and the outside even on sunny days, while adequately lowering the humidity in the early morning periods to avoid condensation on the leaves and cover. During the winter, the greenhouse was partly or fully closed for most of the day in order to heat the greenhouse and reduce the vapor pressure deficit. The greenhouse was opened fully (both roof and side vents) about 2 h before sunrise to expel excess humidity while the roof vents were opened to a maximum of 50% from mid-morning to about 2 h before sunset to allow sufficient ventilation, while at the same time minimizing excessive heat loss. The vents were then closed for about 2 h to reduce rapid temperature drops at sunset, before being open fully again until around midnight when they were then closed to reduce excessive heat loss. The difference in temperature between inside and outside was therefore higher in winter than summer because of this strategy. This ventilation strategy, coupled with the relatively low wind speeds characteristic of most winter days, maintained low air renewal rates (R_a averaged around 5-10 h^{-1} during the day), while keeping the greenhouse air warmer than outside for the greater part of the day. The air renewal rates during the night were mostly low (even when the greenhouse was fully open), owing to the very low external wind speed and difference in temperature between inside and outside. Air renewal rates obtained in this study are of the same order of magnitude as those found by other researchers for similar and other types of greenhouses (Boulard and Draoui, 1995; Dayan et al., 2004; Harmanto et al., 2006; Hong et al., 2008).

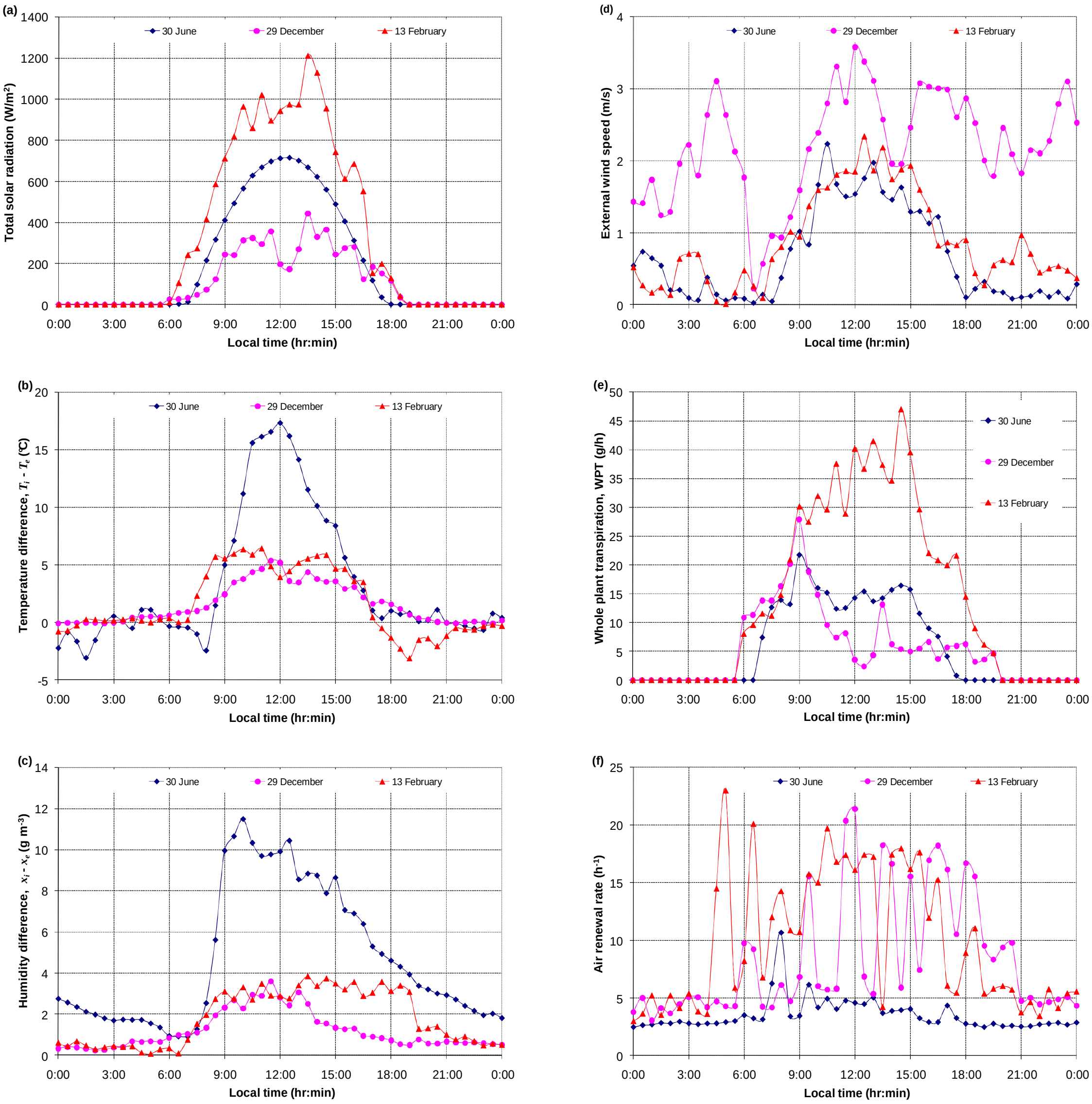

Figure 6. Typical diurnal evolutions of measured (a) outside total solar radiation, (b) greenhouse to outside air temperature difference, (c) greenhouse to outside air absolute humidity difference, (d) external wind speed, (e) whole plant transpiration, and (f) air renewal rates for typical days in summer (29 December, a cloudy day; and 13 February 2008, a clear day) and winter (30 June 2008).

Peak values of whole plant transpiration rates of about 20 and 45 g h^{-1} in winter and summer, respectively, were recorded between mid-day and late afternoon. These values agree with values found by Baille et al. (1994) of about 30 to 60 g h^{-1} per plant for ungrafted and grafted rose plants, respectively, of the cultivar "Sonia" grown in rockwool slabs. WPT was lower on cloudy days than sunny, as expected, due to the lower solar radiation input and vapor pressure deficits. Also of interest is the oscillatory pattern exhibited by WPT with an average cycle period of about 1 h and higher amplitudes on sunny days than on cloudy days. Oscillations in rose transpiration rates were also observed by Rose et al. (1994) with amplitudes of up to 18 g h^{-1} and a period of about 75 min. Values of whole plant transpiration in winter were lower than the corresponding summer values because of the lower radiation input in winter.

Leakage Ventilation Rates

Table 3 shows the range of leakage rates obtained by measurement. The leakage rates were calculated as the averages of the ventilation rates from all the periods during which the greenhouse was closed. Measurements of air temperature and relative humidity and crop transpiration rates sampled every 5 s were used to calculate the leakage rate. In the winter the values indicated here are 30-min averages of these parameters, while the summer values were calculated from 1-min averages of the relevant parameters.

Table 3. Leakage rates obtained in this study.

Dates and Time of Measurement	Avg. Wind Speed (m s^{-1})	Average $T_i - T_e$ (°C)	Leakage Rate $R_{a,0}$ $\left(\overline{R_{a,0}} \pm SD^{[a]}\right)$ (h^{-1})
Summer			
16 Jan 2008 (1257-1306 h)	3.4	9.49	3.3 ± 0.8
24 Feb 2008 (1052-1104 h)	1.9	7.81	2.4 ± 0.3
28 Feb 2008 (1351-1400 h)	1.6	6.09	2.8 ± 0.5
11 March 2008 (1318-1326 h)	1.5	7.24	3.2 ± 0.7
Winter			
5-16 Aug 2007 (daytime)	2.2	5.06	2.1 ± 0.6
5 -16 Aug 2007 (nighttime)	0.4	0.97	1.5 ± 0.4
1-30 June 2008 (daytime)	1.1	3.88	2.4 ± 0.4
1-30 June 2008 (nighttime)	0.35	2.42	1.7 ± 0.2

[a] SD is the standard deviation of the values obtained in each measurement period.

The leakage rate was taken as the mean of these values: 2.9 ± 0.4 h^{-1} for summer and 1.7 ± 0.4 h^{-1} for winter. These values are of the same order of magnitude as the leakage rates ranging from 0.5 to 2 h^{-1} reported elsewhere (Fernandez and Bailey, 1992; Boulard and Baille, 1995; Boulard and Draoui, 1995; Liu et al., 2005; Katsoulas et al., 2006). Differences may be due to the greenhouse structure and shape, prevailing weather conditions or the air-tightness of this greenhouse compared to those in cold climates, where most of these studies were performed. In addition, differences in the full scale air renewal and leakage rates in this study may have resulted due to the presence of buildings and other greenhouses in the vicinity of the greenhouse in which measurements were taken.

SIMULATION RESULTS

Ventilation Model Parameter Estimation and Analysis

Table 4 shows the values of the parameters obtained in this study. The parameters C_D and C_w were determined statistically using SigmaPlot by fitting the experimental data to the ventilation model described earlier (eq. 6) using measured data of air renewal rates from the period 5-16 August 2007 for the winter season and 8-31 December 2007 for the summer season.

Table 4. Discharge (C_D) and wind effect (C_w) coefficients obtained in this study.

Coefficient	C_D	C_w	R^2
Value	0.414 ± 0.006	0.029 ± 0.002	0.857

The discharge coefficient, C_D, and wind effect coefficient, C_w, obtained in this study are generally of the same order as those found by other researchers for greenhouses with the same circumstances (table 5).

Table 5. Discharge and wind effect coefficients determined by other researchers.

Discharge Coefficient, C_D	Wind Effect Coefficient, C_w	$T_i - T_e$ (°C)	External Wind Speed (m/s)	Size and Type of Greenhouse and Opening Angles of Vents	Source
0.64	0.07 - 0.10	0.8 - 12	0 - 2	416 m^2 2-span Filclair; roof vents only; 20°	Boulard and Baille (1995)
0.43	0.07 - 0.10	0.8 - 12	2 - 4	416 m^2 2-span Filclair; roof vents only; 20°	Boulard and Baille (1995)
0.75	0.07	1 - 10	0.1 - 7	416 m^2 2-span Filclair; roof vents only; 0-30°	Kittas et al. (1997)

0.253	0.075	0.9	4.9	149 m^2, mono-span, screened side vents	Teitel et al. (2008)
0.127	0.038	1 - 8	2	504 m^2, 3-span; screened roof and side vents	Liu et al. (2005)
0.363	0.07	1.6	2.2	160m^2 mono-span arch, screened roof and side vents	Katsoulas et al. (2006)

Table 5 shows that the parameters C_D and C_w can vary considerably even for similar greenhouses. Boulard and Baille (1995), Roy et al. (2002), and Fatnassi et al. (2003) suggest that the parameters depend on the greenhouse size and design (including configuration of window openings and the angle between the prevailing wind direction and the window), immediate surroundings of the greenhouse and prevailing weather conditions, particularly wind speed. The values found in this study are intermediate between those for greenhouses with and without screens, further showing the dependence of these parameters on the circumstances of the greenhouse. The greenhouse used in this study had screens installed on the sidewall openings only, while the roof openings were open. In addition, the low values of C_D and C_w found in this study may also have been influenced by the proximity of the greenhouse to another greenhouse less than 2 m away to its north, and buildings at least 5 m high and less than 4 m to the east and north east, respectively, which may have affected the pressure field of the airflow around the greenhouse and reduced the air velocity near the vent openings. In addition, the greenhouse was at least three times as large as the other greenhouses in table 5, so the ratio of wall length to volume is smaller, which could contribute to differences.

VENTILATION MODEL VALIDATION

Figures 7 and 8 show the relationship between the measured and modelled values of the greenhouse air renewal rates for the winter and summer seasons, respectively, while table 6 gives the regression analysis results.

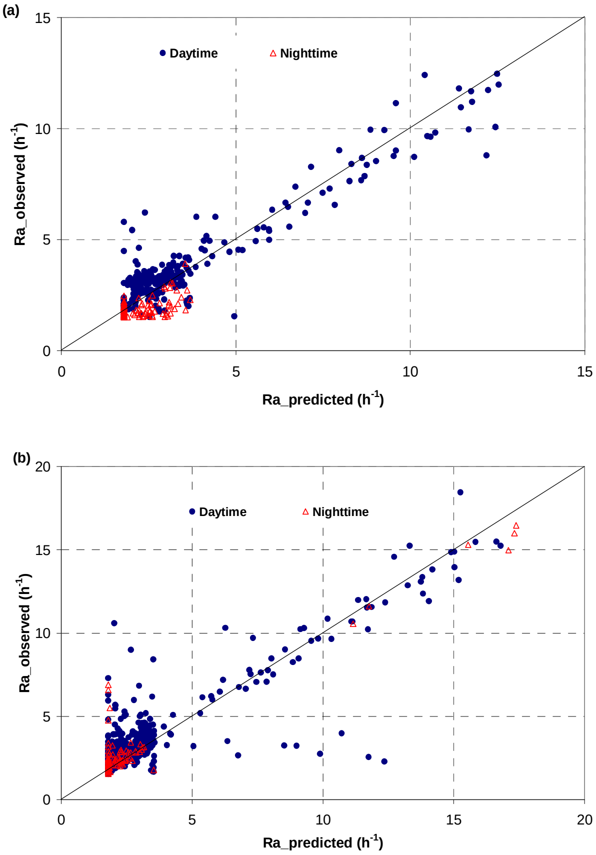

Figure 7. Regression between the experimentally observed and predicted air renewal rates for nighttime (Δ) and daytime (•) during the winter season (a) calibration period from 5 to 16 August 2007, and (b) validation period from 1 to 30 June 2008. Values used are calculated from half-hourly averages of the relevant parameters.

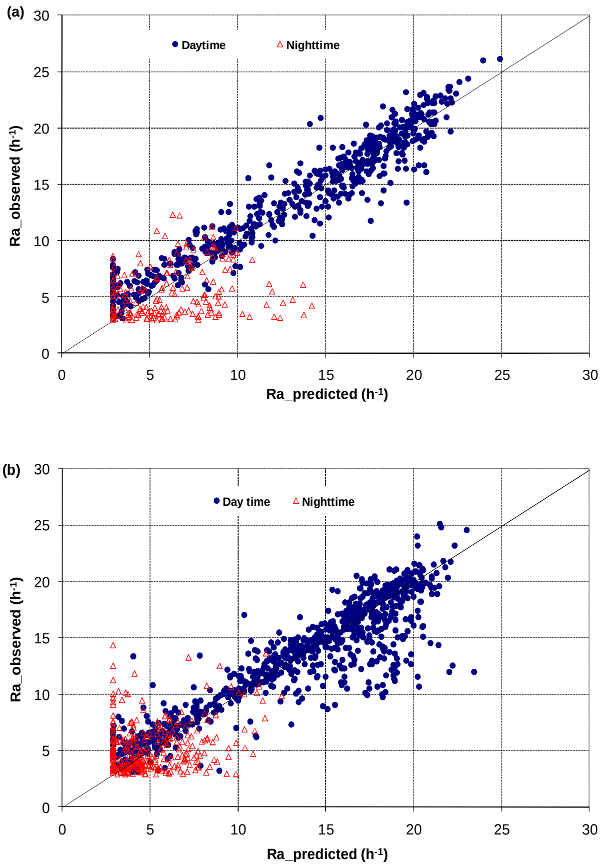

Figure 8. Regression between the experimentally observed and predicted air renewal rates for night-time (Δ) and daytime (•) during the summer season (a) calibration period from 8 to 31 December 2007, and (b) validation period from 1 to 16 January 2008 and 3 to 20 February 2008. Values used are calculated from half-hourly averages of the relevant parameters.

Table 6. Results of regression analysis between the predicted and observed air renewal rates, including the 95% confidence intervals and the slope and intercept for the equation $R_{a(obs)} = m\ R_{a(pred)} + c$

	Number of Observations, *N*	R^2	Slope *m*	SE	95% Confidence Interval of Slope	Intercept, *c*	SE	95% Confidence Interval of Intercept
Winter								
Calibration 5-16 Aug. 07	426	0.863	0.934	0.018	[0.904; 0.976]	0.275	0.072	[0.134; 0.417]
Validation 1-30 June 08	630	0.800	0.852	0.017	[0.818; 0.885]	0.849	0.075	[0.702; 0.995]
Summer								
Calibration 8-31 Dec. 07	764	0.872	0.930	0.013	[0.904; 0.955]	1.036	0.168	[0.705; 1.368]
Validation 1-16 Jan. & 3-20 Feb. 08	1165	0.813	0.857	0.012	[0.834; 0.881]	1.769	0.147	[1.476; 2.062]

The results show a good fit between measured and predicted values, particularly during the day. There is, however, a general over-estimation of the greenhouse air renewal rates. Most of the significant differences between measured and predicted air renewal rates were observed during the night, in the early mornings (around sunrise) and during rain. As shown in figure 8, where there is more scatter in the night-time values than is the case for figure 7, this effect was more pronounced in summer, when nighttime humidity was usually above 90%. This may be explained in terms of instrument errors in the measurement of the high relative humidity that occurs at night, early morning and during rain periods. The humidity probes are quoted as having measurement errors of about ±2% in the range 10% to 90% relative humidity, but above 90%, and as the sensor ages, the errors increase to about ±5% (Delta-T Devices Ltd., 2000; Campbell Scientific Inc., 2007). Since the method employed here relies heavily on the measurement of humidity, errors in the air renewal rates at higher humidities (such as at night, early morning, and during rainfall events) are likely to be larger than those at other times. Errors may also be due to the measurement of air renewal rates resulting from errors in the estimation of the crop transpiration rates in general, and particularly in the early morning and late afternoon. While the heat balance sap flow gauge error is expected to be no more than 10% (Dynamax Inc., 2005), the main source of error with their use in estimating crop transpiration rates lies in the scaling up from single to whole canopy transpiration. In addition, over-estimation and under-estimation of WPT in the mornings (just after sunrise), and late afternoon (just before sunset), respectively, were observed. These have been reported by Baker and van Bavel (1987), Steinberg (1988), Baker and Nieber (1989), and Grime et al. (1995) and explained as follows: in the mornings when soil temperature exceeds air temperature, there is a negative temperature gradient in the sensor as warm sap enters a cooler stem, causing a temporary over-estimation of WPT if the sensor is near the soil (as in this study). In the late afternoon, when the ambient air is at a higher temperature than the soil, the sensor registers a higher positive temperature gradient in the sensor, resulting in an under-estimation of WPT.

During the night, transpiration rates and soil or medium evaporation were assumed to be zero, but research has shown that the transpiration rates of roses may be as much as 10 g h^{-1} under certain conditions (Seginer, 1984; Blom-Zandstra et al., 1995). Because the daytime evaporation from the medium is negligible compared to the total water consumption of the crop, it is of little consequence to the ventilation rate measurement during the day. However, since the plants were well-watered (meaning the medium was always wet) and night-time temperatures of the medium were generally found to be above air temperature, this term may be of significance to the determination of the ventilation rate at night.

Finally, the ventilation control system closed the greenhouse during rain events and storms to avoid wetness of the crop and physical damage to the structure. The sap flow gauges do not respond as rapidly as the ventilation model to such rapid changes as the greenhouse closes, so transpiration rates may have been temporarily over-estimated, consequently under-estimating air renewal rates.

CONCLUSION

The use of heat balance sap flow gauges to measure the mass flow rate of sap, and thus transpiration rates, in roses enabled continuous and automatic determination of greenhouse air renewal rates in a naturally ventilated Azrom-type greenhouse in Zimbabwe using the water vapor balance method. Peak values of whole plant transpiration rates of about 20 and 45 g h^{-1} in winter and summer, respectively, were recorded between mid-day and late afternoon. Full-scale daytime air renewal rates above 10 h^{-1} in summer and between 5-10 h^{-1} in winter were recorded, while nighttime air renewal rates were mostly low (even when the greenhouse was fully open), owing to the very low external wind speed and difference in temperature between inside and outside air. Average leakage rates were 2.9 and 1.7 h^{-1} for summer and winter, respectively. Full-scale air renewal rates obtained here were comparable with the values found by other researchers for greenhouses in Northwest Europe, North America, Mediterranean climates, and Asia. However, leakage rates obtained here were higher than those obtained for these greenhouses. The discrepancy can be explained by differences in the greenhouse structures, shape and orientation of vents and prevailing weather conditions. The selected ventilation model was fitted to experimental data of air renewal rates, and discharge and wind effect coefficients of 0.414 and 0.029 (R^2 = 0.857), respectively, were determined. The model was validated by comparison with measured air renewal rates. The results show a good fit between measured and predicted values (R^2 = 0.80 and 0.81 for winter and summer, respectively), although there is a general over-estimation of the greenhouse ventilation rates, particularly during the night. The theoretical approach to predicting ventilation rates adopted in this study, based on the stack and wind effects, enabled the greenhouse air renewal rate to be modelled, but requires that two parameters, the discharge and wind effect coefficients, be determined by fitting the model to the experimental data. A comparison of the values of these parameters obtained in this study with published values showed that not only are they greenhouse and ventilation system dependent, but also depend on the prevailing weather conditions (including the outside air humidity). These factors should therefore be accounted for in such a model for it to be applicable to another greenhouse and site and are the subject of future research.

It must also be pointed out that, although due care was taken to minimize errors, both the measured and predicted air renewal rates suffered errors due to the circumstances of the measurements, unavailability of ideal equipment and limited control over the greenhouse facilities. The main sources of error in the water vapor balance method lie in the measurement of the crop transpiration rate, particularly the scaling up from single (or a few) plant(s) to the whole canopy transpiration. In addition, the method suffers from the general problems with other tracer techniques: (a) non-uniform water vapor concentration in the greenhouse due to non-ideal mixing of the greenhouse air, (b) short-term fluctuations in external weather conditions (wind speed and direction and air temperature) and the vent opening during the measurement, and (c) measurement errors due to the equipment itself or the operator. Nonetheless, the results obtained show sufficient accuracy, and that the model can be used to simulate the ventilation rates all year round in a naturally ventilated Azrom type greenhouse and gives good estimates of ventilation rate without involving specialized and expensive equipment provided the ambient conditions and geometrical data of the greenhouse are available. The model can be used as a design tool to evaluate and optimize the effects of different ventilation configurations and strategies on greenhouse air renewal rates. In addition, it can be used as a component in a greenhouse climate model in order to further evaluate the effects of ventilation strategies on the inside greenhouse and crop microclimate, and thus lead to better greenhouse climate control.

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