Greenhouse Ventilation Rate: Theory and Measurement with Tracer Gas Techniques

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Leakage and ventilation rates were measured in a four span glasshouse at Silsoe Research Institute. Two tracer gas techniques were used, a decay rate method with different positions of the leeward ventilator (0, 10 and 20% of the maximum opening) and a continuous injection method with the leeward ventilators open 10%. The influences of wind speed, wind direction and temperature difference between inside and outside were analysed for each ventilator position. It was found that wind speed had a strong influence on leakage and ventilation rates. Some influence of wind direction occurred with northeast and southeast winds but no significant conclusions can be drawn because of insufficient data. Temperature difference affected ventilation rates under low wind speeds. For each ventilator position, the air exchange rate was linearly related to wind speed. A dimensionless function was calculated to express the ventilation flux per unit ventilator area and unit wind speed as a function of the angle of ventilator opening. With a 10% opening, the results obtained with the decay and continuous methods were compared and showed good agreement for wind speeds greater than 1 m/s.

The results for 10 and 20% ventilator openings obtained by using the decay method were compared with those obtained by applying the theory of convection, using pressure differences generated by wind forces and temperature differences. It was found that the combined effect of wind and temperature difference gave satisfactory predictions of ventilation rates. Also, the values obtained by measurement and prediction based on pressure difference were in close agreement, with a global wind effect coefficient similar to that found in the literature.

1. Introduction

Ventilation is one of the most important tools for controlling greenhouse climate. The air exchange between the inside and outside of a greenhouse influences the environmental conditions, such as temperature, humidity and carbon dioxide concentration that affect the development and production of the crop. During winter, ventilation must remove the excess humidity and provide a good atmosphere inside the greenhouse; while during summer, the main reasons for ventilation are for cooling and to remove humidity depending on the inside conditions. However, the accuracy of prediction is still uncertain due to difficulties of performing accurate measurements and lack of models that can be applied to a large number of different greenhouses. The measurement of ventilation and leakage rates is necessary to provide a good understanding of climate control in greenhouses. It is necessary to know the ventilation characteristics of a greenhouse in order to provide good control of the inside environmental conditions, and a good crop yield of high-quality produce.

Ventilation and leakage rates are influenced by environmental factors such as wind speed, wind direction, temperature difference between inside and outside and ventilator aperture. Fernandez and Bailey¹² have shown that wind direction does not have a detectable influence on the ventilation rate. As their greenhouse was located in a windy area, however, they were unable to measure the ventilation due to buoyancy. One factor that indirectly influences the ventilation rate is the solar radiation, since it is an important component of the energy balance. When the intensity of the solar radiation is high, the temperature inside the greenhouse increases and the ventilation rate rises as a result of the stronger thermal
buoyancy effect. Thus, in areas where the wind is not so strong, the difference in temperature is more important in the natural ventilation of greenhouses.

Various techniques have been used to measure and predict ventilation and leakage rates such as tracer gas techniques, energy balances and measurements of pressure differences between inside and outside. The energy balance has been used to predict ventilation rates by comparing the results obtained by sequential measurements with the two tracer gas techniques and confirmed that tracer gas techniques may not allow determination of real flow but characterize effective flow through openings.

In this study, leakage and ventilation rates were measured using the decay and continuous injection tracer gas methods. The influence of wind speed, wind direction, ventilator aperture and temperature difference between inside and outside are analysed. Ventilation rates were predicted using various models proposed by different authors: these include the theory of natural convection and the effect of wind forces, assuming that total ventilation is due to the combined effect of both natural forces. Also, a global wind effect coefficient was estimated and used to predict the air exchange. Applying the principles of natural ventilation, good agreement was obtained between measured and predicted ventilation rates.

The purpose of this work was to: (1) compare the results obtained by measurements with the two tracer gas methods; (2) compare results obtained by applying the physical principles of natural ventilation to those obtained experimentally; (3) estimate pressure coefficients; and (4) provide information on ventilation in a new research greenhouse at Silsoe Research Institute.

### 2. Theoretical considerations

#### 2.1. Principles of natural ventilation

Natural ventilation is caused by pressure differences which are induced by two main forces: wind action and buoyancy or stack effect.

##### 2.1.1. Ventilation due to wind forces

Wind around a building creates a pressure field at the openings and hence produces air flow through them. These pressures may be positive, when air flows into the building, or negative (suction) when the air flows out. The

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**Notation**

- $a$: constant
- $A$: area of the ventilator opening, $m^2$
- $A_u$: unit ventilator area, $m^2$
- $C_d$: discharge coefficient, dimensionless
- $C_i$: internal concentration of tracer gas, $\mu l/l$
- $C_o$: external concentration of tracer gas, $\mu l/l$
- $C_w$: wind pressure coefficient, dimensionless
- $E$: effectiveness of the opening, dimensionless
- $g$: acceleration of gravity, $m/s^2$
- $G_T$: ventilation rate due to temperature difference, $m^3/s$
- $G_w$: ventilation rate due to wind, $m^3/s$
- $G(z)$: dimensionless function
- $h$: height of ventilator opening, $m$
- $H$: mean height opening above the ground, $m$
- $M$: mass injection rate of tracer gas, $kg/s$
- $n$: number of observations
- $N$: ventilation rate, air change $h^{-1}$
- $\Delta P$: total pressure difference, $Pa$
- $\Delta P_T$: pressure difference due to temperature difference, $Pa$
- $\Delta P_w$: pressure difference due to wind, $Pa$
- $R$: correlation coefficient
- $v$: wind velocity across the opening, $m/s$
- $v_w$: wind speed, $m/s$
- $V$: volume of greenhouse, $m^3$
- $t$: time period
- $t_1, t_2$: sequential measurements
- $T_o$: outside temperature, $K$
- $\Delta T$: temperature difference between inside and outside, $K$
- $\alpha$: opening angle, deg
- $\rho$: density of air, $kg/m^3$
- $\xi$: resistance of the opening, dimensionless

...than the energy balance at low ventilation rates. However, the results were similar for ventilator openings higher than 20%. The difficulty in using this method is the need to measure a large number of variables, and a single inaccuracy can have a large effect on the final result.

Airflow through an opening is due to pressure difference between inside and outside. Boulard et al., Papadakis et al., Kittas et al., Hoxey and Moran and Hoxey and Wells measured pressure differences between inside and outside in different greenhouses to identify wind pressure coefficients and their variations relating to wind characteristics. Kittas et al. have shown that the wind-induced ventilation rate can be expressed as a function of a wind pressure coefficient $C_w$. Boulard et al. compared measurements of pressure differences with tracer gas techniques and confirmed that tracer gas techniques may not allow determination of real flow but characterize effective flow through openings.

In this study, leakage and ventilation rates were measured using the decay and continuous injection tracer gas methods. The influence of wind speed, wind direction, ventilator aperture and temperature difference between inside and outside are analysed. Ventilation rates were predicted using various models proposed by different authors: these include the theory of natural convection and the effect of wind forces, assuming that total ventilation is due to the combined effect of both natural forces. Also, a global wind effect coefficient was estimated and used to predict the air exchange. Applying the principles of natural ventilation, good agreement was obtained between measured and predicted ventilation rates.

The purpose of this work was to: (1) compare the results obtained by measurements with the two tracer gas methods; (2) compare results obtained by applying the physical principles of natural ventilation to those obtained experimentally; (3) estimate pressure coefficients; and (4) provide information on ventilation in a new research greenhouse at Silsoe Research Institute.
wind effect is usually split into two components: a steady effect, induced by a static pressure distribution related to the mean wind speed and which can be described by Bernoulli’s equation; and (2) a turbulent effect, induced by the fluctuating pressure distribution, linked with the turbulent characteristics of the wind interacting with the greenhouse or with the surroundings.

It is assumed that the wind pressure coefficient $C_w$ is the result of both of these effects. An explanation of this is given by Boulard and Baille. If it is assumed that the wind speed is constant around the opening, the pressure difference $\Delta P$ is given by Bernoulli’s equation

$$\Delta P = \frac{1}{2} \bar{\zeta} \rho v^2$$  \(1\)

where $\bar{\zeta}$ is the pressure drop coefficient, $\rho$ the air density and $v$ the average air velocity across the opening. From Eqn (1), and defining the discharge coefficient of the opening as $C_d = \bar{\zeta}^{-0.5}$, the air velocity is given by

$$v = C_d \sqrt{\frac{2}{\rho} \Delta P}$$  \(2\)

and the air exchange rate $G$ through the opening is

$$G = A C_d \sqrt{\frac{2}{\rho} \Delta P}$$  \(3\)

where $A$ is the total area of the opening and, in the case of a single opening, half of the area is the inlet and half is the outlet. Applying the same principle to air flow due to the wind pressure field, $v_w$ being the wind speed measured at the reference height above the ground, the wind pressure difference $\Delta P_w$ is defined by

$$\Delta P_w = \frac{1}{2} \rho C_w v_w^2$$  \(4\)

Assuming that for wind speeds higher than 1–2 m/s, the buoyancy effect is small, then ventilation rate can be considered to be only a function of the wind. Combining Eqns (3) and (4), the air exchange due to the wind is given by Boulard and Baille and Kittas et al as:

$$G = A \frac{C_d}{2} \sqrt{C_w v_w}$$  \(5\)

Equation (5) can be used to estimate the global wind effect coefficient ($C_d C_w ^0.5$).

Albright and Hellickson et al suggested the following empirical equation to determine the ventilation rate due to wind:

$$G = A \frac{E_v}{2}$$  \(6\)

where $E$ is the effectiveness of the opening depending on the wind direction, being 0.50–0.60 at right angles to the opening winds and 0.25–0.35 for diagonal winds. For agricultural buildings, the value recommended is 0.35, which is the global coefficient of Eqn (5) taking into account the effectiveness of the opening and the pressure due to wind action.

Bot proposed a function $G(x)$, which gives the relation between the ventilation rate $G$ per unit ventilator area $A_v$ and unit wind speed $v$.

$$G(x) = \frac{G}{A_v v}$$  \(7\)

2.1.2. Ventilation due to buoyancy effect

It is possible to regard the roof ventilators as vertical openings. The reference level is in the middle of the opening where the inside and outside pressures are equal and no air exchange occurs. In the lower half, the outside pressure is higher than the inside. As a result, the colder inside air leaves through the lower half and the warmer inside air leaves through the upper half.

Bruce presented an equation to predict the flow through an opening due to temperature difference $\Delta T$ where $g$ is the acceleration due to gravity, $h$ is the height of the opening and $T_o$ is the outside temperature.

$$G = C_d A \frac{3}{2} \sqrt{gh \frac{\Delta T}{T_o}}$$  \(8\)

The pressure difference $\Delta P_f$ due to the stack effect results from the different vertical pressure, caused by the gradient of the air density between the inside and outside and can be expressed in Eqn (9) (Ref. 8), where $H$ represents the height of the opening above the ground.

$$\Delta P_f = \rho g H \frac{\Delta T}{T_o}$$  \(9\)

2.1.3. Combined effect of wind and buoyancy forces

In natural ventilation, both forces of wind and buoyancy are usually present. In areas where the wind is strong, this effect is more important than the temperature difference but the buoyancy dominates when the wind is weaker. Meneses and Raposo considered that, for wind speeds of 0.5–1.5 m/s, the temperature difference dominates the wind effect in greenhouses with openings located both in the roof and lateral walls. At higher wind speeds, the opposite occurs and the thermal influence can be ignored. However, this limit depends upon greenhouse geometry, ventilator position and internal to external temperature differences.

When both forces act together, Albright, De Jong, and Hellickson et al. considered that the resulting air flow is not equal to the sum of the two separate values. The flow through any opening is given by

$$G = \sqrt{G_w^2 + G_f^2}$$  \(10\)
where \( G_w \) is the flux due to the wind and \( G_T \) due to thermal difference.

Boulard and Baille\(^4\) studied several models used to predict ventilation rates, and concluded that those which sum the pressure differences [Eqn (11)], and then determined the air flux with Eqn (13), gave a better agreement with measured values than those which sum the flows due to the individual effects [Eqn (12)]:

\[
\Delta P = \Delta P_w + \Delta P_T \tag{11}
\]

\[
G = G_w + G_T \tag{12}
\]

Using the sum of the pressure differences, the ventilation rate is given by

\[
G = C_d A \sqrt{\frac{2}{\rho}} |\Delta P| \tag{13}
\]

2.2. Tracer gas techniques; methods and instruments for ventilation rate measurements

One of the most important techniques for measuring ventilation and leakage rates is the tracer gas technique, which has been used by Bot,\(^5\) Nederhoff et al.,\(^6\) De Jong,\(^7\) Fernandez and Bailey\(^8\) and Boulard et al.\(^9\) The technique is based on a mass balance of a tracer gas in the greenhouse air. There are two main methods of measuring ventilation and leakage rates with a tracer gas, the continuous injection or static method and the pulse injection or dynamic method. In both methods, selection of the tracer gas is very important. It should have the characteristics\(^9\) of being easy to measure at low concentrations, inert, non-toxic, non-flammable, not a natural component of air and with a molecular weight close to the average weight of the air components. Many gases have been used as a tracer gas, such as sulphur hexafluoride (SF\(_6\)), methane (CH\(_4\)), carbon dioxide (CO\(_2\)), hydrogen (H\(_2\)), nitrous oxide (N\(_2\)O), argon 41 and krypton 85. The two gases which are most frequently used are CO\(_2\) and N\(_2\)O. The latter is best because it meets all the above requirements. Carbon dioxide can be used, but it is necessary to measure the concentration of CO\(_2\) in the external air and the rate of release from the soil. In a cropped greenhouse, N\(_2\)O is the better of the two because its concentration is not influenced by the photosynthesis and respiration of the plants.

The following measurements are made at equal intervals of time (0.5–2 min, for the decay method and 1–5 min for the continuous method): tracer gas injection rate (only for the continuous method), internal gas concentration, external gas concentration, angle of ventilator opening, wind speed, wind direction, internal temperature and external temperature.

2.2.1. Static method

In this method, the injection rate of gas into a greenhouse is held at a constant value until an equilibrium concentration is reached. The gas supply and sampling system must be distributed around the greenhouse in order to obtain good dispersion of the gas and uniform sampling of the air.\(^9\) The ventilation rate is calculated from\(^9\)

\[
G = \frac{M}{[C(t_1) - C(t_2) - (t_2 - t_1)]} \times \ln \left( \frac{C(t_2) - C(t_3)}{C(t_1) - C(t_3)} \right) \tag{14}
\]

where \( M \) is the mass flow of gas entering the greenhouse, \( C_i \) and \( C_o \) are the internal and external gas concentration, \( V \) is the volume of the greenhouse, and \( t_1 \) and \( t_2 \) are sequential measurements.

The advantage of this method is that it provides continuous information, and a range of wind speed and directions can be covered during one measurement. The disadvantage is the high consumption of tracer gas.

2.2.2. Dynamic method

In this case, the tracer gas is injected and distributed uniformly in the greenhouse until a certain pre-determined concentration is reached and then stopped. The decay in the concentration of the tracer gas is then measured. When the concentration has decreased to 80–90% of the initial value, another pulse of gas is injected, and another decay is measured. It is possible to change the angle of ventilator opening between each decay but not during one period of decay.

The ventilation rate is calculated by the following procedure:\(^9\)

1. The natural logarithm of \((C_i - C_o)\) is plotted against time.
2. A time period \( t \) is selected during which \( \ln(C_i - C_o) \) decreases linearly.
3. A linear regression is fitted to the values of \( \ln(C_i - C_o) \) over this period,

\[
\ln(C_i - C_o) = a + Nt \tag{15}
\]

where \( N \) is the ventilation rate in air changes per hour and \( a \) is a constant. This is negative because the concentration of the gas decreases during the measurement. The ventilation rate in m\(^3\)/s is given by \( NV/3600 \).

4. Mean values are obtained for the wind speed, wind direction and internal and external temperature, over the time period selected.

The advantages of the decay method over the static method are that it uses less tracer gas and can be used to
measure over a wide range of ventilation rates while the continuous injection method requires an appropriate flowmeter to measure the injection rate. The disadvantages are the difficulty in obtaining a uniform concentration of the tracer gas throughout the greenhouse and for high ventilation rates, the concentration of the gas decreases rapidly and the data obtained for analysis can be insufficient.

3. Experimental arrangement and methods

The experiments were carried out in a four-span glasshouse at the Silsoe Research Institute. The dimensions of the greenhouse were: length 16·0 m, width 12·8 m, eaves height 4·1 m and ridge height 4·67 m; the volume was 932·2 m$^3$. The walls were of double glass and the roof of single glass. The orientation of the ridge and gutters was east—west. The greenhouse was sheltered by surrounding walls with a height of 5 m, to provide a wind regime more closely representative of commercial greenhouses. Ventilator windows (3·0 m $\times$ 1·0 m) were located in the roof, two on the north side and two on the south side of each span. Only those on the leeward side were opened in this experiment. A tomato crop grown in hydroponics culture was present and at the stage of producing fruit. Figure 1 represents a diagram of the roof openings existing in the experimental greenhouse.

All measurements of leakage (ventilators closed) and ventilation rate (ventilators opened) were made under a range of conditions of wind speed, wind direction, window aperture (0, 10 and 20%) and inside–outside temperature difference. The ventilator aperture is expressed as a percentage of the maximum aperture (42°), which means angles of 0°, 4·2° and 8·4°.

The equipment to measure the environmental factors (inside temperature, N$_2$O concentration, and ventilator position) was located in the greenhouse and the climatic variables (wind speed, wind direction and outside temperature) were measured in a station located outside the greenhouse. Sensors to measure wind speed were located at 5 m above the ground. Data were recorded every 30 s (decay method) and 2 min (static method) using a data logging system. The accuracy of the sensors was follows: the aspirated platinum resistance thermometer, $\pm$ 0·15 at 0°C and $\pm$ 0·35 at 100°C; the infra-red gas analyser, $\pm$ 1% over all the scale; the flowmeter, $\pm$ 1% of the full-scale reading which was 50 l/min and the cup anemometer, $\pm$ 0·1 m/s for wind speeds $>$ 1 m/s, starting at 0·3 m/s.

The distribution of the tracer gas was through four perforated tubes located on the floor along the centre of each span, and through two tubes along the base of the sidewalls. The tubes had holes of 1·5 mm diameter every 1 m along the entire length. Chalabi and Fernandez$^{21}$ have shown that this system of distribution is effective. However, the mixing of the air is never perfect and, in these experiments, the air of the greenhouse was sampled at four positions, equally distributed over the greenhouse at a height of 3 m close to the top of the crop; and the

Fig. 1. Diagram of the location of the roof ventilator CDEF providing an opening ABFE of height $h$ at an angle $\alpha$. 
samples were mixed before entering the infra-red gas analyser. Measurement and injection were controlled by computer.

When the static method was used, the $N_2O$ was injected into the greenhouse at a constant mass flow (between 2·5 and 51/min depending on the wind speed). When the environmental conditions were steady, the internal concentration of $N_2O$ reached equilibrium after some time. However, the outside conditions, especially those related to the wind, were variable and sometimes the $N_2O$ concentration never stabilised. When the inside concentration of $N_2O$ is stable, the logarithmic term of Eqn (14) becomes unity and hence the second term becomes zero, but it is very important when the concentration changes between each measurement.

This method was used only with the ventilators opened to 10% and beyond (angle of 4·2°). When the continuous method is used to measure leakage rates the $N_2O$ mass flow must be very low, and the measurement uncertainty becomes high if a large capacity flowmeter, suitable for ventilation rate measurements, is used. All the data (inside and outside) were recorded over several hours to enable the $N_2O$ concentration to stabilise.

When using the dynamic method, the tracer gas was injected into the greenhouse until the concentration reached 110 µl/l. When the desired concentration was reached, the supply of gas was stopped and after waiting for 10 min to obtain a uniform distribution of gas the ventilators were opened and the data recorded. When the concentration dropped below approximately 8 µl/l the measurement cycle was started again. The ventilation rate is assumed to be proportional to the rate of loss of $N_2O$, and calculation of this using linear regression is explained in Section 2.2.2.

4. Results and discussion

4.1. Tracer gas measurements

4.1.1. Static method

The static method allows information on the effect of wind speed, wind direction and temperature difference to be obtained in one experiment. In these experiments the ventilators were opened 10%.

Due to the variation of wind speed some problems occurred when analysing the data. Therefore, it was necessary to choose periods with stable conditions. It is well known that the wind changes very much over short periods of time. Moreover, there is a time delay between the moment the wind characteristics change and the resulting reaction in the concentration of the tracer gas (ventilation rate). It was necessary to determine this time delay to analyse the data correctly. Experiments were conducted to determine the time delay, which consisted in the injection of the tracer gas into the greenhouse, wait 10 min for stabilization, and then open the vents and verify when the gas concentration started decreasing. This procedure was repeated several times. For high wind speeds, the time delay was short and vice-versa. The data were analysed using the different time delays to find which one gave the best correlation coefficient, and this was found to be 16 min. This time delay is in agreement with those (13–18 min) obtained by Chalabi and Fernandez in experiments in another greenhouse but with similar characteristics. In the linear regression analysis, the averages taken over successive 10 min periods for the wind speed and ventilation rate were used with a delay of 16 min. The regression equation showed that the ventilation rate was

$$G = 0·330 + 0·167v_w$$

The standard errors of the coefficients were 0·179 and 0·010, respectively. 179 data values and coefficient of determination $R^2 = 0·59$. These results are compared with those obtained using the decay method in Section 4.1.3. Figure 2 shows the measured ventilation rates as a function of the wind speed and, as expected, the air exchange increased with increasing wind speed.

4.1.2. Dynamic method

Leakage and ventilation rates were analysed as functions of the wind speed, wind direction and temperature difference between inside and outside. It was found that the effect of buoyancy and wind direction had little influence on the ventilation and leakage rates, which is in agreement with the study of Fernandez and Bailey. However, some experiments with northeast and south-east winds instead of the usual southwest wind direction, associated with low wind speed gave higher ventilation rates than with the usual wind direction (see, for example, Fig. 4). This could have been due to the fact that the greenhouse was less sheltered on the east side and the wind effect was less disturbed, and produced higher pressures. The other matter influencing these results was the buoyancy effect, since the wind speed was very low, with values of the order 0·5 m/s. It was impossible to draw conclusions as the measurements could not be repeated because of non-recurrence of this wind direction. It would be desirable to carry out more studies on the effect of wind direction.

For all ventilator positions it seems that a relation exists between wind speed and ventilation and leakage rates which is in agreement with studies by Bot, De Jong and Fernandez and Bailey. When the wind speed increases the ventilation rate increases in a linear manner and it is possible to obtain the relation between them (Figs 3–5). Table 1 gives the regression equations...
Fig. 2. Ventilation rate measured for the ventilator opening at 10% (4.2°), expressed as a function of the wind speed (above 1 m/s) and regression line obtained by analysis of data.

obtained by analysing the data. For ventilators open at 20% there were no values of wind speed below 1 m/s. For the ventilators opened at 10% the regression was fitted excluding wind speeds below 1 m/s, since the purpose of this work was to compare the static and dynamic methods and when the static method was used there were no wind speeds lower than 1 m/s.

Figure 4 for the ventilator opening of 10% shows some points with low wind speed which correspond to high ventilation rates, indicating that the influence of the temperature difference is important for low wind speeds and further experiments with these conditions are required.

The function \( G(\alpha) \) in Eqn (7) was calculated and expressed as a function of the ventilator angle. Figure 6 shows the function \( G(\alpha) \) obtained in the present experiments and indicates that the ventilation rate increased linearly with the opening angle. This is expected, since air exchange increases with ventilator aperture as shown by Fernandez and Bailey\(^3\) and Kittas \textit{et al.}\(^8\). The constant of the regression equation is equal to \( 0.0007 \pm 4 \times 10^{-5} \) and the slope \( 0.0015 \pm 6 \times 10^{-6} \) with \( R^2 = 0.99 \) and \( n = 3 \).
4.1.3. Comparison between the results obtained by static and dynamic methods

The regression equations obtained by analysing the data collected with the decay method (values for wind speeds below 1 m/s excluded) and the continuous methods are presented in Table 2. The results obtained were similar for wind speeds higher than 1 m/s. The coefficient of determination $R^2$ is lower for the static method than for the dynamic method, and the explanation for this effect is the averaging period, which is larger for the dynamic method. Figure 6 contains values obtained by both methods and indicates consistency in the function $G(z)$.

4.2. Comparison between results obtained by measurement and theoretical predictions

Only the results obtained for the ventilators opened at 10 and 20% when using the dynamic tracer gas method were compared with those predicted by calculation. If these models are used with the ventilators closed, the
Table 1
Regression equations for leakage and ventilation rates $G$ as a function of wind velocity $v$ for different ventilator openings (decay rate method)

<table>
<thead>
<tr>
<th>Ventilator opening deg</th>
<th>Regression equation</th>
<th>$R^2$</th>
<th>$n$</th>
<th>Standard error of the constant</th>
<th>Standard error of the regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$G = 0.002 + 0.017v$</td>
<td>0.55</td>
<td>22</td>
<td>0.021</td>
<td>0.003</td>
</tr>
<tr>
<td>10</td>
<td>$G = 0.277 + 0.1657v$</td>
<td>0.82</td>
<td>26</td>
<td>0.178</td>
<td>0.016</td>
</tr>
<tr>
<td>20</td>
<td>$G = 0.616 + 0.302v$</td>
<td>0.88</td>
<td>26</td>
<td>0.277</td>
<td>0.022</td>
</tr>
</tbody>
</table>

$R^2$ = coefficient determination; $n$ = number of determination.

estimated ventilation rate is zero. In practice, some air exchange occurs which depends on the airtightness of the glazing material, the ventilator closure and the wind speed. Leakage is explained by other physical principles and it is not the purpose of this work.

4.2.1. Pressure differences

In a first approach, the ventilation rates were estimated using Eqns (4), (9), (11) and (13). Wind pressure coefficients $C_w$ were chosen from those in the literature\(^9\),\(^10\) taking into consideration the characteristics of the greenhouse, wind direction and location of the openings. The mean values used were 0.25 and 0.15 for the 10 and 20% openings. For the discharge coefficient $C_d$, an expression defined by Bot\(^15\) ($C_d = 0.64 + 0.001a$) was used and values between 0.64 and 0.65 were found which are in agreement with those given by Boulard and Baille.\(^14\) Results obtained are shown in Figs 7 and 8 and it is apparent that the predicted ventilation rates are generally greater, except at low ventilation rates, than those measured with the tracer gas. This could possibly be due to the fact that the greenhouse is located in a very sheltered place with walls and trees around, and this affects the wind pressure coefficient, which should be smaller than the one used.

In the second approach, the value of $C_d$ was fixed at 0.64 for the opening of 10% and 0.65 for the opening of 20%, and $C_w$ was estimated for the greenhouse using Eqn (5). It was assumed that the air exchange rate was a function of the wind only for wind speeds greater than 2 m/s. The average values found for $C_w$ were 0.10 and 0.09, for opening angles of 4.2 and 8.4\(^\circ\), respectively, which are similar to the results of Boulard and Baille.\(^14\) A significant decrease of wind coefficient was observed with increasing wind speed. The non-dimensional average coefficient $C_dC_w^{0.5}$ was approximately 0.20, and also decreased with increasing wind speed. Table 3 shows $C_dC_w^{0.5}$ obtained as a function of the wind speed. These
values are a little lower than those obtained by Boulard et al.\textsuperscript{6} in a greenhouse with continuous roof openings, and again that can be due to the sheltered greenhouse and the different type of openings in this study.

Figures 9 and 10 show predicted versus measured ventilation rates for the two positions of the ventilators. These results were obtained using the same model referred to above but with the estimated value for $C_dC_w^{0.5}$ of 0.20. These results seem to indicate that the model can be used to predict air exchange rate, but some independent measurements should be done to confirm the estimated values.

### Table 2

<table>
<thead>
<tr>
<th>Tracer gas method</th>
<th>Regression equation</th>
<th>$R^2$</th>
<th>$n$</th>
<th>Standard error of the constant</th>
<th>Standard error of the regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>$G = 0.277 + 0.1657v$</td>
<td>0.82</td>
<td>26</td>
<td>0.178</td>
<td>0.016</td>
</tr>
<tr>
<td>Static</td>
<td>$G = 0.330 + 0.167v$</td>
<td>0.59</td>
<td>179</td>
<td>0.179</td>
<td>0.010</td>
</tr>
</tbody>
</table>

$R^2$ = coefficient of determination; $n$ = number of observations.

4.2.2. Theory of natural convection and wind action: combined effect

In this case, ventilation rate due to temperature was calculated using Eqn (8) and due to wind using Eqns (5) or (6) since they are similar. In Eqn (6), $E$ is the effectiveness of the opening, which was found to be 0.20 after analysing results obtained with the tracer gas and so $E = C_dC_w^{0.5}$. The combined effect of wind and temperature difference was calculated with Eqns (10) and (12) and the results were very similar, with the correlation coefficients being slightly higher in the first case for the opening of 10\% (0.75 and 0.74) and the same for the opening of 20\% (0.88). Figures 11 and 12 show the residuals between measured and predicted ventilation rates versus wind speed, and these are seen to decrease as the wind speed increases. This model seems to give good prediction of the air exchange for this type of greenhouse. In the comparisons, it is possible to see that the difference between the results obtained by experiment and by the theory increased for wind speeds higher than 8 m/s.

5. Conclusions

1. The continuous injection and decay methods can be used to measure ventilation rates in greenhouses. The continuous injection method covers a wide range of wind speeds and wind directions and, for correct

![Fig. 7. Predicted (Eqn (12)) and measured (dynamic N\textsubscript{2}O) ventilation rates for the ventilator opening at 10\% ($R^2 = 0.74$), —, ideal line](image1)

![Fig. 8. Predicted (Eqn (12)) and measured (dynamic N\textsubscript{2}O) ventilation rates for the ventilator opening at 20\% ($R^2 = 0.88$), —, ideal line](image2)
analysis of data, it is necessary to know the time delay for each greenhouse.

2. Ventilation rates are a function of the wind speed, and a relation between them was found for each ventilator position. The effect of wind direction could not be analysed because of insufficient data for each different wind direction. Temperature difference was always in the same range (between 8 and 14°C) and seems not to influence ventilation rate for wind speeds above 1 m/s. However, some experiments should be repeated with low wind speeds and east winds.

3. The results obtained using the decay and continuous methods show good agreement for wind speeds greater than 1 m/s.

4. A global wind effect coefficient \( C_d C_0^{0.5} \) equal to 0.20 was found, which is similar to the values in the literature.

5. Models based on pressure differences and on the combined effect of thermal buoyancy and wind forces can be used to estimate air exchange rates in greenhouses with roof openings. Direct measurements of wind pressure coefficients should be made in order to confirm these data.

6. In all models, linear models overestimate ventilation rates at the higher wind speeds.

7. For the higher ventilator openings measured and predicted values were in close agreement item for small openings because the errors are less for high ventilation rates.

<table>
<thead>
<tr>
<th>Ventilator position, %</th>
<th>Range of wind speed, m/s</th>
<th>2 &lt; v &lt; 4</th>
<th>4 &lt; v &lt; 6</th>
<th>6 &lt; v &lt; 8</th>
<th>8 &lt; v &lt; 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td>0.219</td>
<td>0.208</td>
<td>0.195</td>
<td>0.170</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.210</td>
<td>0.206</td>
<td>0.188</td>
<td>0.161</td>
</tr>
</tbody>
</table>
Fig. 12. Residuals between measured (dynamic N₂O) and predicted [Eqn (9)] ventilation rates for the ventilator opening at 20% versus wind speed

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