MEASUREMENT AND ANALYSIS OF AIR SPEED DISTRIBUTION IN A NATURALLY VENTILATED GREENHOUSE

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Abstract

Air speed distribution is a key factor influencing heat and mass transfer in greenhouses. The air speed profiles in the centre of a naturally ventilated greenhouse with a tomato crop were investigated by means of a customised multi-point two-dimensional sonic anemometer system. The experimental results showed that air speed was linearly dependent both on external wind speed and greenhouse ventilation flux. Under leakage ventilation, however, the air speed remained nearly constant at a low value (<0.1 m s⁻¹), due to negligible wind and temperature effects on greenhouse air exchange rate. Based on the measured air speed profiles and ventilation flux, an estimation method for calculating the average internal air speed was established. This method can be applied to crop aerodynamic resistance calculations and irrigation management.

1. Introduction

Ventilation processes induce an air exchange between the interior air of a greenhouse and its external environment due to wind and temperature effects. Air movement provided by natural ventilation influences the convective heat exchange between the vegetation and the interior air, and thus the microclimate around the vegetation. Most recent studies on natural ventilation have used tracer gas techniques (Bot, 1983; de Jong, 1990; Fernandez and Bailey, 1992) and energy balance models (Fernandez and Bailey, 1992; Wang and Deltour, 1996). These two approaches, however, do not allow the airflow patterns in greenhouses to be determined. More recently, Boulard et al. (1996 and 1997) measured air velocity directly by sonic anemometry in the opening. However, no data were provided to support the hypothesis of a direct relation between greenhouse air exchange rate and inside average air speed.

The objective of the present study is to investigate air speed profiles in the centre of a greenhouse with a tomato crop. Air speeds at different heights are related to air flux within a greenhouse, external wind speed, buoyancy force and vent opening angle. The experimental results are compared with airflow patterns already studied in the same greenhouse. Based on measurements of air speed profiles, a method allowing an estimation of the average air speed in the greenhouse is proposed.

2. Experimental set-up

2.1. Site and greenhouse descriptions

The experimental greenhouse was located in Avignon (44°N latitude), in the south of France. This region is characterised by a predominant northerly wind channelled by the Rhône valley. Measurements were performed during two weeks (10-22 August) in 1998 in a 416 m² two-span greenhouse, equipped with two continuous roof vents (Fig. 1). The greenhouse contained a mature tomato crop, growing on a substrate of rock wool slabs. It was planted in two simple rows at two sides and five double rows in the centre of the
greenhouse. The distance for corridor between rows was 0.8 m. During the measurement period, its height and leaf area index were about 2.1 m and 2.3 respectively. Natural ventilation was provided when the temperature exceeded 24°C. Neither heating nor misting systems were used.

2.2. Sonic anemometer and climatic measuring system

Air speed profiles in the centre of the greenhouse were measured by a synchronised two-dimensional (2D) sonic anemometer system described by Wang et al. (1999). The path length for both arms of each sonic anemometer was 60 cm with an accuracy of about 1.3% for air velocity in the range between 0 and 1.9 m s⁻¹. The system was composed of three 2D sonic anemometers aligned along a vertical support at 0.5 m, 1.25 m and 2 m respectively, above the ground (Fig. 1). The two horizontal components of each sonic anemometer were mounted in the same orientation with an angle of 45° to the north to minimise the distortion introduced by the presence of the instrument itself because the interior air moved from south to north in this situation (Haxaire et al., 1999). The data, were sampled with a frequency of 3 Hz and 2D resultant air speeds in the horizontal plane at six positions, were averaged over 15 minutes and recorded by a micro-computer.

The external wind speed and direction were measured by a cup anemometer and wind vane situated 1 m above the greenhouse. Interior and exterior air temperatures were measured by aspirated platinum resistance thermometers situated in the centre and 1 m away from the greenhouse at a height of 1.5 m. All climatic parameters were sampled every minute and averaged and recorded every 15 minutes using a data logger (Campbell, CR20).

2.3. Climatic conditions during the measurements

Table 1 provides the external wind speed, outside air temperature, interior-exterior air temperature difference and the vent opening angle prevailing during the day and night over the whole sampling period. The day and night periods were defined based on the time of sunrise and sunset. Mean external wind speed was higher during the day (1.84 m s⁻¹) than during the night (0.70 m s⁻¹). The constancy of wind direction from the north was observed due to the dominant regional wind: the Mistral. The vents opening angle reached almost the maximum value during the day but dropped to 0° during the night. The vent opening angle was controlled by a climate microcomputer via a temperature sensor and a temperature set-point. The interior-exterior air temperature difference was nearly 3°C when the vents were open but nearly 0°C while the vents were closed. These significantly different situations between daytime and nighttime periods were well suited for evaluating the inside air speed induced by natural ventilation.

3. Results and analyses

3.1. Time variation of inside air speed

Values for air speed averaged over 15 minute periods, calculated from the two components of sonic measurements, were compared with the climatic measurements. Fig. 2 shows inside air speed at positions 1, 3, 4 and 6 and the external wind speed (a) for 20 August, from 0 to 18 h, together with the vent opening angle (b). Before the vents were open, air speeds inside the greenhouse was smaller than 0.1 m s⁻¹ and independent of the external wind speed. When the vents were open during the day, there was a strong dependence of internal air speeds on the opening angle and the external wind speed.
3.2. Effect of wind speed under maximum opening angle

During the measurements in August 1998, the opening angle of roof vents always reached the maximum value (50.6°) during the day, due to the strong solar radiation and high air temperature. In these conditions, the wind effect on internal air speeds was predominant and it was investigated first. The relationship between V at different heights and the external wind speed was well fitted by a straight line. Internal air speeds were proportional to the external wind speed, with coefficients of determination R² ranging between 0.71 and 0.84 (Table 2). The slope of the linear regression curve tended to increase from higher to lower levels and tended to be larger in the west span than that in the east span except for point 5.

3.3. Effect of ventilation flux under maximum opening angle

Air exchange between the greenhouse and its environment can be derived from the two main driving forces of natural ventilation: wind and stack effects. For greenhouses and ventilation systems similar to those in this study, both effects have been found to be of the same importance when the wind speed was lower than approximately 2 m s⁻¹. Therefore, the relationship accounting for the combination of thermal and wind effects (Boulard and Baille, 1995) was used to calculate the ventilation flux (ϕ_v in m³ s⁻¹):

\[
ϕ_v = \frac{L_0 C_d T_e}{3gΔT} \left[ \left( \frac{gΔT}{T_e} h + C_w U_e^2 \right)^{\frac{3}{2}} - \left( C_w U_e^2 \right)^{\frac{3}{2}} \right]
\]  (1)

where C_d and C_w are empirical discharge and wind effect coefficients, identified for this greenhouse as 0.64 and 0.09 by a tracer gas technique (Boulard and Baille, 1995); g is the gravitational acceleration (m s⁻²); h is the vertical height of the vent opening (m); L_0 is the length of the continuous vents (m); T_e and ΔT are the exterior air temperature and the interior-exterior air temperature difference (K) and U_e is the external wind speed (m s⁻¹). Table 3 shows that internal air speeds were linearly related to ϕ_v.

3.4. Air speed under leakage ventilation

Mean values and standard deviations of air speeds under leakage ventilation conditions at 6 positions were around 0.06 m s⁻¹ and 0.02 m s⁻¹. It shows that the average greenhouse air speed during the night was much lower than during the day. During the night, the vents were closed and the air speed in the greenhouse was dependent on leakage and on natural convection induced by buoyancy forces due to the temperature difference between cold surface (greenhouse roof) and warmer surface (soil surface). The temperature difference between the soil surface and the roof surface was roughly proportional to the interior-exterior air temperature difference. No significant effect on inside air speeds was observed for either the temperature difference between 0 and 2.1 °C or the external wind speed between 0.3 and 2.3 m s⁻¹.

4. Discussion

The heat and mass transfer between vegetation and interior air are largely dependent on the value of crop aerodynamic resistance. This resistance is mainly related to a mean inside air speed, assumed constant in most energy balance models (Bot, 1983; Wang and Deltour, 1997). However, this is only true when the greenhouse is closed or when natural ventilation is maintained at a small and constant value.

The present results suggest that inside air speeds are well related to the ventilation flux (Eqn. 1). From analyses of the airflow pattern in the greenhouse (Boulard et al., 1997), vertical air speed profiles perpendicular to the airflow can be used to estimate the
mean greenhouse air speed $V_{\text{cal}}$ (m s$^{-1}$):

$$V_{\text{cal}} = \frac{\phi_v}{A}$$ (2)

where $A$ is the greenhouse section area perpendicular to the ventilation flux. In this study, it was the vertical cross section area (13×4.08 m$^2$) situated at the position of the air speed measurements. This simple calculation was compared with the average air speed value deduced from the measurements at the six positions (Fig. 3). There was a good correlation between the measured and estimated air speeds ($R^2 = 0.87$). It was observed that the calculated air speed was lower than the measured value due to 0.837 of the regression slope. This underestimation was probably caused by a larger airflow through the measured corridor section than through the tomato crop row.

5. Conclusions

The average air speed value in greenhouses is a key factor for calculating heat transfers between greenhouse components and the interior air. Experimental air speed profiles in the centre of a naturally ventilated greenhouse with a tomato crop were investigated at two locations by using six sonic anemometers. For the maximum roof opening angle, inside air speeds were highly correlated to the external wind speed ($R^2 = 0.71-0.84$). For the minimum roof opening angle, no significant relationship between the air speed and the external wind speed or the interior-exterior air temperature difference was found because air speeds in the greenhouse were maintained at a low constant value.

Based on the experimental airflow pattern, an estimation method for calculating the average inside greenhouse air speed at crop level can be established from the global ventilation flux and the section area perpendicular to the airflow. This relationship can be applied to crop aerodynamic resistance calculations, then to irrigation control.

References


Tables

1. Statistics of climatic conditions during the measurements (10-22 August)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>During the day</th>
<th></th>
<th>During the night</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>External wind speed, m s⁻¹</td>
<td>1.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
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<tr>
<td>Outside air temperature, °C</td>
<td>29.4</td>
<td>4.2</td>
<td>22.9</td>
<td>2.4</td>
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<tr>
<td>Temperature difference, °C</td>
<td>3.0</td>
<td>2.9</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Vent opening angle, °</td>
<td>45</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

2. Linear regression equations with R² values for air speed (V) versus the external wind speed (Uₑ) at 6 positions under maximum opening angle

<table>
<thead>
<tr>
<th>Position</th>
<th>Linear regression equation</th>
<th>Coefficient of determination (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V₁ = 0.049 + 0.070Uₑ</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>V₂ = 0.008 + 0.098Uₑ</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>V₃ = 0.007 + 0.106Uₑ</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>V₄ = 0.056 + 0.082Uₑ</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>V₅ = 0.041 + 0.080Uₑ</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>V₆ = -0.085 + 0.190Uₑ</td>
<td>0.84</td>
</tr>
</tbody>
</table>

3. Linear regression equations with R² values for air speed (V) versus the ventilation flux (φᵥ) at 6 positions under maximum opening angle

<table>
<thead>
<tr>
<th>Position</th>
<th>Linear regression equation</th>
<th>Coefficient of determination (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V₁ = 0.034 + 0.013φᵥ</td>
<td>0.73</td>
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<tr>
<td>2</td>
<td>V₂ = -0.012 + 0.018φᵥ</td>
<td>0.82</td>
</tr>
<tr>
<td>3</td>
<td>V₃ = -0.016 + 0.020φᵥ</td>
<td>0.86</td>
</tr>
<tr>
<td>4</td>
<td>V₄ = 0.039 + 0.015φᵥ</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>V₅ = 0.026 + 0.015φᵥ</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>V₆ = -0.127 + 0.036φᵥ</td>
<td>0.87</td>
</tr>
</tbody>
</table>
1. Schematic plan of the greenhouse with the measurement locations of sonic anemometers and climatic parameters (U_e, external wind speed; T_i, interior air temperature; α, vent opening angle; h, vertical height of the opening; L_0, vent length)
2. Internal and external air speeds and vent opening angle for 20 August, (a) air speeds at positions 1, 3, 4 and 6 ($V_1$, $V_3$, $V_4$ and $V_6$) and (b) external wind speed ($U_e$), (b) vent opening angle

3. Comparison of average air speed between measurement and estimation from 208 observations. The straight line ($V_{\text{cal}} = 0.036+0.837 \ V_{\text{mea}}$) was obtained by linear regression ($R^2 = 0.87$)