Lee-side Ventilation-induced Air Movement in a Large-scale Multi-span Greenhouse

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Lee-side ventilation-induced air movement was experimentally investigated in a 1728 m² multi-span glasshouse. Air velocity measurements were performed by means of a customized multi-point two-dimensional sonic anemometer system which simultaneously measured the horizontal air velocity components parallel and normal to the ridge at 3 Hz frequency. The airflow pattern in the horizontal plane of a greenhouse was analysed qualitatively under different external wind conditions. The experimental results show both the vertical and the horizontal profiles of the normalized interior air speed as a function of the measurement height, the external wind speed and opening angle were acceptably presented by the simple linear functions. The airflow in the horizontal plane was of low turbulence with large eddies.

1. Introduction

Large-scale multi-span greenhouses, commonly designated as Venlo-type greenhouses, are widely used in Belgium, The Netherlands and more generally in the northern region of Europe. Natural ventilation due to roof ventilators alternatively hinged on each side of the ridge is a most common climate control method in this kind of greenhouse and is thus an important physical process in both greenhouse energy management and mass (H₂O, CO₂) balances. Therefore, the overall optimization of the indoor greenhouse microclimate requires a thorough knowledge of the quantitative (rates) and the qualitative (patterns) of natural ventilation.

The determination of the ventilation rate in greenhouses has been studied by many researchers since 1980. Most experimental researches in full-scale greenhouses were carried out by means of tracer techniques and differential pressure methods. These included measurements in both glasshouses (Bot, 1983; De Jong, 1990; Fernandez & Bailey, 1992) and plastic greenhouses and tunnels (Boulard & Baille, 1995; Boulard & Draoui, 1995; Kittas et al., 1995; Papadakis et al., 1996). However, tracer techniques allow only the prediction of gross air renewal rates in greenhouses. More recently, direct measurements of air velocities through greenhouse ventilators were conducted using one-dimensional (Boulard et al., 1997a) and three-dimensional sonic anemometers (Boulard et al., 1997b; Wang & Deltour, 1997).

Ventilation-induced airflow patterns in greenhouses have been simulated by the use of computational fluid dynamics (CFD). Okushima et al. (1989) did not obtain good agreement between simulation results and measurements, probably due to the limited computational power. More recently, Mistriotis et al. (1997) obtained more accurate simulation results for a two-span greenhouse with a continuous roof opening. Ventilation-induced air movement in large multi-span greenhouses, however, has not been studied extensively.

In the present study, the lee-side ventilation is discussed in detail because it is frequently used and supposed to produce a more homogeneous air exchange and thus a more uniform growth of the crop compared with the windward side ventilation. The objectives of this study are: (1) to obtain vertical profiles of the horizontal air velocity in a greenhouse and to establish the relationship between the slope of vertical profiles and the external wind speed; (2) to explore the lee-side ventilation-induced air movement distribution at a fixed height in the greenhouse under different external wind speeds and window.
openings, and to find a relationship between the air velocity at different positions and the external wind speed and the window opening angle; (3) to further investigate the turbulence characteristics of the air movement in the horizontal plane.

2. Materials and methods

2.1. Site and greenhouse description

The experiments were performed in a large (1728 m²) multi-span greenhouse located in Rumeke, Belgium (latitude 50°5’N), about 40 km from the sea. It was orientated east–west and bordered at the north and east sides by other greenhouses (Fig. 1). It was composed of 12 spans with 2·85 m eaves height and 3·75 m ridge height. The ventilators were distributed on the roof, alternately on the north and south slopes of each span. They are 1·60 m long and 0·73 m wide. This greenhouse was constructed about 30 years ago and was covered with normal glass. The vent opening was controlled by a manual system. It was empty and unheated during the measurement period.

2.2. Measurement system

2.2.1. The multi-point two-dimensional sonic anemometer system

For the measurement of the airflow patterns, sonic anemometers were chosen because of their good performance at the low air velocities often found in greenhouses. However, variable airflow conditions in space and time are usually found in greenhouses under natural ventilation. The airflow pattern in the entire greenhouse is affected by the variable external wind conditions and the modification of the opening angle on the leeward side. In order to have an instantaneous general picture of air movement through the whole greenhouse, a synchronized multi-point two-dimensional sonic anemometer system was developed. The system, described by Wang et al. (1999), consisted of 12 two-dimensional sonic anemometers equipped with a microprocessor and operated at 3 Hz frequency. Measurement values were temporarily stored in the random access memory of the sonic anemometers and transferred to a central personal computer (PC) at 5 min intervals. The path length for both arms of each sonic anemometer was 60 cm. Calibration and validation results showed that the given combination of path length and low sampling frequency was accurate to about 1·3% for air velocity ranging from 0 to 1·9 m/s.

2.2.2. Climatic parameters and wind measurement

The climatic parameters were measured at a height of 1·5 m in the centre of the greenhouse. The air temperature and humidity were measured by a ventilated thermometer/psychrometer. The window opening angle was monitored by a potentiometer. A meteorological station measuring wind speed and direction, solar radiation, dry and wet bulb air temperatures was installed at a height of 6 m outside the greenhouse and 4 m above the building (garage) (Fig. 1). The measurements were recorded using a programmable multimeter (Model: 8840A, Fluke) controlled by a data logger made in the department. All the variables were averaged and recorded every 5 min on a PC and they were synchronized with the sonic anemometer system. External wind speed and direction were measured by a cup anemometer and a wind vane with a start threshold of 0·4 m/s. Its direction was defined as 0° from north to south, increasing in a clockwise direction. During measurement periods, the temperature effect was minimized by selecting an overcast day.
2.2.3. Mean and turbulent characteristics

The $x$- and $y$- axis of each two-dimensional sonic anemometer were mounted parallel and perpendicular to the greenhouse ridge, respectively. The directions of the instantaneous velocity components $V_x$ and $V_y$ were defined as positive from west to east and from south to north, respectively. These two components of the air velocity can be seen as the averaged velocities ($\bar{V}_x$ and $\bar{V}_y$) plus their turbulent parts ($\bar{\sigma}_x$ and $\bar{V}_y$):

$$V_x = \bar{V}_x + \bar{\sigma}_x$$  
$$V_y = \bar{V}_y + \bar{V}_y$$

The mean horizontal wind vector specified by its magnitude $\bar{V}$ in m/s and direction $\phi_v$ in deg was expressed mathematically as follows:

$$\bar{V} = \sqrt{\bar{V}_x^2 + \bar{V}_y^2}$$

$$\phi_v = \tan^{-1} \left( \frac{\bar{V}_y}{\bar{V}_x} \right)$$

The horizontal airflow direction was defined as that $0^\circ$ is the direction of the north, the angle was counted positively in an easterly direction and negatively in a westerly direction. The formulation of Stull (1994) and Heber et al. (1996) was used for a non-dimensional measure of the turbulence intensity in the $x$ direction, $\psi_x$:

$$\psi_x = \frac{\sigma_x}{\bar{V}}$$

where $\sigma_x$ is the standard deviation of the velocity in m/s in the $x$ direction. The normalized total turbulence kinetic energy $K$ per unit of mass is defined as

$$K = \frac{1}{2} \frac{\sigma_x^2 + \sigma_y^2}{\bar{V}^2}$$

The air velocity measured by the fast-response sonic anemometer system over a time period gives time-series data. The normalized autocorrelation function $R(t)$ was defined as

$$R(t) = \frac{V_x(t)V_x(t + j\Delta t)}{\sigma_x^2}$$

where $V_x(t)V_x(t + j\Delta t)$ is the mean product of $V_x$ at two different instants $t$ and $t + j\Delta t$, the time increment $\Delta t$ for the time step $j$. The function $R(t)$ measures the persistence of a velocity wave within the whole time series. A random fluctuation would give a rapidly decreasing autocorrelation function while a regular oscillation would lead to a wave. Such variation might be associated with a physical phenomenon such as an eddy. An integral length scale $L_i$ in m used by Heber et al. (1996) was also calculated:

$$L_i = \bar{V} \int_0^{t_0} R(t) \, dt$$

where $t_0$ is the time in s when the autocorrelation $R(t)$ equals zero for the first time.

3. Results and analyses

3.1. Vertical profile

The measuring system used for the vertical profile of horizontal air velocities is shown in Fig. 2. It was composed of four aligned two-dimensional sonic anemometers at 0-40 m intervals from the ground. The vertical aluminium square tube used to support the anemometers was fastened to a heating pipe at its top and anchored to
the soil at its bottom. The sonic anemometers were attached to the vertical tube by a 40 cm rod to minimize obstruction of the ultrasonic pulse by the support. The measurements were carried out at nine positions (Fig. 3). During the measurements, the external wind was from northwest to southeast and only the windows at the lee-side (south) of the greenhouse were opened.

The horizontal air movement appeared to be a predominant function of the height \( h \). During 5 min measurement periods, the external wind speed varied frequently. The air velocities measured at different heights were affected simultaneously by the fluctuations in the external wind conditions. The influence of these fluctuations on the vertical profile was significantly reduced when the normalized speed \( V(h)/V(0.40) \) was plotted as a function of the measurement height.

The velocity at height 0.40 m was chosen here for normalization because its absolute value was the largest one in the vertical profile in most instances. In this way, the airflow distribution in the horizontal plane could be determined at this height and the relation between the vertical profile and the horizontal airflow distribution could be established.

The vertical profiles were fitted by linear regression. As an example, the normalized horizontal air speed at positions 2 and 5 plotted as a function of the height is given in Fig. 4. The 80 observations, obtained over a 5 min period of time, result each from the averaging over 10 readings from the sonic anemometer. The linear vertical profile equations with the value of the coefficient of determination \( R^2 \) at the nine positions are shown in Table 1 where \( V(h) \) and \( V(0.40) \) are the air speeds at height \( h \) and at 0.40 m in m/s, respectively. The external wind speed and direction averaged over 5 min periods are also presented.
The results in Fig. 4 show that the horizontal air speed below 1.6 m in the vertical plane decreased with the height under lee-side ventilation. However, the horizontal air speed at position 2 decreased with height much slower than that at position 5. It is because the external wind speed (7.62 m/s) during the measurements at position 2 was much higher than at position 5 (0.66 m/s). For greenhouses with roof vents, the wind effect is greater than temperature effect when the external wind speed is higher than 2 m/s (Bot, 1983; Boulard & Baille, 1995; Papadakis et al., 1996). At position 2, the air movement induced by the natural ventilation can be considered as a dominant effect of the wind. The slopes of the linear regression at the nine positions in Table 1 were plotted as a function of the external wind speed (Fig. 5). It was observed that the vertical profiles at those positions were to be considered as the result of the combined effect of both wind and temperature except for positions 2 and 3 where only the wind effect was the driving force for the interior air movements.

3.2. Horizontal distribution

The two-dimensional sonic anemometers were distributed at 12 locations in the greenhouse at a height of 0.40 m above the ground. The air velocity measurements were performed simultaneously for 5 min sampling.

Table 1
Linear vertical profiles of the horizontal air velocity at height h relative to that at 0.40 m for 9 positions from 80 observations

<table>
<thead>
<tr>
<th>Anemometer position</th>
<th>External wind Speed, m/s</th>
<th>Direction, deg</th>
<th>Normalized air velocity $[V(h)/V(0.40)]$</th>
<th>Coefficient of determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.61</td>
<td>64</td>
<td>1.202–0.501 h</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>7.62</td>
<td>295</td>
<td>1.148–0.345 h</td>
<td>0.78</td>
</tr>
<tr>
<td>3</td>
<td>7.62</td>
<td>295</td>
<td>1.118–0.311 h</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>1.53</td>
<td>278</td>
<td>1.172–0.435 h</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>0.66</td>
<td>339</td>
<td>1.206–0.717 h</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>0.61</td>
<td>346</td>
<td>1.361–0.966 h</td>
<td>0.66</td>
</tr>
<tr>
<td>7</td>
<td>0.99</td>
<td>21</td>
<td>1.202–0.577 h</td>
<td>0.74</td>
</tr>
<tr>
<td>8</td>
<td>0.55</td>
<td>346</td>
<td>1.225–0.768 h</td>
<td>0.55</td>
</tr>
<tr>
<td>9</td>
<td>0.83</td>
<td>15</td>
<td>1.311–0.748 h</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Fig. 6. Polar graphs of airflow distribution at 12 positions in the horizontal plane: (a) $U_e = 3.87 \text{ m/s, } \varphi_{Ue} = 301^\circ, \alpha = 20^\circ$; (b) $U_e = 8.33 \text{ m/s, } \varphi_{Ue} = 270^\circ, \alpha = 0^\circ$; (c) $U_e = 0 \text{ m/s, } \alpha = 14^\circ$; $U_e$ and $\varphi_{Ue}$ denote external wind speed and direction; $\alpha$: vent opening angle; $V_x$ and $V_y$ denote air velocity components in $x$ and $y$ directions.

The graphs in Fig. 6c show the pattern when the vent opening angle was $14^\circ$ but the external wind was lower than the threshold value of the cup anemometer ($< 0.4 \text{ m/s}$). No dominant direction of the airflow at the central positions was found. However, the airflows on the east and west sides were toward the vertical end walls, probably due to the convection loops induced by the temperature gradient.

A normalized mean speed function ($\bar{V}_{0.40}(z)/U_e$) was calculated for each position. It was based on the mean value of the measurements at 5 min intervals. For each of the 12 positions, plotting $\bar{V}_{0.40}(z)/U_e$ against the opening angle $z$ of the ventilation windows gave rise to points situated along a straight line. Figure 7 shows an example of the 48 measurements at a same position. The directions of the internal airflow on the graph were illustrated

periods which coincided with the meteorological system sampling one.

Polar graphs of airflow direction at each position are shown in Fig 6. Figure 6a shows the airflow pattern for an external west-north westerly ($301^\circ$) wind with a speed $U_e$ of 3.87 m/s for a vent opening angle $\alpha$ of 20°. Significant transverse airflow occurred in the horizontal plane of the greenhouse, from the north-east corner to the south-west one. The projection on the external wind direction of the general inside airflow was clearly opposite, indicating a counter flow. A similar situation was found for all measurements, irrespective of the external wind speed and the opening angle. The observed phenomena was in conformity with the results of Boulard et al. (1997a), who found that wind parallel to the vents created a circulating flow with inflow at the downwind end of the opening and a steady outflow of air at the upwind end in a two-span greenhouse with continuous roof openings.

When the lee-side windows were closed ($\alpha = 0^\circ$) (Fig. 6b), with a strong external westerly wind parallel to the ridge ($U_e = 8.33 \text{ m/s, wind direction } \varphi_{Ue} = 270^\circ$), the internal airflow was the reverse of the external wind. In a closed shelter, this induced air circulation is the contribution of the inside free convection due to the buoyancy forces (Boulard et al., 1996) and of the forced convection due to leakage.

The graphs in Fig. 6c show the pattern when the vent opening angle was $14^\circ$ but the external wind was lower than the threshold value of the cup anemometer ($< 0.4 \text{ m/s}$). No dominant direction of the airflow at the central positions was found. However, the airflows on the east and west sides were toward the vertical end walls, probably due to the convection loops induced by the temperature gradient.

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The linear regression equations with $R^2$ values of normalised mean horizontal velocity ($\bar{V}_{0;40}(x)/U_e$) versus the opening angle $x$ in the horizontal plane, at a height of 0·40 m, at 12 locations from 48 observations; $U_e$, external wind speed

<table>
<thead>
<tr>
<th>Positions</th>
<th>$\bar{V}_{0;40}(x)/U_e$</th>
<th>Coefficient of determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data missing</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>0·001139 $x + 0·31572$</td>
<td>0·79</td>
</tr>
<tr>
<td>3</td>
<td>0·000711 $x + 0·30159$</td>
<td>0·77</td>
</tr>
<tr>
<td>4</td>
<td>0·009616 $x + 0·27298$</td>
<td>0·90</td>
</tr>
<tr>
<td>5</td>
<td>0·001091 $x + 0·29097$</td>
<td>0·87</td>
</tr>
<tr>
<td>6</td>
<td>0·00860 $x + 0·33644$</td>
<td>0·73</td>
</tr>
<tr>
<td>7</td>
<td>0·00817 $x + 0·20392$</td>
<td>0·89</td>
</tr>
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<td>8</td>
<td>0·001212 $x + 0·21664$</td>
<td>0·92</td>
</tr>
<tr>
<td>9</td>
<td>0·00802 $x + 0·31863$</td>
<td>0·77</td>
</tr>
<tr>
<td>10</td>
<td>0·00968 $x + 0·25500$</td>
<td>0·88</td>
</tr>
<tr>
<td>11</td>
<td>0·001344 $x + 0·16631$</td>
<td>0·90</td>
</tr>
<tr>
<td>12</td>
<td>0·00927 $x + 0·18618$</td>
<td>0·81</td>
</tr>
</tbody>
</table>

Table 2

by the different symbols. The results for all 12 measurement positions are given in Table 2 except for position 1 where a technical failure affected the measurements. The interior air speed was not zero for zero opening angle due to internal circulation caused by air leakage and buoyancy forces.

3.3. Air turbulence characteristics

In Fig. 6a, the mean horizontal air speed in the greenhouse ranged from 0·15 m/s to 0·22 m/s (Table 3). The normalized turbulence intensity of the airflow ranged from 0·16 to 0·47 for the $x$ and from 0·14 to 0·38 for the $y$ direction. The maximum turbulence intensity occurred mainly near the doors (positions 1, 7 and 10) due to the leakage combined with the border effects. The normalized total turbulent kinetic energy of the air movement in the greenhouse ranged from 0·06 to 2·37 and corresponded to the turbulence intensity. Frequency spectra are transformed to the turbulent length scale based on the Taylor’s hypothesis of frozen turbulence where the integral length scale is the average size of the largest eddies in the flow field (Heber et al., 1996). The integral length scale in the $x$ direction reached high values (11·6 m at position 1 and 11·9 m at position 5) due to the initial slow decrease in the autocorrelation function. The related integral length scale refers to the large eddies associated with a reduced turbulence frequency. The mean integral length scale (6 m) was much larger than the sound path (0·60 m) of our sonic anemometer. This means that the sonic anemometer is a suitable device to measure the instantaneous air velocity in a large greenhouse.

4. Conclusions

Experimental study of the airflow induced in greenhouses by natural lee-side ventilation allows the air circulation to be defined and can help designers and managers to optimize ventilation. Usually, the measurement of the air renewal rate is carried out by means of tracer gas technique and differential pressure methods. However, the air pattern in large greenhouses has not yet been properly

<table>
<thead>
<tr>
<th>Position</th>
<th>Mean velocity, m/s</th>
<th>Turbulence intensity</th>
<th>Kinetic energy</th>
<th>Integral length scale, m</th>
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</thead>
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<tr>
<td></td>
<td>$\bar{V}_x$</td>
<td>$\bar{V}_y$</td>
<td>$\bar{V}$</td>
<td>$\psi_x$</td>
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<tr>
<td>1</td>
<td>0·13</td>
<td>0·11</td>
<td>0·17</td>
<td>0·47</td>
</tr>
<tr>
<td>2</td>
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<td>0·15</td>
<td>0·10</td>
<td>0·18</td>
<td>0·19</td>
</tr>
<tr>
<td>Min.</td>
<td>0·21</td>
<td>0·15</td>
<td>0·15</td>
<td>0·16</td>
</tr>
<tr>
<td>Max.</td>
<td>0·12</td>
<td>0·04</td>
<td>0·22</td>
<td>0·47</td>
</tr>
<tr>
<td>Mean</td>
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<td>0·09</td>
<td>0·19</td>
<td>0·29</td>
</tr>
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</table>
presented. The multi-point sonic anemometer system combined with non-dimensional analysis has allowed the simultaneous study of the air movement at different locations for a lee-side wind driven ventilation.

A measuring system of two-dimensional sonic anemometers was successfully used to investigate the vertical profiles of the horizontal airflow below 1.6 m. The measurement results showed that the horizontal air movement appeared to be a linear function of height.

Under given experimental conditions, it was found that the horizontal air velocities at different locations were proportional to the external wind speed and the opening angle. Significant transverse velocities in the horizontal plane of the greenhouse were displayed using polar graphs. At high wind speed, even when the greenhouse was completely closed, the relatively high inside air velocity found for zero opening angle explained by free convection due to buoyancy forces and forced convection due to wind forces and air leakage.

The direct air velocity measurement made it possible to clearly identify airflow patterns. The turbulent characteristics study showed that the airflow in the horizontal plane was of low turbulence with large eddies. It implies that our two-dimensional sonic anemometer system is a suitable device to measure the instantaneous air velocity inside the greenhouse.

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**References**


Boulard T; Papadakis G; Kittas C; Mermier M (1997a). Air flow and associated sensible heat exchanges in a naturally ventilated greenhouse. Agricultural and Forest Meteorology, 88, 111–119

Boulard T; Roy J C; Lamrani M A; Haxaire R (1997b). Characterising and modelling the air flow and temperature profiles in a closed greenhouse in diurnal conditions. IFAC Mathematical and Control Applications in Agriculture and Horticulture, pp. 37–42 Hannover, Germany


Kittas C; Draoui B; Boulard T (1995). Quantification of the ventilation of a greenhouse with a roof opening. Agricultural and Forest Meteorology, 77, 95–111


