AIR FLOW, TEMPERATURE AND HUMIDITY PATTERNS IN A GREENHOUSE TUNNEL

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Abstract

Air distribution and climatic heterogeneity in greenhouses interfere with plants activity and influence largely crop activity and more particularly transpiration and photosynthesis. This is particularly true for the tunnel, which is likely the most frequently used greenhouse type in the Mediterranean basin, but which generates also a high climatic heterogeneity. Up to this time, most experimental studies of ventilation on full-scale greenhouses have used tracer gas techniques that allow neither clear identification of the component of the total flux, nor predictions of the air flow pattern. This lack of experimental data and the complexity of the turbulent flows around intricate boundary conditions explain why detailed air motion inside greenhouse remain poorly known and seldom considered in greenhouse numerical simulation. It is the reason why we characterised the mean air flows together with air temperature and humidity patterns in a classical 8 m width “Ficclair” tunnel situated in the region of Avignon in the south of France. Using three- dimensional sonic anemometers and krypton hygrometers, the mean air speed, temperature and humidity were investigated in two vertical cross sections of a tunnel. The spatial distribution of air flow is presented, together with the associated temperature and humidity patterns. These results reveal a strong climatic heterogeneity in the tunnel.

1. Introduction

Spatial heterogeneity of air velocity and climate inside greenhouses interfere with plants activity and influence largely crop behaviour through their effects on crop gas exchanges, particularly transpiration and photosynthesis. This heterogeneity is high in the case of plastic tunnels, which is the type of greenhouse most frequently used in the Mediterranean basin, and in turn induces a high heterogeneity of the plant activity, which leads the growers to practice excess fertirrigation, as observed for example on lettuce crops (De Tardournet, 1998). The ventilation process is responsible for a large part of this heterogeneity. It affects the convective transfer and consequently the crop gas exchange rate (photosynthesis, transpiration). Up to now, most experimental studies of ventilation in full-scale greenhouses have used tracer gas techniques (de Jong, 1990; Fernandez and Bailey, 1992; Boulard and Draoui, 1995) that do not allow a clear identification of the components of the energy and mass fluxes exchanged through the vent openings and do not provide detailed information on the airflow pattern. This lack of experimental data and the complexity of the turbulent flows around intricate boundary conditions explain why detailed air motion inside greenhouse remains poorly known and seldom considered in numerical simulation of greenhouse climate. With the use of computational fluid dynamics programs, Mistriotis et al. (1997) simulated the ventilation process driven by external wind in a greenhouse and Boulard et al. (1998) studied both experimentally and numerically the detailed temperature and flow patterns driven by thermal effects in a greenhouse equipped with roof openings. These studies conclude that
the validations of numerical models required further experimental studies in realistic situations. Particularly, the determination of the turbulent characteristics (turbulent kinetic energy) that represent the most critical factors to take into account in the simulation task (Mohammadi and Pironneau, 1994).

More insight into the mean and turbulent air flows and associated sensible heat exchange in a naturally ventilated bi-span greenhouse was provided using an ultrasonic anemometer in a horizontal plane at the level of continuous openings (Boulard et al., 1997). Similar studies for tunnel type greenhouses are not available until now. This is why the study presented in this paper deals with the characterisation of the mean and turbulent flows and air temperature and humidity patterns inside a classical 8 m width tunnel situated near Avignon, in the south of France. To be representative of the environment associated with tunnels, the study was carried out in tunnel protected from the dominant wind by other tunnels situated windward and oriented perpendicularly to the wind direction. Natural ventilation was performed by means of non-continuous openings disposed every four meters on each side of the tunnel and obtained by separation of the plastic sheets constituting the greenhouse cover. All these conditions are generally met in the south part of France and in all the Mediterranean regions where the tunnel is widely spread.

The present study builds upon measurements of mean and fluctuating air speed, temperature and humidity to (1) investigate the air pattern and the climatic heterogeneity in the vertical cross sections of a tunnel, and (2) evaluate the mean and turbulence characteristics of air velocity components. This study should also provide a better resolution for validating computer fluid dynamics models and particularly to characterise the turbulent quantities such as the turbulent kinetic energy, k. Ultimately, it will be discussed how these results might also serve as a basis to assess the consequences of the climate heterogeneity on plants activity in tunnels.

2. Experimental Set up

2.1. Site and tunnel description

The measurements were carried out in an empty 22 x 8 m² tunnel equipped with non-continuous openings obtained by separation, by means of pieces of wood, of the plastic sheets every four meters on both sides of the tunnel. Schematic views of the tunnel are shown in Fig 1. Assuming a weak influence of the gable ends and symmetric air flows along v (see Fig 1) with respect to each opening, we had only to explore the tunnel's flow and climatic patterns in two transverse sections parallel to the wind direction:

- a “vent” section (II) situated just in the middle of the vent openings, with a northern air inlet situated in windward side and a southern air outlet situated in leeward one;
- a middle section (I), parallel to section II, situated 2 m westward from this section, in the middle of two consecutive vent openings.

In order to have a continuously evaporating soil surface, the tunnel was abundantly watered the day before and during the experiments, so that the soil surface was maintained continuously wet during the measurements periods.

2.2. Wind conditions

The tunnel was located at Avignon in a region characterised by a frequent northerly wind channelled by the Rhône Valley. This wind (the Mistral) provides remarkable conditions for wind research because of its frequency, constancy of direction (north) and persistence (McAneney, 1988). Measurements were made one day (24/10/97) during a strong mistral with an average wind speed of 3.8 m.s⁻¹. Table 1 summarises the prevailing weather conditions during the experiment and illustrates the constancy of wind direction and of the main scaling parameters $U_0$, $(T, T_0)$, $(X, X_0)$. 

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2.3. Instrumentation

Air speed and temperature were measured by means of two three-dimensional sonic anemometers (research ultra sonic anemometer, Gill Research & Development) and air humidity by means of two krypton hygrometers (K H2O, Campbell Scientific). These four instruments were used simultaneously to sense air velocity and temperature and humidity at two locations in each section. For each location, the krypton hygrometer and sonic anemometer were placed close enough (less than 0.2 m distant) to minimise the sampling errors due to the distance between sensors.

Three components of wind velocity, air temperature and humidity fluctuations were measured at 24 positions in each section together with the thermal boundary conditions at 14 positions along the inside soil surface and plastic cover surface. These surface temperatures were measured by means of thin thermocouples stuck on the plastic cover or soil surface (Fig.2). The manufacturer’s calibration was accepted for \( u, v, w \), air temperature and humidity. The sampling frequency was 5 hz. The time duration of each record (for characterisation of two locations) was about from 10 minutes. Outside air temperature \( (T_o) \) and humidity \( (X_o) \), wind speed \( (u_g) \), and direction \( (\theta) \) and inside air temperature \( (T_i) \) and humidity \( (X_i) \) at the centre of the tunnel (Fig. 2) were measured each second and averaged over the length of each record. The analogue signals of the sonic anemometers and krypton hygrometers were processed on line and stored in a portable computer. Outside and inside mean climatic conditions and thermal boundary conditions were averaged on line and results stored in a data logger (Campbell CR20).

With only two instruments of each type, the main difficulty arose from changing external conditions together with the necessity to reposition the sensors in order to characterise the airflow and climatic patterns at 24 different positions along each section. This problem was overcome:

(i) by selecting measurements for a fixed external wind direction (north wind direction, perpendicular to the tunnel axis)

(ii) by using the simultaneous wind speed \( U_0 \) and the difference in air temperature \( (T_i - T_o) \) and humidity \( (X_i - X_o) \) between the centre of the greenhouse and outside air as scaling parameters.

\( T_i, \ X_i \) and \( T_o, \ X_o \) were measured at 1.5 m above the soil surface inside and outside the tunnel and \( U_0 \) was measured at 5 meter height, distant from about 20 m of tunnel centre. A detailed list of the climatic parameters normalisation formula is described in annexe 1 together with the description (annexe 2) of the relations allowing to derive physical values from the normalised values knowing also the average values of the scaling parameters

\[ (U_0, \ \Delta T_o, \ \Delta X_o) \]

measured during the experiment.

3. Results and Discussion

3.1. Tunnel flow field

*Polar plots*

Frequency distributions of air flow direction in the vertical plane (\( u, w \)) are shown as polar graph at each position of section I and II in figures 3 and 4 respectively. The origin of each plot is the measurement position and the probability densities were calculated, accumulated and plotted at each 10° intervals from 0° to 360°. These values are plotted at the angle representing the interval mid points and their extremity are connected by a line to form a polar graph. In this way the mean flow direction in the \( u, w \) plane together with the deviations form the flow, can be more easily represented.

Air flow pattern (Fig. 4) in the vent opening section (section II) was characterised by a very strong air flow entering through the north opening, crossing the tunnel and escaping through the south opening. As evidenced in Figure 3, air speed was much weaker in the
mid section (section I) between two consecutive openings, with an airflow pattern characterised by two air loops, rotating anticlockwise and centred on the south part of the tunnel on one side, and rotating clockwise and centred on the northern part of the tunnel on the other side.

*Two dimensional vectors*

The mean vector \((U_j^*=u(j)/U_0)\) fields are presented in Figures 5 and 6 for sections I and II respectively. They exhibit more clearly that the air stream crossed the tunnel and escaped perpendicularly to the northern vent opening of section II, and that the two air loops rotated counter clockwise in section I. If we only consider air circulation in the vertical section II, the mass conservation principle was not verified because the inflow was much greater than the outflow. This is probably due to the fact that outside wind was not exactly perpendicular to the tunnel axis. In consequence, contrary to our first assumption, the lateral air circulation along \(v\) was not symmetrical with respect to the middle of each vent opening.

The vertical profiles of the reduced 3 D resultant air velocity in the middle of the tunnel (Figure 7) are similar for both sections. Approximately the same values (13%<\(U_j^*<18\%\)) can be observed between 0.25 m and 2.7 m height, with a peak value (\(U_j^*=18\%\)) at 0.9 m height and a decrease at soil and roof level. As illustrated by the horizontal of Figure 8, this similarity of profiles was only observed between the middle of the greenhouse. Conversely, air velocity is maximum in the air inlet (\(U_j^*=100\%\)) and outlet (\(U_j^*=30\%\)) of section II and null at the same positions in section I.

3.2. Air temperature patterns

The patterns of reduced air temperature

\[
T^*(j) = \frac{T(j) - T_o}{T(j) - T_o}
\]

are shown in Figures 9 and 10 for sections I and II respectively. The lateral heterogeneity was not very large and the same temperature patterns with similar order of magnitude were observed in both sections. On average, section I was only slightly warmer than section II because of less cold air penetrating in this section. The transversal heterogeneity (parallel to the wind direction) was much larger, particularly in section II where a strong north to south gradient due to the cold air penetration was observed. In the north opening and along the north side of the tunnel cover in section I, the air inflow temperature was close to the outside air temperature (0 < \(T^* < 0.5\)). On contrary the area situated along the south side of the tunnel cover and near the south opening, was significantly warmer (1.5 < \(T^* < 2.5\)). Solar absorption at soil level generated also a vertical gradient (1.5 < \(T^* < 2.5\)) through the soil surface boundary layer in the first 20 cm over the soil surface.

3.3. Air humidity patterns

The normalised air water vapour distributions

\[
X^*(j) = \frac{X(j) - X_o}{X(j) - X_o}
\]

are observed in Figures 11 and 12 for sections I and II respectively. Similar distributions were observed in both sections, with “dry” regions (\(X^*<1\)) situated in the northern and upper parts of the tunnel and “humid” areas (1.8 < \(X^*<3\)) concentrated along the soil surface where water vapour was evaporated and in the leeward part of the tunnel. This pattern is significantly different of the air temperature pattern presented before because contrary to the heat diffusion from the cover to the inside air observed in Figures 9 and 10, a gradient of water vapour can only be observed above the soil surface. Yet, water vapour diffusion over the soil surface seemed to be more important than heat diffusion, as
indicated by the larger extension of the areas with $1.8 < X^* < 3$ when compared to the area with $1.8 < T^* < 3$.

3.4. Air turbulence characteristics

The map of the normalised turbulent kinetic energy

$$K^*(j) = (1/2)(\frac{u^2(j) + v^2(j) + w^2(j)}{U_0^2}(100))$$

obtained by least-squares method in section II is shown in Figure 14. Turbulence intensity was weak in the centre, and increased strongly toward the windward opening where $K^*(j)$ was about ten times more important than in the centre of the tunnel. The value of $K^*(j)$ in the northern opening and in the areas situated just leeward reached 10%. Due to the outside air penetration, it increased moderately in the leeward opening ($K^*(j) = 4\%$), when compared to the values measured in the centre of the tunnel ($K^*(j) < 2\%$). However, even the stronger values measured in the opening were rather low when compared to the wind values ($K^* = 26\%$), measured outside at 1.8 m height for the same wind regime.

Longitudinal (along v) heterogeneity of turbulence intensity was also very important because $K^*(j)$ was much lower in section I ($K^*(j) < 2\%$) than in section II. Transversal heterogeneity in section I was characterised (figure 13) by decreasing values of $K^*$ from the tunnel centre (where the airflow was maximum) to the tunnel cover and soil surface.

4. Conclusion

The air streams, temperature and humidity distributions generated by wind and buoyancy forces were experimentally studied in a full-scale naturally ventilated tunnel. Air velocity and temperature fields were measured by three-dimensional sonic anemometry and humidity distribution was characterised by krypton hygrometers. High speed sampling frequency (5 HZ) allowed computing both mean and turbulent quantities. For a wind perpendicular to the axis of the tunnel, airflows were characterised by a strong air current crossing the tunnel between the windward and leeward openings, while the air along the floor and the walls stayed still. It also revealed moderate air speed in the vertical section situated between two consecutive series of openings, with two air loops, one in the south of the tunnel rotating anticlockwise and a second one in the northern part rotating clockwise.

This study is a first step toward the determination of the true microclimatic picture at plant level in a tunnel. It must be completed by: (i) the characterisation of the radiative heterogeneity, and the analysis of the consequences of aerodynamic and radiative heterogeneity on plant transpiration and photosynthesis; (2) a simulation study aimed at describing the aerodynamic and climatic situation in the presence of plants which will act as a porous medium in the lower volume of the greenhouse.

References


Carpenter W. J.; Bark L. D.,1967. Temperature Patterns in Greenhouse Heating. Florists’
Fig. 1 Schematic plan of the experimental plastic tunnel. (u, v, w are three components of the air velocity measured by the sonic anemometer in two sections)

Fig. 2 Measurement positions in the central section of the tunnel. All dimensions are in meter. ● Air temperature, humidity and velocity measurements by sonic anemometers and krypton hygrometers (1-24)
× Surface temperature measurements (Tc1-Tc14)
Δ reference inside air temperature and humidity measurements (T_i, X_i)

Fig. 3 Polar graph of the experimental air velocity in section I

Fig. 4 Polar graph of the experimental air velocity in section II
Fig. 5 Normalised air velocity (%) distribution obtained by experiment in section I

Fig. 6 Normalised air velocity (%) distribution obtained by experiment in section II

Fig. 7 Normalised air speed (%) in the two vertical sections situated in the middle of the tunnel

Fig. 8 Normalised air speed (%) in the two horizontal sections situated at 0.8 m height in the tunnel

Fig. 9 Normalised \( T^*(j) = \frac{T(j) - T_o}{T(j) - T_o} \) temperature distribution obtained by experiment in section I

Fig. 10 Normalised \( T^*(j) = \frac{T(j) - T_o}{T(j) - T_o} \) temperature distribution obtained by experiment in section II
Fig. 11 Normalised \( x^*_{(j)} = \frac{x(j) - X_o}{X(j) - X_o} \)
water vapour distribution obtained by experiment in section I

Fig. 12 Normalised \( x^*_{(j)} = \frac{x(j) - X_o}{X(j) - X_o} \)
water vapour distribution obtained by experiment in section II

Fig. 13 Normalised turbulent kinetic (%) energy distribution obtained by experiment in section I

Fig. 14 Normalised turbulent kinetic energy (%) distribution obtained by experiment in section II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean</th>
<th>Standard deviation</th>
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<tr>
<td>( T_0 ) (°C)</td>
<td>14.45</td>
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<td>( RH_0 ) (%)</td>
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<tr>
<td>( T_i ) (°C)</td>
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<tr>
<td>( RH_i ) (%)</td>
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<td>( U_0 ) (m/s)</td>
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<tr>
<td>Dir (°)</td>
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</tr>
</tbody>
</table>

Table 1: Climatic boundary conditions during the experimental period. \( T_0 \) and \( T_i \), exterior and interior air temperature; \( RH_0 \) and \( RH_i \), relative humidity of the exterior and interior air; \( U_0 \) and Dir, external wind speed and direction. The direction is defined as 250° for north and increases clockwise.