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MAPPING OF AIR AND ENERGY FLUXES ALONG A GREENHOUSE LARGE OPENING THROUGH THREE DIMENSIONAL ANEMOMETER

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Abstract: Although natural ventilation is a key parameter of the greenhouse climate, the relevant physical mechanisms are still insufficiently studied. This paper aims to the determination of the air and energy fluxes along a greenhouse ridge opening. Direct measurements of the mean and turbulent components of the wind velocity through a tridimensional sonic anemometer at the level of the opening allow us to map the mean and turbulent air and sensible heat fluxes along the greenhouse ventilator. We notice that a wind parallel to the ridge (a) induces an inflow of cold air at the leeward part of the opening and a warmer outflow of air at the windward part of the opening; (b) the mean sensible heat flux represents the 58% of the total flux whereas the turbulent flux is of about 42%.

INTRODUCTION

Natural ventilation strongly contributes to the heat and mass exchange between the greenhouse inside air and the environment and is the main control device for climate control of air temperature, humidity and CO_2 content. Therefore the greenhouse and vents design is particularly important.

However, ventilation mechanisms are complex and involve driving forces which physical natures are very different: there is a mean flux of air driven by "steady" pressure fields created by direct wind and stack effects (described by approaches based on Bernoulli's equation) and a "turbulent" flux driven by fluctuating wind pressures (the modeling of which calls for a different approach).

Up to now, the experimental studies on ventilation are based on tracer gas measurements on full-scale greenhouses equipped with either roof ventilators (de Jong, 1990; Fernandez and Baily, 1992) of roof and side ventilators (Boulard, 1993) and the global estimation of air exchange rates based on tracer gas measurements allows neither a clear identification of the components of the total flux nor the prediction of the air flux pattern. It is why it is necessary to characterize the convective in the vent opening by measuring directly the various components of the air exchange.

Eddy correlation system comprising three dimensional sonic anemometer was already used by Yang et al. (1995), for the determination of heat and mass exchange between plants and air in a greenhouse in absence of ventilation.

In this present paper, we investigate the three dimensional distribution of the heat and mass flux at the vent opening using a three dimensional sonic anemometer. The major experimental approaches will be applied to the simple case with roof ventilators all facing the same direction and with the wind parallel to the roof opening.

MATERIAL AND METHODS

Eddy correlation techniques for determining the flux within the ventilator opening

Let us consider the transport of heat with a velocity V(u, v, w) at the vent opening. An elemental volume of air at temperature T and speed V will then be effacing transport of heat at a rate Q ($\rho u C_pT$, $\rho v C_pT$, $\rho w C_pT$). Using now the Reynolds's formulation:

$$u = \overline{u}+u', \qquad v = \overline{v}+v', \qquad w = \overline{w}+w', \qquad T = \overline{T}+T' \qquad (1)$$

where the prim symbol denote the instantaneous departure from the mean, we may write the classical relation of energy transfer along respectively x, y and z:

$$\overline{\rho Cp\ u\ T} = \overline{\rho Cp\ u\ T} \quad \overline{(\rho\ u)'\ (Cp\ T')} \qquad (2)$$

$$\overline{\rho Cp\ v\ T} = \overline{\rho Cp\ v\ T} \quad \overline{(\rho\ v)'\ (Cp\ T')} \qquad (3)$$

$$\overline{\rho Cp\ w\ T} = \overline{\rho Cp\ w\ T} \quad \overline{(\rho\ w)'\ (Cp\ T')} \qquad (4)$$

Thus, the flux in (2) is composed of a mean normal flow of air $\overline{\rho u\ Cp\ T}$ and a part due to eddying motion $\overline{(\rho u)'\ (Cp\ T')}$.

A direct measurement of both the mean and eddy fluxes demands measurements of fluctuations of ρu, ρv, ρw and T over the range of time scale or eddy sizes contributing to the transfer. The development of inexpensive, three-dimensional sonic anemometers has proved that such measurements are technically feasible.

The main difficulty arises from the necessity to displace the sonic anemometer for exploring the air flux at the greenhouse opening while the driving forces of ventilation, depending on the outside climatic conditions (wind speed and direction, air temperature), are rapidly changing. For a fixed wind direction parallel to the vent opening, it is possible to use the wind velocity V and the difference in temperature between the inside and outside as scaling parameters and to sample the heat and mass flux by displacing the three dimensional sonic along the vent opening in order to map the pattern of heat and mass exchange.

The data are then presented in the following non-dimensional forms i.e. for u:

- mean and turbulent composants of air velocity, $\overline{u}/V$, u'/V;

- mean and turbulent composants of flux of sensible heat, $\overline{u(T-T_i)}/V(T_i-T_o)$ and $\overline{u'T'}/V(T_i-T_o)$.

Where $(T_i - T_o)$ is the temperature difference between inside (in the center of the greenhouse at 1.5 m height) and outside and T the temperature at the point of measurement.

EXPERIMENTAL

Site and greenhouse description

The experiments were carried out using a $416m^2$ plastic 2 span greenhouse, equipped with continuous roof vents situated near the gutters. A scheme of the greenhouse, its dimensions and its environment is shown in figure 1.

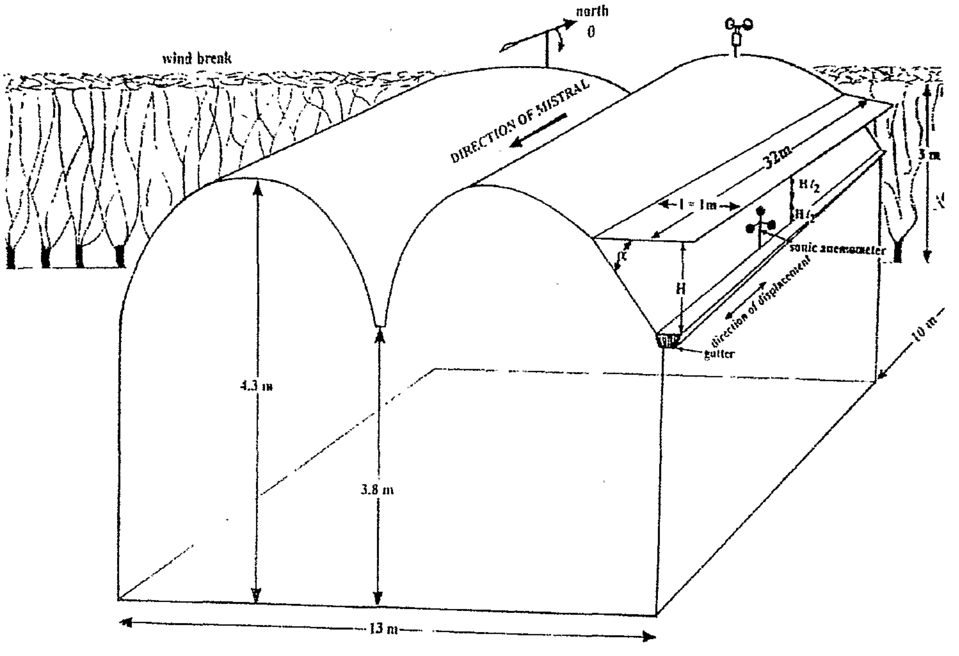

Figure 1. Experimental greenhouse

Wind conditions

The greenhouse was located in Avignon in the South of the Rhone Valley, characterized by a North wind channeled by the Rhone Valley, the Mistral, that provides remarkable conditions for wind research because of its frequency, constancy of direction (North) and persistence (Mc Aneney and al., 1989).

Measurements were performed during two days when strong Mistral was blowing (19^{th} and 20^{th} of May 1995) with an average windspeed between 4.9 ms^{-1}. Table (1) summarizes the prevailing climatic conditions during the experiment and demonstrates the constancy of wind conditions, mainly of direction, that condition the normalization of the measurements.

Table 1: Statistics of the climatic conditions prevailing during the experiment

	Mean	Standard deviation
Wind speed, V (m/s)	4.94	0.2
Wind direction, ö (deg.)	-9.2	3.1
Outside air temperature (°C)	16.3	0.1
Inside air temperature (°C)	24.8	0.3

Instrumentation

Eddy correlation measurements

Fluctuating air velocity and temperature were measured at 12 positions equally distributed along of the vent opening (in the middle of the opening situated at 3.2 m height with 1 m of width x 32 m of length). Air speed and temperature was measured with 3 dimensional ultrasonic anemometer (Gill Electronic Research and Development) providing u, v, w and air T measurements. The manufacturer's calibration was accepted for the u, v, w and air temperature but the offset of the $\overline{u}$, $\overline{v}$, $\overline{w}$ measurement was recorded before and after each set of measurements.

Outside, wind speed and direction and inside air temperature at the middle of the greenhouse (and at 1.5 m height) were measured every second and averaged each minute. Velocity flux and temperature T of air were measured with a frequency of 5 Hz. All the analog signals were processed by and results only stored in data logger (21X Campbell Scientific Co) with eddy correlation and Fast-Fourier-Transform program options.

The 3 dimensional sonic anemometer was mounted on a 3.2 m mast fixed on a moving mast and displaced every 2 meters along the 32 meters of the opening length. The time duration of the record was from about 10 minutes for each location.

RESULTS AND DISCUSSION

Distribution of air flux

The pattern of the "steady" inflow, outflow for the 12 measurement locations along the opening (3.2 m height) are shown in Figure 2, for the horizontal components of the wind velocity and in Figure 3, for the vertical components of the wind velocity. We see that (i) the wind parallel to the vent gives rise to an influx at the leeward (downwind) part of the opening and a steady outflux of air at the windward (upwind) part of the opening; (ii) the vertical component remains almost constant and weak.

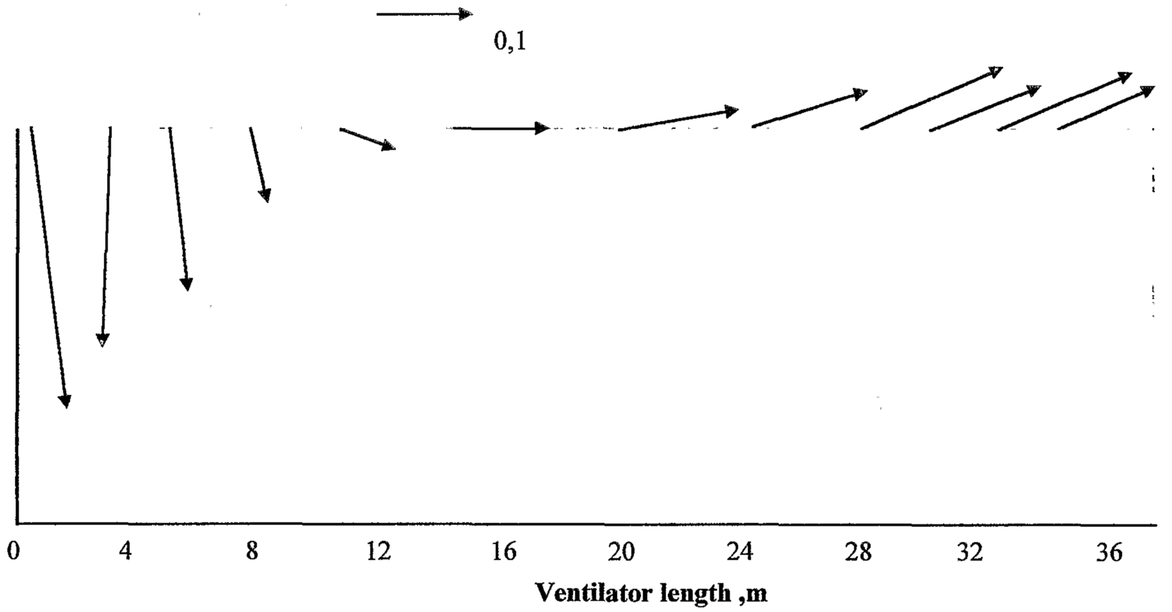

Figure 2. Normalized horizontal wind velocity components pattern along the greenhouse opening

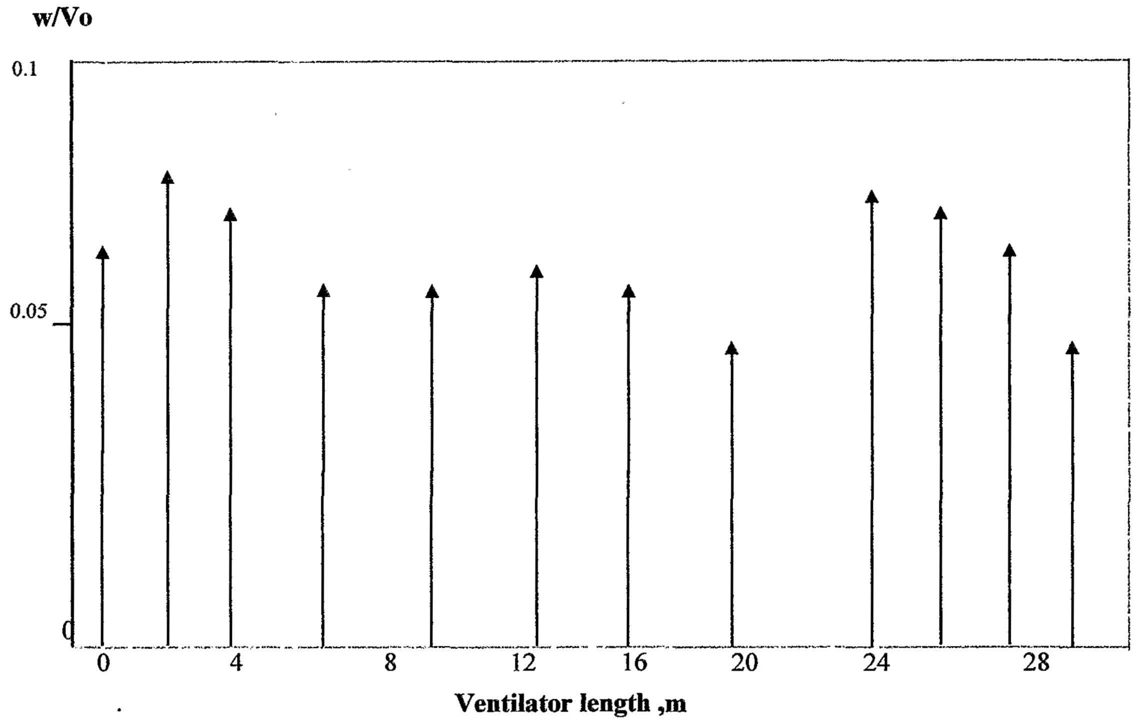

Figure 3. Normalized vertical wind velocity pattern along the greenhouse

Figure 4 shows the magnitude and distribution of the steady and turbulent airflow along v (perpendicularly to the vent opening surface) which is the main direction of exchanges between inside and outside the greenhouse. We can see that (i) there is an increase of the turbulent flow as we move from the leeward part of the greenhouse to the windward part of the greenhouse, so that the mean inflow is more turbulent than the mean outflow; (ii) the mass concentration principle is not well supported. In fact, if we sum inflows and outflows along $\vec{V}$ over the whole opening surface in order to verify that $\sum$inflow = $\sum$outflow we obtain respectively 0.85 and -0.50 for inflow and outflow. It suggests that either imprecisions in the orientation of the anemometer during the measurements or on the offset of the air speed measurements can be responsible of this difference.

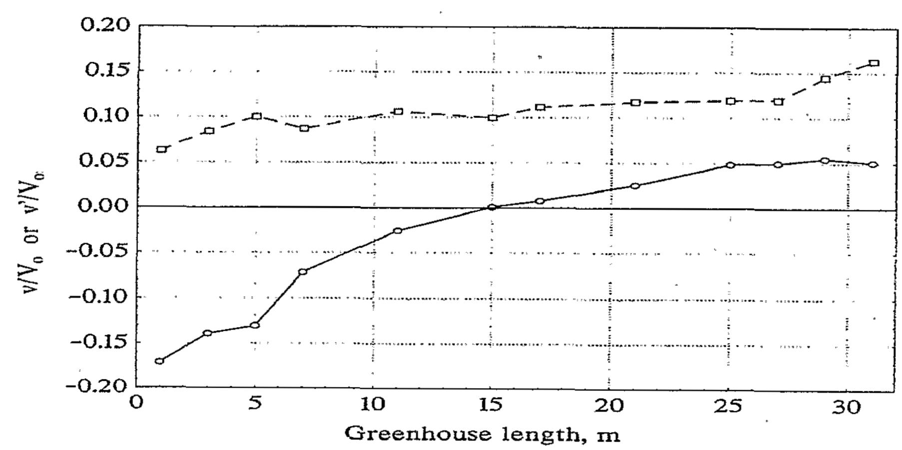

Figure 4. Distribution of normalized mean $\frac{\overline{V}}{V}$ and turbulent $\frac{V'}{V}$ flux of air along the greenhouse opening

Air Temperature

Normalized forms of the air temperature pattern $(T-T_o)/(T_i-T_o)$ are presented in Fig. 4. It is shown that inflow has the same or slightly warmer temperature as the exterior ($\frac{T-T_o}{T_i-T_o} < 0.25$) and the out flow has a warmer temperature (average of temperature between inside and outside (1 < $\frac{T-T_o}{T_i-T_o} < 0.3$).

Thus the mixing inside the greenhouse is not perfect and we can use temperature as a tracer to map the pattern of air exchange: inside cold, very turbulent air from outside flows in at the downwind end of the vent opening and a mixture of inside and outside air less turbulent than the outside one, flows out at the upwind end of the same opening.

Distribution of sensible energy flux

Integrating along the surface of vent opening S in direction of the vector $\bar{V}$ (perpendicularly to the vent opening surface) allow computation of the respective contributions of steady and turbulent flux of sensible energy (eq. 2) and allows us to evaluate the total sensible energy exchange:

$$H = \rho Cp \int ((\bar{v}\,\bar{T}) + (v'\,T'))\, ds \qquad (5)$$

Table 2 shows the relative magnitude of mean and turbulent sensible energy fluxes through the roof vent opening. For the whole opening, the mean flux contributes 58% and the turbulent flux 32% of the total of sensible heat exchange between inside and outside the greenhouse.

Table 2. Turbulent, mean parts and the total sensible heat fluxes exchanged through the vent (along $\bar{V}$ and over the whole opening surfaces).

Turbulent part	Mean part	Total
0.025	0.035	0.060
(42%)	(85%)	(100%)

The turbulent sensible heat transfer along $\bar{V}$ across the vent opening is particularly important in the areas between 4 and 16 m (figure. 5), where the difference of temperature between the location of the sonic anemometer and the outside becomes great (figure. 4) and where the turbulent flux of air is still important

Mean flow and side wall effect

As already stated in the analysis of sensible energy flux, the mean flow of air is particularly important near the edges of side walls of the greenhouse (figure. 6). Moreover, this exchange of air is very effective because cold is (having outside air conditions) goes in and warm air (having inside air conditions) comes out of the greenhouse at these places.

This pattern of mean flow is similar to a "side wall effect" deduced by several authors from tracer gas measurements. This steady effect is induced by gables affecting the static pressure field surrounding the vent opening and the relative contribution of the "steady" effect is inversely proportional to the size of the greenhouse.

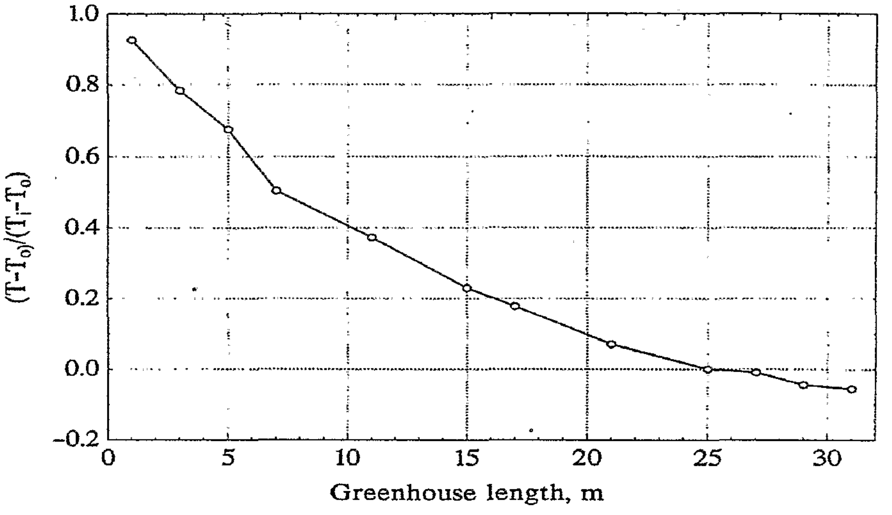

Figure 5. Air temperature distribution (in normalized form) along the greenhouse opening

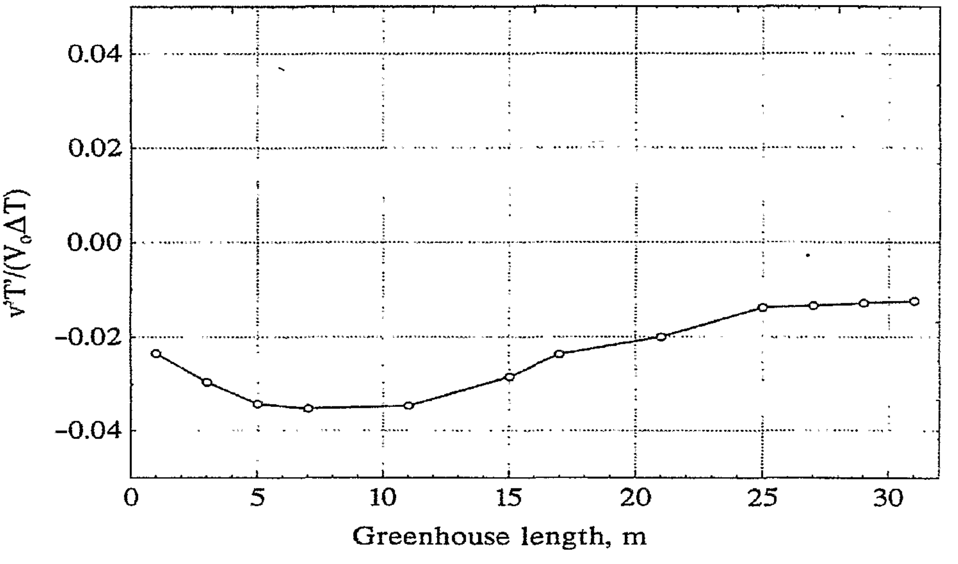

Figure 6. Magnitude of turbulent sensible heat fluxes (in normalised forms) along the greenhouse opening

CONCLUSION

The characterization and measurement of the air flow involved in greenhouse natural ventilation is usually done by the classical tracer methods. However, other techniques may be used as direct measurement of air and energy fluxes through 3 dimensional anemometers. This last technique when combined with a non-dimensional analysis allows the description of both air velocities and sensible heat fluxes according to their mean and turbulent components.

For large roof openings we have found that (i) a parallel wind produces an inflow of cold air in the downwind part of the opening and an outflow of warmer air at the upwind part of the same opening; (ii) turbulent air fluxes play an important role on the total air exchange rates but their efficiency is small as far as transport (of sensible heat and probably of CO_2 and water vapor) is concerned. The mean air flow due to wind pressure differences at the openings level generates air currents that are more efficient for the transport of energy, CO_2 and water vapor than the turbulent flow.

From a modeling point of view the precise characterization of the wind effects on the fluxes suggests a distinction between turbulent air exchange (difficult to model) and mean air exchanges (defined through Bernoulli's theorem).

ABBREVIATIONS

C_p	thermal capacity of air	J kg^{-1}
Q	sensible heat flux	W
S	effective opening area	m^2
T	temperature of air at the level of the anemometer	°C
$\overline{T}$	mean temperature of T	°C
T′	standard deviation of temperature of T	°C
T_i	inside air temperature	°C
T_o	outside air temperature	°C
V	wind speed	m s^{-1}
u, v, w	components of the wind velocity along x, y, z respectively	m s^{-1}
u′, v′, w′	standard deviation of u, v, w respectively	m s^{-1}
φ	wind direction	°
ρ	air density	kg m^{-3}

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