

NATURAL VENTILATION INDUCED AIRFLOW PATTERNS MEASURED BY AN ULTRASONIC ANEMOMETER IN VENLO-TYPE GREENHOUSE OPENINGS

S. Wang* and J.M. Deltour*

*Department of Physics and Chemical Physics
Gembloux Agricultural Faculty
Avenue of the Faculty, 8
B-5030, Gembloux, Belgium*

Abstract

Airflow distribution in the greenhouse windows is important for us to understand the mechanism of natural ventilation and thus is helpful for designers to have the optimal ventilation system. The full-scale measurements of the airflow in a large Venlo-type greenhouse were carried out by use of an ultrasonic anemometer. The clear airflow patterns around the greenhouse under leeward ventilation were found by polar plots. The air velocity in a greenhouse central ventilator was proposed as a function of the opening angles both in leeward and windward sides.

1. INTRODUCTION

Natural ventilation is realized by regulating the roof opening angle in the Venlo-type greenhouse which is the most representative type in Belgium and The Netherlands. The experimental investigations of the air exchange through the openings are very useful to clearly picture the air movement around the greenhouse and are thus helpful for designers to provide optimal ventilation systems. The commercially available ultrasonic anemometer makes it possible to measure the airflow patterns both in magnitude and direction, it has no moving parts to come into dynamic equilibrium with the flow, has absolute calibration and can measure extremely slow or fast wind speed accurately 21 times per second.

The different phenomena of natural ventilation in greenhouses have been studied for a long time by different techniques. Tracer gas techniques [Bot, 1983; De Jong, 1990; Fernandez and Bailey, 1992; Boulard and Draoui, 1995; Papadakis et al., 1994], energy balance models [Fernandez and Bailey, 1992; Wang and Deltour, 1996] and pressure distribution method [Kozai and sase, 1978; Boulard and Baille, 1995, Kittas et al., 1995] were the most widely used up to now. Since the initial typical version was proposed by Kaimal and Businger [1963], a lot of applications of the sonic anemometer to the boundary meteorology were carried out [Campbell and Unsworth, 1979; Smith, 1980; Coppin and Taylor, 1983]. More recently, Boulard et al. [1996] made a series measurements of air velocity in a continuous roof opening of a

greenhouse using a single component sonic anemometer. Heber et al. [1996] investigated air patterns and turbulence in some cross-sections of a livestock building with the mechanical ventilation using a three-dimensional sonic anemometer.

The objectives of this paper are to study the air movement in the different openings of a large scale multi-span Venlo-type greenhouse under leeside ventilation. The measured data are used to present the general airflow patterns around the greenhouse by use of the polar plots. Further more, the measurements of airflow at six positions in a single greenhouse central window are provided. The influence of the opening angle on the air velocity in the center of the greenhouse is tested by a non-dimensional ventilation function.

2. MATERIALS AND METHODS

2.1 Principle of the sonic anemometer

The basic principle is the measurement of the flight time of an ultrasound pulse between two transducers. It is well known that the speed of sound (c [$\text{m}\cdot\text{s}^{-1}$]) is increased if the air is moving in the same direction as the sound. This pair of transducers act alternately as transmitters and receivers, exchanging high frequency ultrasound pulses between themselves. If the flight time in each direction, say t_1 [s] and t_2 [s], is measured, the air velocity v' [$\text{m}\cdot\text{s}^{-1}$] along the path of the transducers can be obtained:

$$v' = 0.5L \cdot \left(\frac{1}{t_1} - \frac{1}{t_2} \right) \quad \text{.....(1)}$$

where L [m] is the distance between the transducers. This gives an absolute calibration which is a function only of the distance apart of the transducers. In our experiments, the commercial sonic anemometer GILL SOLENT 1010-K-055 has been used throughout the whole experiments. It has three pairs of transducers in different orientations, so that the direction as well as the magnitude of the incident airflow may be unambiguously derived (Fig. 1). This instrument gives the instantaneous wind speed and direction with respective accuracy of $\pm 3\%$ and $\pm 2^\circ$ in the speed range $0\text{-}30 \text{ m}\cdot\text{s}^{-1}$. From the top view, there is a transducer (T1) 30 degrees anti-clockwise from this n direction and the u speed axis is aligned with this pair of transducers. The v axis is obviously at right angles to the u axis. The w speed axis is vertical and a positive speed indicates that the flow is in an upwards direction.

2.2 Experimental setup

The measurements were carried out in a 14-span Venlo-type greenhouse situated in Breda, The Netherlands (Latitude is 51.48°). This greenhouse is orientated east-west. Its dimensions are 48 m in length and 44.8 m in width. The ground area and volume are about 2150 m^2 and 7365 m^3 respectively. The 168 ventilators are alternately

located on the roof, half of them on the north side and half on the south side. Each is 2 m long (L_0) and 0.785 m wide (H_0) with an aspect ratio (L_0/H_0) of 2.548. These windows are defined by coordinates (x, y), where x is from 1 to 6 in the length direction and y is from 1 to 14 in the width direction (Fig. 2).

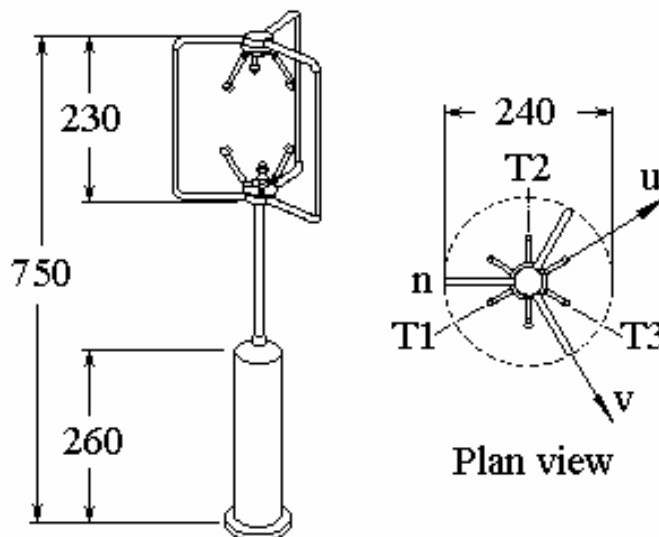


Fig. 1: Configuration of the sonic anemometer (all dimensions in mm)

A tomato crop was grown in the test greenhouse using the Nutrient Film Technique (NFT). It was fully grown at the time when the experiments were performed during August-October of 1994. The opening angle of the greenhouse was controlled automatically by a commercial system (Brinkman) except for the last experiment on the empty greenhouse in November.

The general measuring system for the required environmental variables was installed in the greenhouse, which was the same as described by Wang and Deltour [1996]. The outside variables were measured with sensors in a meteorological station near the greenhouse. The readings of all the sensors were averaged and recorded every 5 minutes using a self-made data logging computer system. The recording period was set to match that of the sonic anemometer.

The sonic anemometer was installed near the window opening, parallel to and about 25 cm below the roof because of its size. The reference direction (n) specified by the sonic anemometer was perpendicular to the roof and towards the inside of the greenhouse for both the south and north ventilators (Fig. 3a).

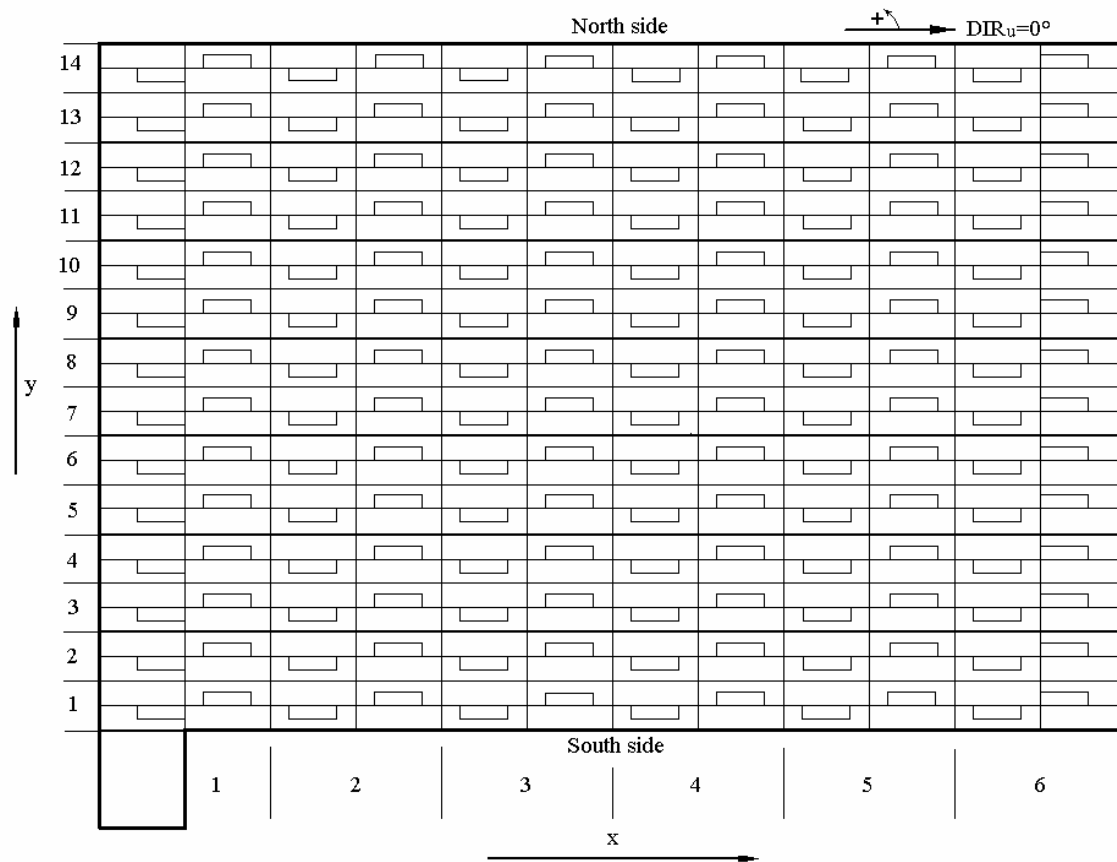


Fig. 2: Ventilation window distribution of the test greenhouse

2.3 Data treatment of the measurement results

The three components u , v , w of air velocity measured by the sonic anemometer are projected into two planes : the roof plane (r) which is parallel to the roof surface and the vertical plane (v) which is perpendicular to the roof and parallel to the end wall. In the vertical plane, the velocity component in y direction (V_{yv} [$\text{m}\cdot\text{s}^{-1}$]) for north (Fig. 3b) or south window (Fig. 3c) can be found as :

$$V_{yv} = u \cos 30^\circ + v \cos 60^\circ \quad \text{.....(2)}$$

but the velocity component in x direction (V_{xv} [$\text{m}\cdot\text{s}^{-1}$]) is :

$$V_{xv} = \begin{cases} w & \text{for north window} \\ -w & \text{for south window} \end{cases} \quad \text{.....(3)}$$

the resultant direction (DIR_{Vv} [$^\circ$]) from above two components is defined that 0° is from eaves to the ridge for north window and just reverse for south one and increases in anti-clockwise.

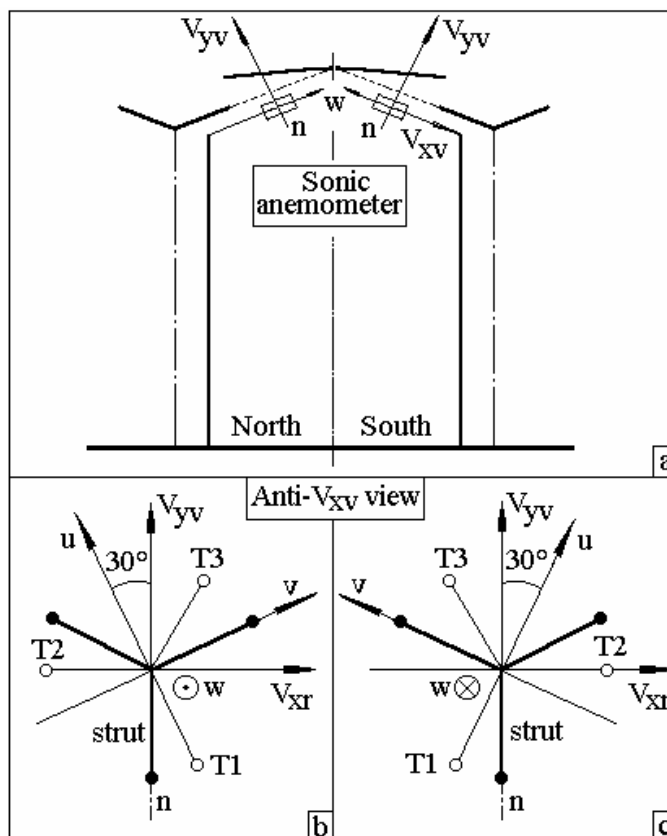


Fig. 3: The components of the sonic anemometer in vertical plane (a) as well as their anti- V_{xv} view for the north window (b) and the south window (c)

But in the roof plane, the direction (DIR_{Vr} [$^{\circ}$]) of the air velocity is defined as 0° from west to east along the ridge and also increases in anti-clockwise, that is the same for north and south windows as well as for external wind direction (DIR_u [$^{\circ}$]) recorded by the wind vane. The velocity components in both x and y directions are calculated as follows :

$$V_{xr} = \begin{matrix} v \text{ COS}30^{\circ} - u \text{ COS}60^{\circ} & \text{for north window} \\ u \text{ COS}60^{\circ} - v \text{ COS}30^{\circ} & \text{for south window} \end{matrix} \quad \text{.....(4)}$$

$$V_{yr} = \begin{matrix} -w & \text{for north window} \\ w & \text{for south window} \end{matrix} \quad \text{.....(5)}$$

Because of to the large amount of data recorded by the sonic anemometer, the results are presented by polar plots at each position to clearly understand the frequency distribution of airflow direction. Polar plots are similar to the meteorological wind roses. The measurement position is used as the origin of each plot. Probability densities are calculated and plotted at 10° intervals from 0 to 360° . Densities are plotted at the angle representing the interval midpoints which are connected by a line to form the

polar plot. In this way, it is clear whether the flow in the opening is mainly entering or outgoing from the vertical plane diagram and how its direction relates to the external wind direction.

3. RESULTS AND DISCUSSIONS

3.1 Leeside ventilation

In commercial production greenhouses uniform growth of the crop is required so that the leeside windows should be opened first, since this type of ventilation provides a more homogenous air exchange compared to windward side ventilation. Therefore, leeside ventilation is discussed here due to its importance.

On Sept. 21, 1994, North windows (windward) were closed during the measurements and south windows contributed the leeside ventilation. The sonic anemometer was installed in the center of each window opening located at the coordinates x_1, x_4 and x_6 with $y_1, y_3, y_5, y_7, y_9, y_{11}$ and y_{13} to measure the air velocity. The measurement at each position took 5 minutes. During the measurement period (10:30-17:40), the external wind speed (u_e [$\text{m}\cdot\text{s}^{-1}$]), the internal-external temperature difference (ΔT_{ie} [$^{\circ}\text{C}$]) and the opening angle (α [$^{\circ}$]) varied between 2.4-3.8 $\text{m}\cdot\text{s}^{-1}$, 4.8-8.8 $^{\circ}\text{C}$ and 9-28 $^{\circ}$ respectively (Fig. 4). The wind direction DIR_u was around 250 $^{\circ}$. The external conditions were considered to be stable for our purpose during individual measurements and their behavior was not qualitatively modified during the whole series.

From polar plots in the roof plane (Fig. 5a), it can be found that the airflow near the windows in the center of the greenhouse moved along the ridge with a small angle. The magnitude of the mean air velocity in the opening near the center of each span is larger than that of the two sides. From the vertical plane diagram (Fig. 5b), the results show that there are clear differences of the airflow among the windows : nearly half of the windows in the north part of the greenhouse provides the outgoing flow and the other half of the windows in the south contributes to the entering flow except some windows near the border of the greenhouse. It seems that an internal air movement for leeside ventilation exists against the external one. For each opening the dominant entering or outgoing flow has been found and there are clear differences between them.

In order to use the direct measurement of airflow across a greenhouse opening, a non-dimensional ventilation function $g(\alpha)$ for each individual window is introduced, which relates the ventilation flux per unit window aperture area to the wind flux per unit the window area :

$$g(\alpha) = \frac{A_{\text{eff}} \cdot V_v}{A_w \cdot u_e} \quad \dots\dots(6)$$

where V_v is the measured mean air speed in vertical plane [$\text{m}\cdot\text{s}^{-1}$], A_{eff} is the effective ventilation area of the window opening [m^2], A_w is window area [m^2].

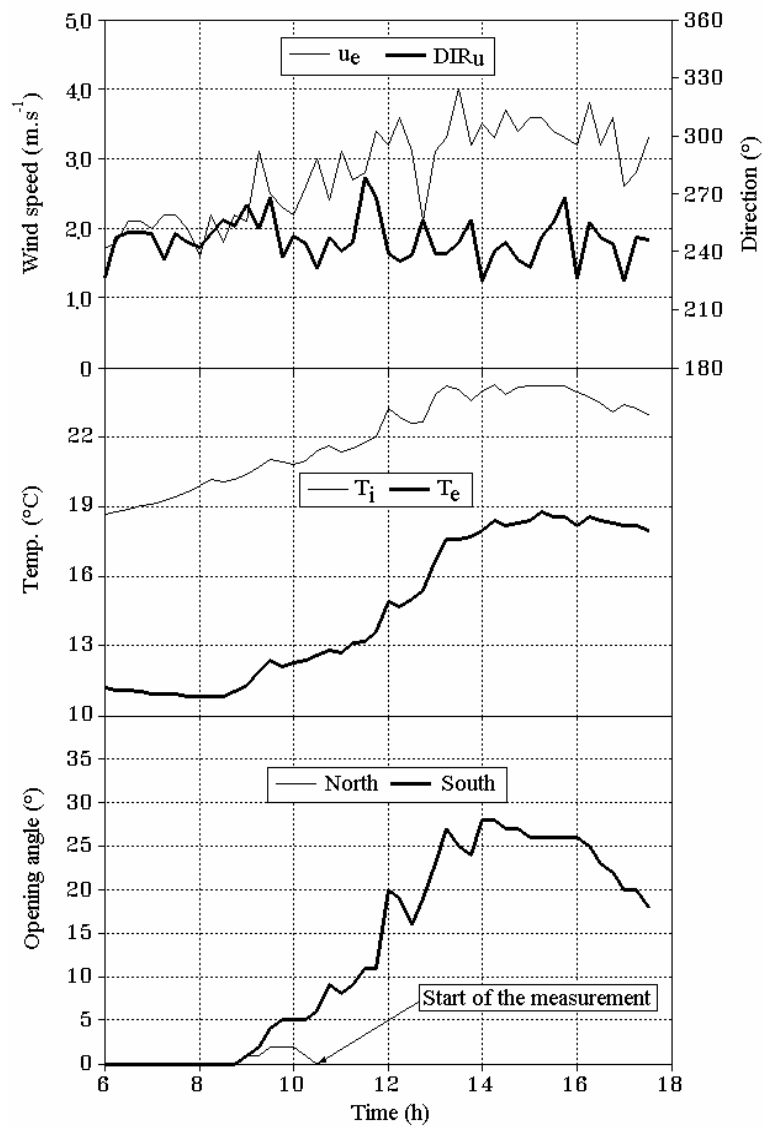


Fig. 4: The conditions related to the ventilation measurements (Sept. 21, 1994)

According to the window geometry, Eq. (6) becomes :

$$g(\alpha) = \frac{V_v}{u_e} \cdot tg(\alpha) \tag{7}$$

An approximate mass balance of the above average air exchange measurements can be checked by summing normalized inflows and outflows over the partly measured windows so as to verify that :

$$\sum_{DIR_{V_v} > 180^\circ} inflow + \sum_{DIR_{V_v} < 180^\circ} outflow = 0 \tag{8}$$

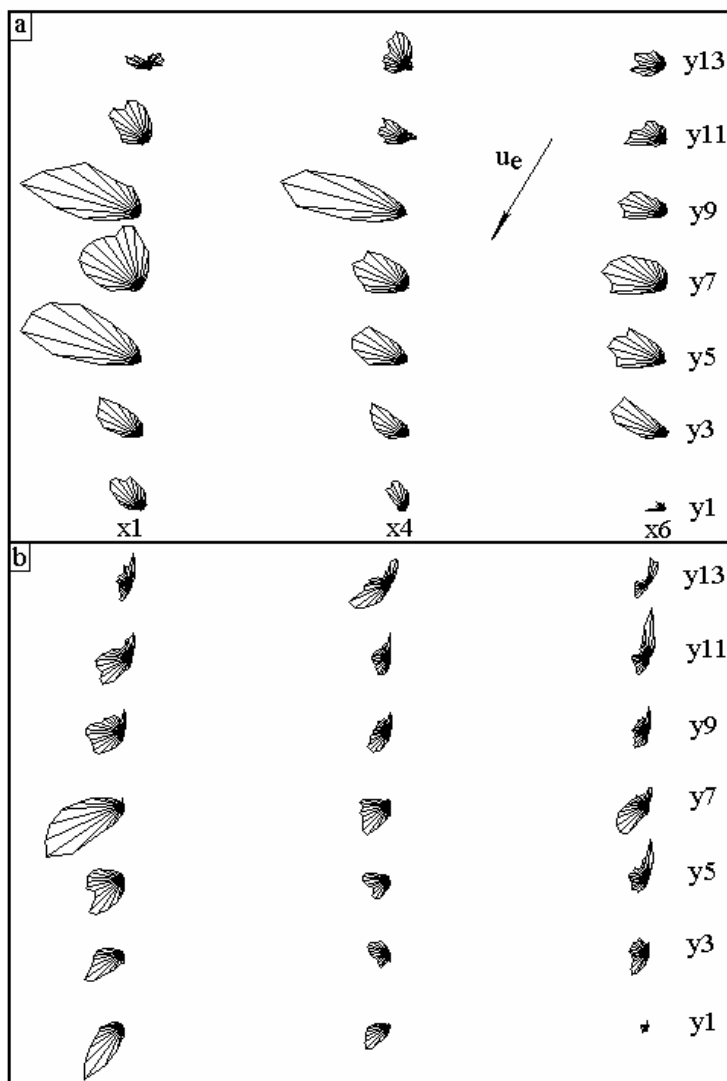


Fig. 5: Polar plots of probability densities of airflow in roof (a) and vertical (b) planes under leeward ventilation (Sept. 21, 1994)

This mass conservation principle is nearly supported in our measurements with, respectively : $\Sigma_{inflow} = +0.266$, $\Sigma_{outflow} = -0.212$ due to the fact that the measured windows are only 21 of 84 total leeward ones.

This result may explain the leeward ventilation in a large multi-span greenhouse, that is, a static pressure distribution is created around the greenhouse due to the leeward ventilation. This point of view is very different from that of the previous researchers.

3.2 Airflow pattern of an opening in the greenhouse center

To know the airflow pattern through a leeward opening, the center window ($x4$, $y7$) was selected on Oct. 13, 1994. Six measurement points were distributed uniformly in the opening of the south window. They were located at the upper and lower parts of the opening as well as separated to left, median and right positions. During the

measurements, the external wind direction was $DIR_u=198-221^\circ$ with the speed about 3.1 m.s^{-1} . Therefore, the leeside ventilation was provided with the constant opening angle of 16° .

The results are presented by the polar plots in which the measured air velocity is projected in the roof plane (Fig. 6a) and in the vertical plane (Fig. 6b) as in the above section. It is found that the airflow enters the greenhouse along the ridge with an angle about $4-28^\circ$. The velocity at the upper or lower part is nearly the same but at the median points is a little larger than that on the left side. However, the airflow near the right edge of window is very small and seems to go up and out. It is because the temperature effect is dominant there and the wind passes over there. It is necessary to keep in mind that the sonic anemometer is not in the opening but is about 25 cm below the roof alignment.

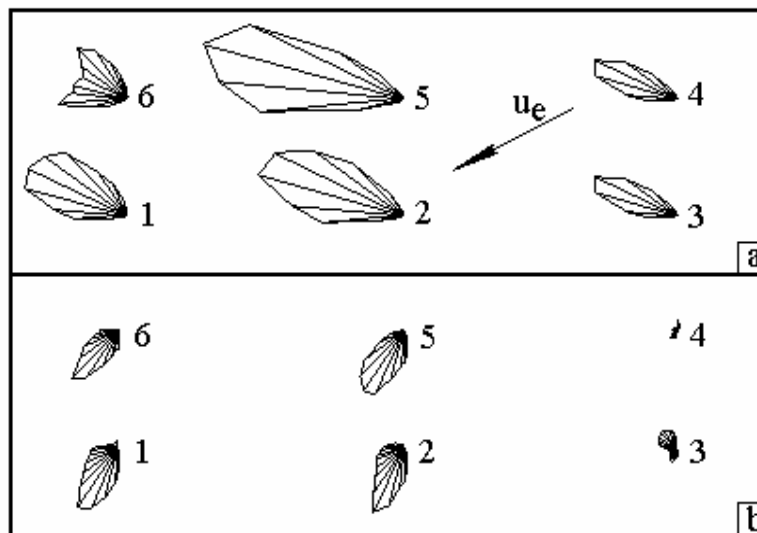


Fig. 6: Polar plots of probability densities of airflow in roof (a) and vertical (b) planes at six positions of a greenhouse central window (Oct. 13, 1994)

3.3 Influence of the opening angle on the airflow

In order to investigate the air velocity changes caused by different opening angles, measurements were carried out on Nov. 17, 1994 when there was no crop in the greenhouse. Therefore, the opening angles both in leeside and windward sides could be controlled by the needs of the experiment. The sonic anemometer was installed at the center of the north window ($x4, y8$). The external wind direction was from south to north ($13-78^\circ$) with the magnitude of $4-5 \text{ m.s}^{-1}$. A series of leeside air velocities were measured at different opening angles : $1^\circ, 3^\circ, 6^\circ, 9^\circ, 15^\circ, 20^\circ, 26^\circ, 35^\circ, 39^\circ$ for each opening angles : $0^\circ, 1^\circ, 3^\circ, 6^\circ, 9^\circ$ of windward side. The direction difference between the roof plane airflow and the external one as well as the non-dimensional ventilation function for the single window are plotted as a function of the opening angle both on leeside and on windward sides.

The results (Fig. 7) show that the direction of air movement in the leeside windows in the roof plane is nearly parallel to the external wind direction except for the small opening (about $\leq 3^\circ$) and the non-dimensional ventilation function $g(\alpha)$ increases with the opening angle α of the leeside window but decreases while the opening angle of windward side window increases.

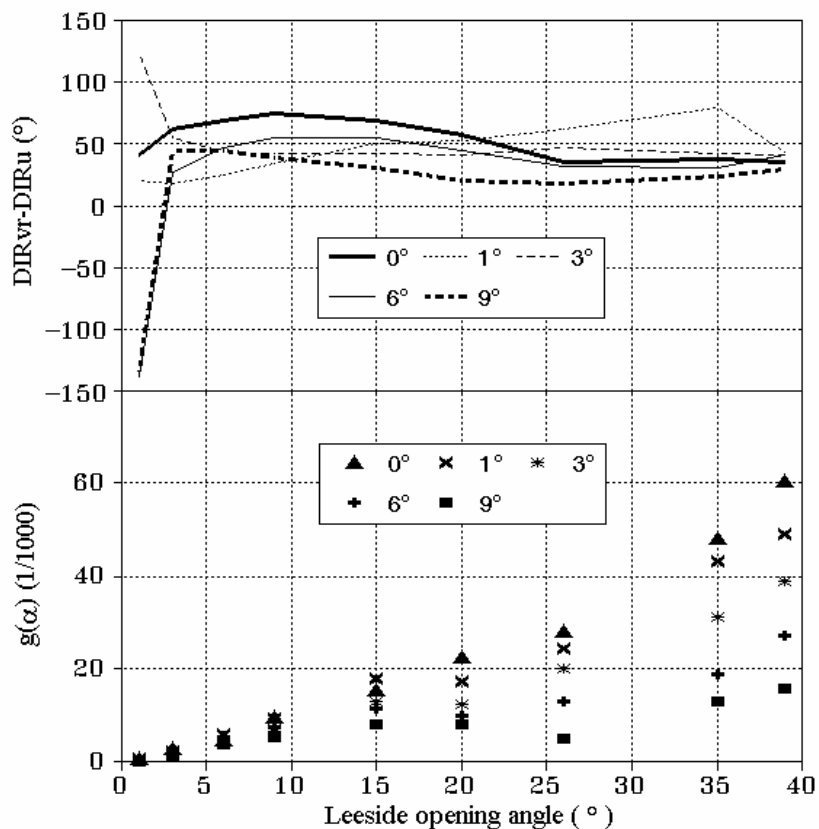


Fig. 7: Air movement variation with the opening angles (Nov. 17, 1994)

4. CONCLUSIONS

The airflow measurements involved in greenhouse natural ventilation are usually obtained by tracer gas techniques and pressure difference method. However the new method to measure directly the air velocity by a sonic anemometer allows us to measure the airflow distribution in the opening under different conditions and to build a non-dimensional ventilation function.

The three components of the air velocity are projected both in the roof plane and in the vertical one. It is useful for us to understand clearly the airflow across the opening affected by the external wind and the opening angle. The recording period of the measurements is reduced from the traditional 15 minutes to 5 minutes so as to accelerate the measurements.

The airflow distribution under lee-side ventilation shows that there is a clear difference from one window to another. The air admission occurs predominantly in the lee-side part of the greenhouse while the air rejection occurs in the windward part. It seems that a general internal air movement exists against the external wind direction. An approximate balance of the inflow and outflow can be reached by means of the specific non-dimensional ventilation functions.

The air velocity in the greenhouse center is greatly affected by the opening angle of leese side and windward side. The results show that the non-dimensional ventilation function of leese side increases with the opening angle but decreases with the opening angle of windward side. The air velocity at the middle point in an opening can be used to represent the typical distribution of that window from our measurements.

It takes a long time to make the above measurements in the test greenhouse by moving the sonic anemometer from one position to another. Thus it is difficult to do all the measurements under an accepted stable condition. It seems that the air speed and direction in the same opening can be changed significantly with the external wind direction and opening angle of the two sides. Consequently we need to develop a more powerful measuring system which can measure the air velocity at different positions simultaneously.

ACKNOWLEDGMENTS

This is a part of Dr. WANG's Ph. D. thesis supported financially by a scholarship of " Bourse Coopération Stagiaires Chinois " awarded by Prof. J. DELTOUR. We wish to express our deepest thanks to Mr. M. YERNAUX for his hard and efficient work throughout the whole experiment, Dr. M. AUBINET for his comments and useful suggestions.

REFERENCES

1. Bot G.P.A. (1983). Greenhouse climate : from physical process to a dynamic model. Ph. D. Thesis, Agricultural University Wageningen, The Netherlands, 240p.
2. Boulard T. and Baille A. (1995). Modelling of air exchange rate in a greenhouse equipped with continuous roof vents. *J. agric. Engng. Res.*, 61 : 37-48.
3. Boulard T. and Draoui B. (1995). Natural ventilation of a greenhouse with continuous roof vents : measurements and data analysis. *J. agric. Engng. Res.*, 61 : 27-36.
4. Boulard T., Menses J. F., Mermier M. and Papadakis G. (1996). The mechanisms involved in the natural ventilation of greenhouses. *Agric. For. Meteorol.*, 79 : 61-77.
5. Campbell G. S. and Unsworth M. H. (1979). An inexpensive sonic anemometer for eddy correlation. *J. Appl. Meteorol.*, 18 : 1027-1077.

6. Coppin P. A. and Taylor K.J. (1983). A three-component sonic anemometer / thermometer system for general micrometeorological research. *Boundary-Layer Meteorol.*, 27 : 27-42.
7. De Jong T. (1990). Natural ventilation of large multi-span greenhouses. Ph. D. Thesis, Agricultural University Wageningen, The Netherlands, 116p.
8. Fernandez J. E. and Bailey B. J. (1992). Measurement and prediction of greenhouse ventilation rates. *Agric. For. Meteorol.*, 58 : 229-245.
9. Heber A. J., Boon C. R. and Peugh M. W. (1996). Air patterns and turbulence in an experimental livestock building. *J. agric. Engng. Res.*, 64 : 209-226.
10. Kaimal J. C. and Businger J. A. (1963). A continuous wave sonic anemometer-thermometer. *J. Appl. Meteorol.*, 2 : 156-164.
11. Kittas C., Draoui B. and Boulard T. (1995). Quantification of the ventilation of a greenhouse with a roof opening. *Agric. For. Meteorol.*, 77 : 95-111.
12. Kozai T., Sase S. (1978). A simulation of natural ventilation for a multi-span greenhouse. *Acta Hortic.*, 87 : 339-349.
13. Papadakis G., Mermier M., Meneses J. F. and Boulard T. (1996). Measurement and analysis of air exchange rates in a greenhouse with continuous roof and side openings. *J. agric. Engng. Res.*, 63 : 219-228.
14. Smith S. D. (1980). Evaluation of the mark 8 thrust anemometer-thermometer for measurement of boundary-layer turbulence, *Boundary-Layer Meteorol.*, 19 : 273-292.
15. Wang S. and Deltour J.(1996). An experimental ventilation function for large greenhouses based on a dynamic energy balance model. *Agric. Eng. J.*, 5(3&4) : 103-112.