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**GREENHOUSE NATURAL VENTILATION:
REVIEW OF NUMERICAL METHODS AND ANALYSIS
OF VENTILATION EFFICIENCY**

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GREENHOUSE NATURAL VENTILATION: REVIEW OF NUMERICAL METHODS AND ANALYSIS OF VENTILATION EFFICIENCY

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1. INTRODUCTION

1. Introduzione

During the last twenty years, the use of greenhouses for flower or vegetable production has expanded all over the world corresponding to a total covered area of approximately 500,000 ha in 1999. In particular, protected cultivation under low-cost plastic-covered greenhouses has become an important dynamic sector of agriculture in areas with warm climate, like Mediterranean region, where winter is mild and the greenhouse covered area amounts to more than 120,000 ha. In this way, the production period can be extended or shifted in order to increase the economic output, with the use of simple, low-investment-cost structures (fig. 1). However, the international competition with respect to greenhouse products leads to continuously higher productivity requirements, while increasing environ-

mental regulations impose more restrictions with respect to energy consumption, use and emissions of agrochemicals (Scarascia-Mugnozza, 1995). For this reason, the optimisation of both the design and the operation of greenhouses have become necessary. Such optimisation studies have first been performed for glasshouses but they are gradually extended also to plastic covered greenhouses.

One of the principal factors influencing production is the ventilation efficiency of the greenhouse. Ventilation is the only mechanism for mass exchange, and one of the principle mechanism for heat exchange. Therefore, it can be used for regulating the indoor air temperature, relative humidity and CO₂ concentration. For this reason, efficient control and high capacity of ventilation is required for optimal plant growth and quality production. However, most of the commercially available greenhouses lack forced ventilation systems due to its high investment and operational cost.

Natural ventilation is characterised, on the other hand, by lower investment and operational costs, even if an efficient removal of internal air requires careful design of the greenhouse ventilation system: including

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Fig. 1 - Multi-span plastic-covered tunnel greenhouse in Southern Italy.

Fig. 1 - Serra-tunnel multipla con copertura in film plastico in Italia Meridionale.

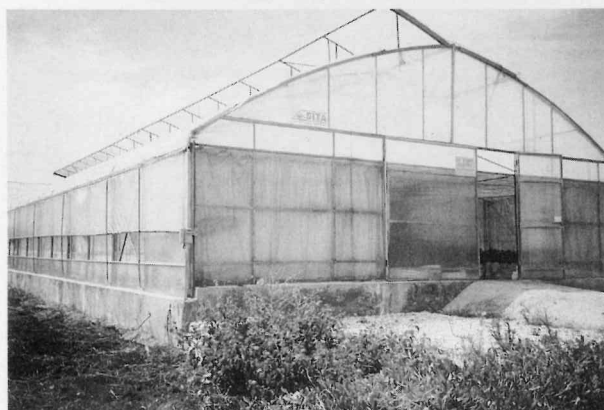


Fig. 2 - Tunnel greenhouse with side and ridge vents for natural ventilation.

Fig. 2 - Serra-tunnel con sportellature laterali e di colmo per la ventilazione naturale.

devices like ridge and side vents (fig. 2) in the greenhouse structure increases its cost (even 40-50% more) compared with a simple structure where no ventilation openings are included in the design and ventilation is only due to the openings of doors.

The importance of the ventilation process for optimally controlling the indoor microclimate in greenhouses has already been understood since the early attempts to develop microclimate models for control applications in greenhouses (Bakker et al., 1995). Initially, research concerning greenhouse ventilation, has focused on measuring average air renewal rates in Venlo-type glasshouses, which were the most popular greenhouse type in Northern Europe (Bot, 1983; De Jong, 1990; Fernandez & Bailey, 1992). In these experiments the «tracer gas» method has been widely used. However, it has become evident that the average air renewal rate obtained by the «tracer gas» method, which neglects the variations with respect to ventilation in specific greenhouse compartments, was not sufficient for fully describing the ventilation mechanism in greenhouses. Therefore, a more detailed investigation of the air flow at the ventilators as well as inside the greenhouse is necessary. For this reason, the most recent studies analyse the characteristics of the greenhouse ventilation mechanism by detailed measurements of the air velocity (Boulard et al., 1996) or numerical simulations of the air flow (Mistriotis et al., 1997/a; Mistriotis et al., 1997/b). In this way, important misunderstandings concerning greenhouse ventilation efficiency have been clarified.

In the present article, we will present the most popular methods for investigating the natural ventilation performance of greenhouses and explain advantages offered by the newly developed research tools for fully analysing the ventilation air flow in greenhouses. This analysis can lead towards a further optimisation of the design and the control system of a greenhouse.

2. METHODS FOR THE INVESTIGATION OF THE NATURAL VENTILATION IN GREENHOUSE

2. Metodologie di analisi della ventilazione naturale nelle serre

2.1. MEASUREMENTS OF THE AVERAGE AIR RENEWAL RATE

2.1. *Misure del tasso medio di ricambio d'aria*

Natural ventilation is generated by pressure differences along open surfaces at the greenhouse cover due to the action of wind (wind-driven ventilation) or/and differences between internal and external air temperature or humidity (buoyancy-driven ventilation). The global average characteristics of ventilation are usually quantified in a simplified way (Picuno, 1996), by the global ventilation rate Q , defined as the total air volume exchanged per time unit. This quantity is usually presented normalised with respect to the greenhouse volume V , by introducing the air renewal rate $R = Q/V$.

Several analytical phenomenological expressions have appeared in the scientific literature for the estimation of the global ventilation rate Q . Fernandez & Bailey (1992) have used the formula:

$$Q = A \sqrt{f_v^2 v^2 + f_T^2 \Delta T_{i,e}} \quad (1)$$

where Q ($\text{m}^3 \text{s}^{-1}$) is the ventilation rate, A (m^2) is the ventilation opening area, v (m s^{-1}) is the wind velocity, $\Delta T_{i,e}$ (K) is temperature difference between inside and outside, and f_v and f_T are phenomenological coefficients to be determined experimentally, describing the ventilation capacity of a greenhouse due to its design. This formula estimates the airflow rate when both, wind-driven and buoyancy-driven ventilation are considered. The value of f_v and f_T are considered independent of the ventilators opening angle and location. Typical values of f_v and f_T for Venlo-type greenhouses which are popular in Northern Europe are presented in Fernandez & Bailey (1992). Papadakis et al. (1996) measured the values of coefficients f_v and f_T for tunnel greenhouses which are widely used in Mediterranean countries.

An analytical expression commonly used for estimating the airflow rate in greenhouses due to the wind is:

$$Q = A_0 G(\alpha) v \quad (2)$$

where Q ($\text{m}^3 \text{s}^{-1}$) is the ventilation rate, A_0 (m^2) is the maximum ventilator opening area, $G(\alpha)$ is the dimensionless ventilation coefficient, depending on the ventilator opening angle α , and v (m s^{-1}) is the wind velocity. Expression (2) neglects the influence of the temperature difference to the ventilation rate. This is possible in

cases when the wind speed exceeds a «threshold» value, so that the wind becomes the dominant driving force of the ventilation process. Several authors (Papadakis et al., 1996; Boulard et al., 1996; De Jong & Bot, 1992; Feuilloley et al., 1994; Fernandez & Bailey, 1992) have shown that the buoyancy-driven ventilation is negligible for wind speeds higher than 2 m s^{-1} . Formula (2) is particularly useful in estimating ventilation rates in greenhouse designs such as the Venlo glasshouses, where all ventilators are operated by the same mechanism and open at the same angle. In these cases, $G(\alpha)$ can be easily determined experimentally as a function of the ventilator opening angle α (Fernandez & Bailey, 1992; Bot, 1983; De Jong, 1990).

The above presented expressions (1) and (2) provide a simplified quantitative description of the ventilation performance of greenhouses. In this approach, in fact, the ventilation rate is independent of the geometrical characteristics of the greenhouse and of the configuration of the ventilation system (orientation with respect to the wind, shape and design of roof and ventilators, current configuration of different ventilation openings); moreover, the dimensionless coefficients f_v and $G(\alpha)$ cannot distinguish among situations corresponding to different wind direction, so they usually express average values calculated over all wind directions. However, the ventilation mechanism can be quantitatively and qualitatively different when the wind direction varies. Similarly, variations with respect to operation strategy can result into qualitatively different ventilation mechanisms, as we shall show in section 3 of this paper. Finally, the characterisation of the ventilation performance of a greenhouse by a single value of the ventilation rate neglects the details of the indoor air flow such as the air velocity field and the air renewal rate at the canopy level. However, such characteristics of the indoor air flow may strongly influence the quality and quantity of the production.

For these reasons, a more detailed analysis of the indoor airflow is necessary. Such analysis will reveal the important qualitative characteristics of the ventilating flow and serve as guide for better optimised designs and operating strategies.

2.2. MEASUREMENTS OF THE AIR VELOCITY FIELD DURING VENTILATION

2.2. *Misure dei campi di velocità dell'aria durante la ventilazione*

The necessity for a deeper understanding of the air flow appearing during ventilation in greenhouses has been realised already since the 80's. However, most of the relevant experimental studies appeared recently.

Sase et al. (1984) have used wind tunnel experiments for studying the ventilation flow in a single span model greenhouse of a scale 1/10. The indoor velocity field

has been determined by hot wire anemometers and has been visualised by smoke. The steady-state temperature distribution has also been measured when a heat flux was generated at the ground inside the greenhouse.

Boulard et al. (1996) have used a one-dimensional sonic anemometer for measuring the velocity component normal to the ventilator opening in full-scale experiments.

Two-dimensional or three-dimensional sonic anemometers can be used for more accurate measurements of the air velocity vector components in greenhouses or at the ventilator openings. However, these measurements are expensive with respect to both equipment and labour costs (Deltour and Wang, 1998).

All these techniques provide detail information about the ventilation flow in greenhouses. However, they require the use of expensive equipment operated by highly specialised scientists and they give information only for specific greenhouse types, but no general indications. For these reasons, they are not popular with the greenhouse designers for the characterisation of the greenhouse ventilation efficiency. As a consequence, they are only used in basic research for the investigation of the fundamental characteristics of the ventilation in greenhouses.

2.3. CFD (COMPUTATIONAL FLUID DYNAMICS) ANALYSIS OF GREENHOUSE NATURAL VENTILATION

2.3. *Analisi mediante CFD della ventilazione naturale in serra*

The Computational Fluid Dynamics (CFD) method is a numerical alternative to the above described experiments. It consists in solving the set of partial differential equations that analytically express the fluid mass, momentum and energy conservation (Awbi, 1991). These conservation equations are of the general form:

$$\frac{\partial \phi}{\partial t} + \vec{V} \cdot \phi \vec{V} = \vec{V} \cdot (\Gamma_{\phi} \vec{V} \phi) + S_{\phi} \quad (3)$$

where \vec{V} is the velocity vector, Γ_{ϕ} the diffusion coefficient and S_{ϕ} the term expressing possible sources. The symbol ϕ represents the concentration of transported quantities. For example, in the mass transport (continuity) equation, ϕ corresponds to density ρ . When the momentum conservation is considered, ϕ corresponds to $\rho \vec{V}$. In this case, the equation (3) represents three equations, the Navier-Stokes equations, corresponding to the three components of $\rho \vec{V}$. If also energy is transported by the flow field, an extra equation, with ϕ corresponding to $\rho C_p T$ (where C_p is the specific heat at constant pressure, and T is temperature) is introduced. Finally, if buoyancy significantly influences the

flow, the gravity force $\vec{p}g$ has to be included in the Navier-Stokes equations.

The equations describing the flow are numerically solved on a discretised grid using the Finite Volume or the Finite Elements methods. In the case of turbulent flows, an approximation is necessary for solving the flow equations on a discrete grid. For this reason turbulence models have been developed. The most popular one, called k- ϵ model, expresses turbulent transport by means of two extra phenomenological variables, the turbulent energy k and its dissipation rate ϵ . The basic k- ϵ model, however, fails in realistically describing recirculating flows. For this reason, it has been further refined with the introduction of two-scale k- ϵ models, which are proven to exhibit good accuracy in the computational prediction of airflow inside greenhouses (Mistriotis et al., 1997/a).

The flow equations are solved under boundary conditions describing selected meteorological factors (e.g. wind speed, air temperature, solar radiation) influencing the ventilation flow. The solution provides full details of the air flow (pressure, temperature, air velocity components, etc.). Therefore, quantitative and qualitative characteristics of the ventilating flow can be determined.

CFD simulations have recently developed into an efficient and popular tool for studying flows. The development of commercial CFD software packages combined with the very rapid reduction of the cost of computing time allow for low-cost, high-accuracy CFD calculations. For this reason, CFD simulations can be a valuable tool for analysing the internal airflow and understand the functionality of the greenhouse structural characteristics with respect to ventilation.

CFD simulations have already been applied in the analysis of greenhouse ventilation (Bot et al., 1996; Mistriotis et al., 1997/a; Mistriotis et al., 1997/b; Mistriotis et al., 1997/c; Mistriotis et al., 1997/d; Scarascia & Picuno, 1997). In these works it has been shown that CFD simulations can successfully predict both wind-driven and buoyancy-driven ventilation in greenhouses, providing interesting information to greenhouse designers concerning a more efficient management of ventilation.

CFD simulations can provide a qualitative estimation of the ventilation efficiency in greenhouses through the graphical visualisation of the ventilation flow. Moreover, a variety of indicators which quantitatively determine ventilation efficiency can be calculated, such as the average air renewal rates or the local ventilation effectiveness of specific compartments related to the functionality of the greenhouse. The indoor air temperature distribution can also be explicitly calculated for specific weather conditions. Even though certain CFD results have been validated by measurements, further comparisons between computed and measured ventilation indicators are required before the numerical results are fully trusted at a quantitative level.

2.4. VENTILATION EFFICIENCY INDICATORS CHARACTERISING GREENHOUSE DESIGN

2.4. *Indicatori di efficienza della ventilazione per la progettazione delle serre*

Characterising the ventilation efficiency of a greenhouse structure requires the definition of proper indicators. Such indicators should take into account the functional role of the ventilation in conditioning the indoor microclimate. The average air renewal rate is an indicator describing the average ventilation efficiency of a greenhouse.

Another indicator providing more detail information about the ventilation process in a confined space, like the greenhouse building, is the local ventilation effectiveness, η_p . It is defined as:

$$\eta_p = \frac{C_{out} - C_{in}}{C_p - C_{in}}$$

where C_{out} , C_{in} , and C_p are the time-average concentration of a gas in the greenhouse (e.g. water vapour or CO_2) at the outlets, the inlets and at a point p in the greenhouse respectively (Breum et al., 1990). This local indicator can distinguish stagnation regions, where η is small, to efficiently ventilated regions where η is close to 1. However, measuring the local ventilation effectiveness could be an intriguing task since it requires a large number of measuring points, while C_{out} and C_{in} are not uniform over all ventilators.

Another definition of the local ventilation effectiveness can be based on measuring the air temperature during a sunny cool day, when the temperature difference between internal and external air is high:

$$\eta_p = \frac{T_{out} - T_{in}}{T_p - T_{in}}$$

where T_{out} , T_{in} , and T_p are the time-average air temperature at the outlets, the inlets and at a point p in the greenhouse respectively.

This indicator, however, can be used with difficulty in the case that there are many outlets and the temperature of the outgoing air varies among the different outlets.

The average temperature difference between indoor and outdoor air measured at the canopy level could be a more easy and direct indicator characterising the average ventilation efficiency, but it gives only a global information about the process of heat surplus removal; on the other hand, the indoor temperature distribution expressed by the standard deviation of indoor air temperature indicates the magnitude of internal air temperature variations, due to the ventilation process in the greenhouse. As an empirical indicator of the ventilation efficiency we propose to assume the square root of the product of the standard deviation (σ) by the average temperature difference between inside and

outside air (ΔT), since it is minimum where both those values are low.

All the above indicators can be determined experimentally with difficulty, because they require a large number of measuring points. Full-scale experimental characterisation with respect to ventilation efficiency of new greenhouse design for commercial reasons would be tedious and expensive. The numerical estimation of the greenhouse ventilation efficiency by the CFD method can greatly simplify the evaluation of various greenhouse types and ventilation techniques. However, the use of the CFD method in simulating ventilation flows is not yet established and further investigation concerning boundary conditions is required before the numerical results are accepted without any doubt.

3. NUMERICAL PREDICTION OF GREENHOUSE NATURAL VENTILATION EFFICIENCY

3. Formulazione numerica dell'efficienza della ventilazione naturale nelle serre

Plastic-covered greenhouses with arch roof are widely used in Mediterranean countries. A typical span width is 6.5 m, the height at the ridge is 4.3 m and at the gutter 3.3 m. These greenhouses are usually equipped with roof or side ventilators, or both roof and side ventilators.

In this section, the ventilation efficiency of a twin-span Mediterranean-type plastic greenhouse is investigated with the use of CFD simulations as an example of the optimising capabilities of the method. A particular situation is considered when a moderate wind (wind speed 2 m s^{-1} at a height of 10 m) is blowing transversely to the greenhouse (wind normal to the greenhouse ridge). The wind speed is increasing with the height and its dependence of the height is expressed by a logarithmic function (Mistriotis et al., 1997/d). Under these conditions, a two-dimensional CFD calculation is sufficient for simulating the air flow, while buoyancy-driven ventilation can be neglected. A uniform heat source is considered at the greenhouse ground which, in combination with the ventilating flow, generates a temperature distribution characterising the ventilation efficiency. The convective heat flux transferred from the greenhouse ground to the air is considered 100 W m^{-2} due to the solar radiation absorbed and re-emitted from the ground.

There are many variations with respect to the design of the ventilators in Mediterranean-type greenhouses. In the present example we study three of the commonly used configurations with roof and side vents. The first two cases are equipped with only roof ventilators which are 1 m wide. In the first design (fig. 3 - design 1), the ventilators are located just above the gutter, while in the second they are placed just below the ridge (fig. 3 - design 2). Three alternative strategies are considered aiming at maximising the ventilation efficiency: a) the two windward ventilators are open; b) all ventilators

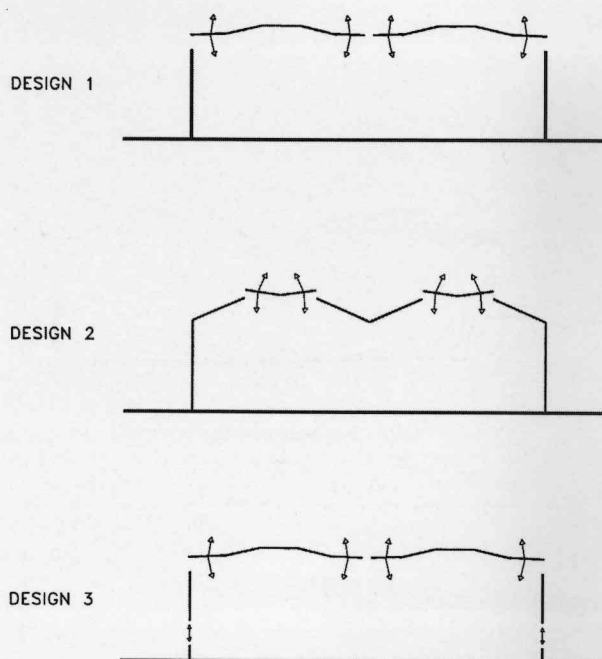


Fig. 3 - Three examined configurations of natural ventilation system: gutter vents only (design 1) ridge vents only (design 2) and gutter + side vents (design 3).

Fig. 3 - Configurazioni esaminate di sistemi di ventilazione naturale: con solo sportellature di gronda (schema 1), con solo sportellature di colmo (schema 2), con sportellature sia laterali che di gronda (schema 3).

are open; and c) the windward ventilator of the windward span and the leeward ventilator of the leeward span are open. The ventilation efficiency is determined by calculating in the greenhouse cross-section area occupied by the canopy (6.5 m width \times 2.5 m height, generally for vegetable cultivation) the average temperature difference between indoor and outdoor air, its standard deviation and, consequently, the square root of their product.

The CFD simulation was performed modelling the greenhouse cover with the help of a variable orthogonal grid (101×63 cells) modelling an area $90 \times 50 \text{ m}$ around the greenhouse. The RNG model (Mistriotis et al., 1997/b) is used for describing the turbulent transport, while the air is assumed to be an incompressible fluid.

Figure 4 presents the internal airflow and the distribution of temperature difference between inside and outside air in a greenhouse of the design 1 when the three above strategies are considered. Figure 5 presents the results corresponding to the same three strategies when the design 2 is considered. In all cases, the windward ventilators act as inlets while the leeward ventilators as outlets. However, the location of the ventilators induce different flow patterns in the greenhouse influencing also the intensity of the ventilation flow.

In particular in case (a), the incoming air flux through the windward ventilator follows the internal surface of the roof of the windward span and is directed towards the ground near the middle of the greenhouse.

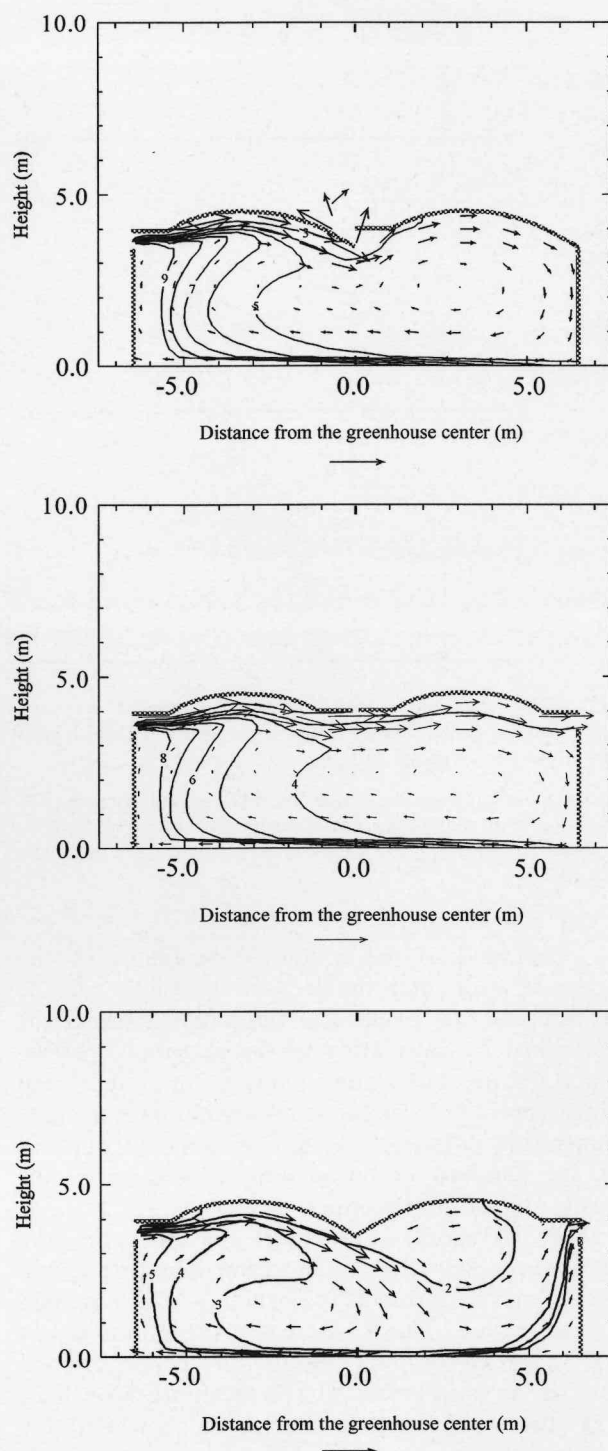


Fig. 4 - Airflow and isothermal distribution of air temperature differences between inside and outside, obtained by CFD analysis for design 1 in three different opening strategies.

Fig. 4 - Flusso aerodinamico e distribuzione delle isoterme relative alle differenze di temperatura tra aria interna ed esterna, ottenuti con l'analisi CFD per lo schema n. 1 nei tre differenti casi di apertura delle sportellature.

Then in the leeward span the flow becomes circular and the air exits through the opening of the leeward span. The numerical results presented in Tables 1, 2 and 3, show that design 2 is more efficient in this case,

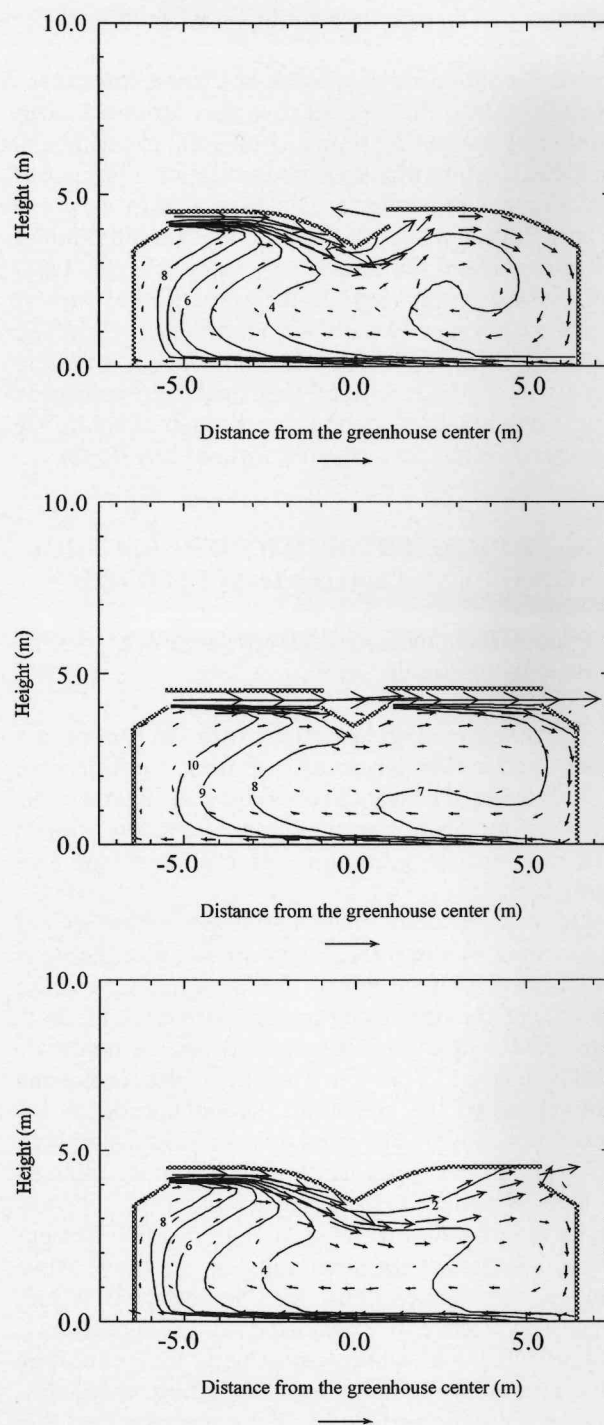


Fig. 5 - Airflow and isothermal distribution of air temperature differences between inside and outside, obtained by CFD analysis for design 2 in three different opening strategies.

Fig. 5 - Flusso aerodinamico e distribuzione delle isoterme relative alle differenze di temperatura tra aria interna ed esterna, ottenuti con l'analisi CFD per lo schema n. 2 nei tre differenti casi di apertura delle sportellature.

probably due to the increase of the wind speed with the height.

On the contrary, in case (b), design 1 is more efficient than design 2. This is a result of the strong

TABLE 1 - Average temperature difference (degrees °C) between indoor and outdoor air (ΔT) in the Mediterranean-type greenhouses studied in section 3.

TABELLA 1 - Differenza media di temperatura (°C) tra aria interna ed esterna (ΔT) nella tipologia di serra mediterranea studiata.

	Design 1	Design 2	Design 3
(a)	6.14	4.84	0.9
(b)	5.1	8.8	1.1
(c)	3.6	4.6	0.5

TABLE 2 - Spatial standard deviation of the temperature difference (degrees °C) between indoor and outdoor air (σ) in the Mediterranean-type greenhouses studied in section 3.

TABELLA 2 - Deviazione standard spaziale delle differenze di temperatura (°C) tra aria interna ed esterna (σ) nella tipologia di serra mediterranea studiata.

	Design 1	Design 2	Design 3
(a)	3.0	2.6	0.9
(b)	2.4	2.7	1.0
(c)	2.1	2.3	0.6

TABLE 3 - Square root (degrees °C) of the product of average temperature difference between indoor and outdoor air (Table 1) by standard deviation of the temperature difference (Table 2) ($\sqrt{\Delta T \sigma}$) for different cases studied in section 3.

TABELLA 3 - Radice quadrata (°C) del prodotto tra la differenza media di temperatura tra aria interna ed esterna (Tabella 1) per la deviazione standard della differenza di temperatura (Tabella 2) ($\sqrt{\Delta T \sigma}$) nei diversi casi studiati.

	Design 1	Design 2	Design 3
(a)	4.29	3.55	0.9
(b)	3.5	4.87	1.05
(c)	2.75	3.25	0.55

short-circuit flow appearing when all the roof windows are open. In design 1 however, the short-circuiting current spends a longer path in the greenhouse so it induces a stronger circulating flow in the lower layers of the greenhouse in comparison to the case 2b. The induced circulating flow moving in the opposite direction to the wind produces more efficient ventilation even in comparison to case 1a (tables 1, 2 and 3).

The configuration (c) generates the highest ventilation rate for both the studied designs because air flow has to cross all the greenhouse width before going out.

The results presented in Tables 1, 2 and 3 show that the configuration 1c has a slight advantage over the 2c, due to the location of the windward ventilator which allow better ventilation of the region near the windward side-wall.

A similar analysis concerning side ventilators is presented in figure 6. Three different cases have been

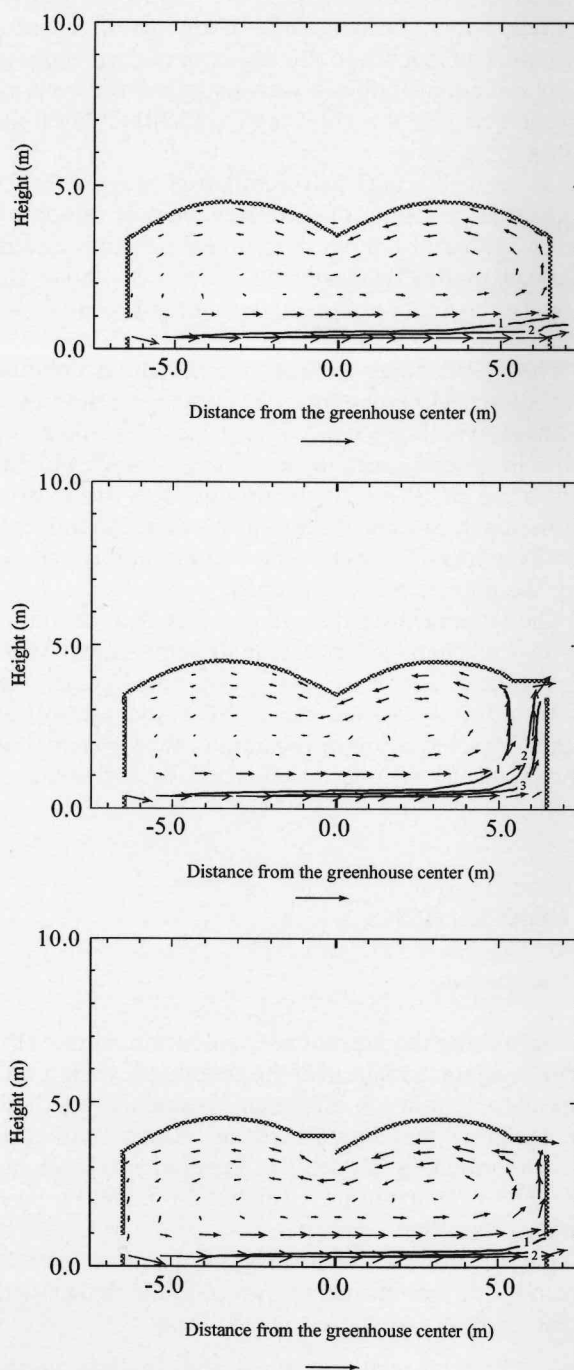


Fig. 6 - Airflow and isothermal distribution of air temperature differences between inside and outside, obtained by CFD analysis for design 3 in three different opening strategies.

Fig. 6 - Flusso aerodinamico e distribuzione delle isoterme relative alle differenze di temperatura tra aria interna ed esterna, ottenuti con l'analisi CFD per lo schema n. 3 nei tre differenti casi di apertura delle sportellature.

examined. In case 3a, only the two side ventilators are open. This ventilator configuration induces an air current at the canopy level parallel to the external wind due to the particular wind direction (transverse to the greenhouse axis), while a weaker circulating flow appears at the upper part of the greenhouse. As a result, the indoor air temperature at canopy level is almost the same as the outdoor temperature (Table 1, 2, 3). The same effect is also observed in case 3c where extra roof ventilators have been added. In this case, the roof ventilators enhance the outlet capacity of the greenhouse, but their contribution is only marginal, while the air current between the side ventilators dominates the ventilation process.

In case 3b, only two ventilators are open, the windward side ventilator and a leeward roof ventilator. Such a ventilator configuration blocks the air current observed in the two previous cases just above the ground. This reduces slightly the ventilation efficiency (Table 3).

The above three examined cases of greenhouse ventilation neglect the existence of other greenhouses or buildings, windbreaks and other vegetation which are common around greenhouses. These obstacles highly disturb the air flow near the ground. For this reason, ventilation due to side ventilators measured in full scale field experiments may be found considerably weaker than the numerically determined.

The numerical results presented in this section do not have a general validity. Similar simulations should be performed for every new greenhouse design. The results of this section are presented as a demonstration of the characterisation capabilities of the CFD method concerning the ventilation efficiency of a greenhouse type.

4. CONCLUSIONS

4. Conclusioni

Optimising the greenhouse ventilation requires the accurate characterisation of the greenhouse design with respect to ventilation efficiency. Numerical methods can facilitate the characterisation of the ventilation flow by providing full details of the velocity field and the indoor temperature distribution under a large variety of weather conditions.

The most important advantages of using numerical methods for optimising the greenhouse design with respect to ventilation are the following:

— CFD calculations allow the analysis of the ventilation efficiency of a greenhouse design under a large variety of weather conditions accurately simulated by the boundary conditions.

— CFD simulations can easily provide values of a variety of indicators characterising ventilation efficiency. Moreover, they provide a visualisation of the flow pattern revealing the ventilation mechanism corre-

sponding to specific ventilator configurations and weather conditions.

— CFD simulations can provide a low-cost analysis of the influence of design modifications on the ventilation efficiency avoiding expensive test constructions and field experiments.

For the moment, the accuracy of the CFD method for calculating ventilation flows is not established despite several promising results. For this reason, further validation experiments are required. Moreover, the application of the numerical method is not straightforward and requires experience in Fluid Dynamics and Numerical Analysis. Current research aims at clarifying the methodology for applying CFD in greenhouse ventilation problems.

Future developments of this method may analyse the distribution of humidity and CO₂ concentration by two-fluid, two-phase simulations. Moreover, the influence of radiometric properties of the cladding material on the energy balance of the greenhouse soil system may be investigated.

One must also keep in mind that the CFD results discussed in this paper concern empty greenhouses. Therefore, they offer only a rough picture of the ventilation flow in real greenhouses, where crops, internal structural elements and equipment may alter the internal air flow. Further investigation is required for obtaining a simplified but realistic representation of these blocking elements in CFD simulations.

REFERENCES

- [1] AWBI H.B., *Ventilation in Buildings*, E & FN Spon. Chapter 7 (1991).
- [2] BAKKER J.C., BOT G.P.A., CHALLA, H. and BRAAK N.J. VAN DE, *Greenhouse climate control: an integrated approach*, Wageningen Press, Wageningen, The Netherlands (1995).
- [3] BOT G.P.A., *Greenhouse climate: from physical process to a dynamic model*, Thesis Agric. University, Wageningen, The Netherlands (1983).
- [4] BOT G.P.A., BOULARD T., MISTRIOTIS A., PAPADAKIS G., PICUNO P. & SCARASCIA MUGNOZZA G., *New techniques in greenhouse ventilation analysis*, Proceedings of the International Conference on Agricultural Engineering AgEng 96, Madrid (Spain), 23-26 September 1996, Paper 96B-037: 392-393 (1996).
- [5] BOULARD T., MENESES J.F., MERMIER M. & PAPADAKIS G., *The mechanisms involved in the natural ventilation of greenhouses*, Agric. For. Meteorol. (1996), 79, 61-77.
- [6] BREUM N.O., TAKAI H., ROM H.B., *Upward vs. downward ventilation air flow in swine house*, Transactions of the ASAE (1990), 33, (5), 1693-1699.
- [7] DE JONG T., *Natural ventilation of large multi-span greenhouses*, Thesis Agric. University, Wageningen, The Netherlands (1990).
- [8] DE JONG T. & BOT G.P.A., *Air exchange caused by wind effects through (window) openings distributed evenly on a quasi-infinite surface*, Energy and buildings (1992), 19: 93-103.

- [9] DELTOUR J., WANG S.J., *Ventilation-induced interior air movement in large scale Venlo-type greenhouse*, Proceedings of the International Conference on Agricultural Engineering AgEng 98, Oslo (Norway), 24-27 August 1998: 43-44 (1998).
- [10] FERNANDEZ J.E. & BAILEY B.J., *Measurement and prediction of greenhouse ventilation rates*, Agric. For. Meteorol. (1992), 58: 229-245.
- [11] FEUILLOLEY P., MEKIKDJIAN C., LAGIER J. & YARD C., *Natural aeration of plastic tunnels in mediterranean area*, CEMAGREF internal report (1994).
- [12] MISTRIOTIS A., BOT G.P.A., PICUNO P. & SCARASCIA MUGNOZZA G., *Analysis of the efficiency of greenhouse ventilation using computational fluid dynamics*, Agric. For. Meteorol. (1997a), 85, 217-228.
- [13] MISTRIOTIS A., ARCIDIACONO C., PICUNO P., BOT G.P.A., & SCARASCIA MUGNOZZA G., *Computational analysis of ventilation in greenhouses at zero- and low-wind speed*, Agric. For. Meteorol. (1997b), 88, 121-135.
- [14] MISTRIOTIS A., PICUNO P., BOT G.P.A., & SCARASCIA MUGNOZZA G., *Computational study of the natural ventilation driven by buoyancy forces*, Proceedings of the 3rd IFAC workshop on: «Mathematical and control applications in Agriculture and Horticulture», Hannover (Germany), 28 September - 2 October 1997, 67-72 (1997c).
- [15] MISTRIOTIS A., DE JONG T., WAGEMANS M. and BOT G.P.A., *Computational Fluid Dynamics (CFD) as a tool for the analysis of ventilation and indoor microclimate in agricultural buildings*, Netherlands J. of Agricultural Science, 45, 81 (1997d).
- [16] PAPADAKIS G., MERMIER M., MENESES J.F. & BOULARD T., *Measurements and analysis of air exchange rates in a greenhouse with continuous roof and side openings*, J. Agric. Engng. Res. (1996), 63 (3): 219-228.
- [17] PICUNO P., *Greenhouse natural ventilation: airflow rate calculation and plant efficiency* (in italian), Colture Protette (1996), 25 (9): 127-133.
- [18] SASE S., TAKAKURA T. and NARA M., *Wind tunnel testing on airflow and temperature distribution of a naturally ventilated greenhouse*, Acta Hortic. (1984), 148, 329-336.
- [19] SCARASCIA MUGNOZZA G., *Sustainable greenhouse production in Mediterranean climate: a case study in Italy*, Medit (1995), 6, (4), 48-53.
- [20] SCARASCIA MUGNOZZA G. & PICUNO P., *The optimisation of greenhouse ventilation with numerical simulation for a sustainable agriculture* (in italian), Proceedings of the Congress of AIIA - Italian Association of Agricultural Engineering, Ancona (Italy), 10-12 September 1997, 95-105.

SUMMARY

Greenhouse cultivation are diffused in Mediterranean countries thanks to mild climatic conditions and high solar radiation, but protected crop production is actually limited by high temperatures that may be reached during summer or also in sunny days of the rest of the year. Moreover, excess in relative humidity, that may cause pathogen attacks, and diurnal reduction of CO₂ concentration often occur in Mediterranean plastic greenhouses.

Natural ventilation is the most easy and inexpensive way to regulate greenhouse internal microclimate, even if it offers a limited control over the air flow. In this paper natural ventilation process is studied by means of the analysis of the indoor temperature distribution for different geometrical configurations of the greenhouse ventilation openings.

A fluid dynamic numerical model was used in order to define design criteria for optimised natural ventilation systems of plastic greenhouses. A ventilation efficiency coefficient, taking into account the average temperature difference between inside and outside air and the distribution of temperature inside the greenhouse, has also been calculated and discussed.

Key words:

Natural ventilation, Greenhouse, CFD.

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