IFAC

International Federation of Automatic Control

MATHEMATICAL AND CONTROL APPLICATIONS IN AGRICULTURE AND HORTICULTURE

IFAC Workshop, Hannover, Germany,
28 September - 2 October 1997

Edited by

A. MUNACK and H.-J. TANTAU

PREPRINTS

PERGAMON

CONTENTS

GREENHOUSES I

GREENHOUSES II

POSTER SESSION 1

COMPUTATIONAL STUDY OF THE NATURAL VENTILATION DRIVEN BY BUOYANCY FORCES

A.Mistriotis (1), P. Picuno (2), G.P.A. Bot (3,4), G. Scarascia-Mugnozza (5)

(1) *Department of Agricultural Engineering, Agricultural University of Athens, Iera Odos 75, Athens 11855, Greece.*
(2) *Technical-economical Department, University of Basilicata, 85100 Potenza, Italy.*
(3) *Department of Agrophysics, IMAG-DLO, P.O. Box 43, Wageningen 6700 AA, The Netherlands.*
(4) *Department of Agricultural Engineering and Physics, Wageningen Agricultural University, Bomenweg 4, NL-6703 HD Wageningen, The Netherlands.*
(5) *Institute of Farm Building, University of Bari, 70126 Bari, Italy.*

Abstract: The ventilation behaviour of greenhouse structures when the wind speed is low and the "buoyancy effect" is the main driving force of the indoor air flow has been analysed with the use of Computational Fluid Dynamics. These numerical (CFD) simulations offer a detailed picture of the temperature spatial distribution and the air velocity field. These data can be used for analysing the contribution of every ventilator to the general ventilating performance of the greenhouse. As an example, the great importance of both roof and side ventilators for an efficient thermally driven ventilation was numerically demonstrated.

Keywords : agriculture, flow, simulation, model, wind

1. INTRODUCTION

Ventilation is one of the most important physical processes influencing the indoor greenhouse microclimate. An efficient ventilation performance is a crucial feature of a greenhouse in both northern humid winter climates and in Mediterranean hot summer conditions. Ventilation can be used for optimally controlling temperature, humidity and concentration of gases, such as CO_2 in the greenhouse (Bailey, 1988). In this way, the plant photosynthetic and transpiration activity is properly regulated, and the quality of crops improves.

Forced ventilation systems are not common in greenhouses. Therefore, natural ventilation is usually the only air renewal process in protected cultivation. Natural ventilation systems, however, offer a limited control over the air flow through the greenhouse. As a result, there are difficulties in controlling the indoor temperature, the relative humidity and the carbon dioxide concentration. Hence a deeper analysis of the mechanisms of natural ventilation is necessary in order to understand dependence of the ventilation rate on the greenhouse design and improve its ventilation efficiency.

Natural ventilation is driven by pressure differences created at ventilating openings either by the wind or by temperature differences. It has been experimentally shown that winds stronger than 2 m/s dominate the ventilation process (Bot 1983, Kittas *et al* 1996). In that case the influence of air temperature differences can be neglected. On the contrary, in case of a weak wind (v_w<0.5 m/s) the thermally driven ventilation is very important. The generation of air flow by temperature differences of air layers is described by the term "buoyancy effect" or "stack effect". In the intermediate case, where 0.5 m/s <v_w< 2 m/s, the ventilation is mostly driven by the wind but some influence of the buoyancy effect can be also observed.

In many regions with intense greenhouse cultivation, weak wind situations coincide with high temperatures, when high ventilation efficiency is mostly required. Therefore, the investigation of the structural characteristics of greenhouses influencing the ventilation process at low wind speeds can offer hints for improvements of the greenhouse design towards a more efficient thermally driven ventilation.

Computational Fluid Dynamics (CFD) simulations are a powerful tool for analysing separating and circulating flows as those appearing during ventilation. In particular, CFD has already been used for predicting both wind-driven and buoyancy driven ventilation in greenhouses with success (Mistriotis *et al* 1996, 1997).

The thermally driven ventilation in greenhouses has been poorly studied so far. Few laboratory measurements performed on scale models (Sase *et al* 1984) are available. Moreover, the location and the intensity of sensible heat sources in a greenhouse has not been clearly enough determined. Therefore, an accurate definition of the heat sources in a numerical model is not possible. However the present numerical results based on rough estimations of the heat sources in greenhouses will stimulate and guide future experimental works for further investigating the indoor greenhouse microclimate.

2. THE NUMERICAL METHOD

Numerical techniques known as Computational Fluid Dynamics (CFD), are necessary for solving the set of partial differential equations (conservation equations) describing the flow. The most common numerical method in Fluid Dynamics is the finite-volume method. The solution is obtained by discretising space and time (for transient cases), and solving the transport equations on a grid. The flow is calculated in a finite domain which is spanned by the grid. The influence of external factors such as the wind, the solar radiation, etc., on the flow is simulated by boundary conditions.

Nevertheless, turbulent flows, where dynamics takes place in a scale smaller than the grid, can not be solved with the above numerical method. For this reason, turbulence models were introduced to avoid the complexity of turbulent dynamics. During the recent years, the most popular turbulence model is the k–ε model (e.g. Awbi 1991). In this model, turbulence is expressed in terms of two phenomenological variables, the turbulence kinetic energy k, and its dissipation rate ε, which are calculated by solving two extra conservation equations.

The k–ε model or his modifications such as the Chen and Kim (CK) model or the Renormalization Group (RNG) model have been applied to numerous indoor air flow problems with good predictive accuracy (e.g. Awbi 1991). Recent results specifically show that the CK and the RNG models are quite successful in simulating ventilation flows in greenhouses (Mistriotis *et al* 1996, 1997).

3. SOURCES OF SENSIBLE HEAT IN AN UNHEATED GREENHOUSE

The realistic definition of the heat sources and the other boundary conditions is crucial for successfully modelling a Fluid Dynamics problem by CFD. In the case of thermally driven ventilation in a greenhouse, the air flow depends on the spatial distribution of sensible heat sources and their intensity. Therefore accurate numerical modelling of the ventilation process requires a systematic analysis of the heat generation in the greenhouse.

A typical case where ventilation due to the buoyancy effect is important is a situation of relatively high outdoor temperature combined with high solar radiation and low wind speed. Under these conditions, no heating system is in operation. Therefore the sensible heat released in the greenhouse is induced by the absorbed solar radiation. The greenhouse cover, the structural elements, the soil and the crop contribute to the solar radiation absorption and consequently to the generation of sensible or latent heat.

Following the usual modelling technique found in the literature, we consider a one-dimensional model greenhouse divided into four layers: a) the cover, b) the area between the canopy and the cover, c) the canopy and d) the soil.

The cover protects the indoor greenhouse environment from the external weather conditions. Usually it has a very high solar radiation transmittance since light is necessary for photosynthesis. The total solar radiation transmittance of a greenhouse varies between 80% for a glasshouse (Bot 1983, De Zwart 1993) and 65% for a plastic house (Papadakis *et al* 1989)

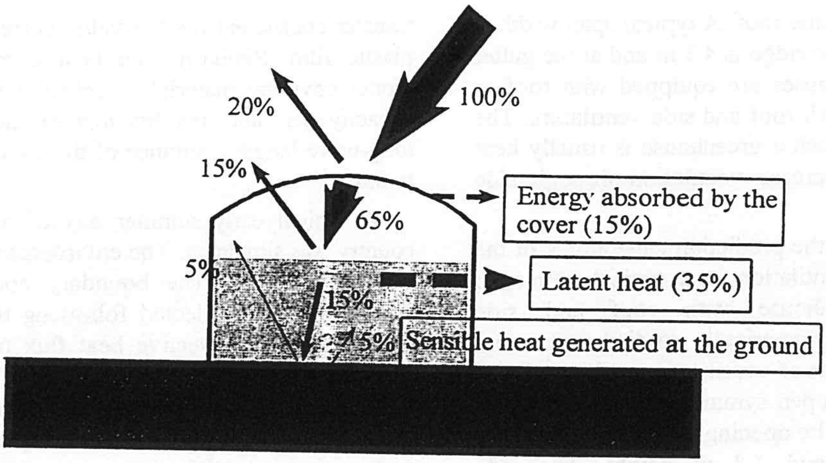

Fig 1: Rough estimation of the solar radiation transmittance of the greenhouse layers and the spatial distribution of heat sources in a typical plastic covered greenhouse. The plants are considered as a uniform partially opaque material.

The above data allow us to estimate the solar radiation absorbed by the cover including the glazing bars and other supporting structural elements. Typical values of the cover reflectance ranges between 20 and 25%. Therefore, one can conclude that 10 to 15% of the incoming radiation is absorbed by the cover. Such high values of reflectance and absorptance are expected particularly for dirty and altered plastic cover which exhibit low solar radiation transmittance. Therefore, in the case of a bright sunny summer day in Mediterranean countries, when the maximum solar irradiance is 900-1000 W/m^2, the corresponding energy absorbed by a plastic greenhouse cover ranges between 100 and 150 W/m^2.

A part of the absorbed energy is radiated away as thermal radiation. The long-wave-length emittance of the agricultural plastics varies depending on the material (from 0.6-0.7 for EVA or PE-IR to 0.2-0.4 for the ordinary LDPE). The sensible heat released at the greenhouse cover can be estimated by subtracting the emitted thermal radiation from the absorbed energy.

Inside a greenhouse, the lower structural elements, the equipment and the plants intercept a part of the solar radiation transmitted by the cover before it reaches the ground. In particular, the crop intercepts a large percentage of the incoming solar radiation. Most of the absorbed solar energy is transformed into latent heat by transpiration since the plants try to maintain a constant moderate temperature inside the canopy. Another smaller part of the absorbed radiation (1-2%) is used by the plants for their photosynthetic activity. The intensity of the transpiration process depends on the incoming irradiance, the temperature at the crop layer, the indoor humidity and the type of the plants (Stanghellini 1987).

The temperature difference between the leaves and the surrounding air has been determined experimentally under a variety of external conditions (Stanghellini 1987, Papadakis *et al* 1994). These measurements indicate that the temperature difference is small, its absolute value not exceeding 2.5 degrees K. It can be positive or negative depending on radiation, temperature and humidity conditions. Negative temperature differences correspond to absorption of sensible heat by the plants. The range of sensible heat generated in the canopy due to the temperature difference between the leaves and the air is estimated between 45 and -45 Wm^{-2}.

A part of the incoming radiation at the crop layer is transmitted to the ground. The short-wave-length transmittance of the canopy is approximately 25% depending on the density and the type of the canopy. Hence, in the case of a summer sunny day in Mediterranean countries (irradiance 900 W/m^2), approximately 150 W/m^2 reach the ground assuming a cover light transmittance equal to 65%. A part of this energy is reflected and another part is stored in the soil.

The greenhouse ground during a sunny day has been measured to be 4 to 5 degrees hotter than the air (Fichera *et al* 1996). Such temperature differences correspond to a maximum convective energy flux from the ground to the air equal to 85 W/m^2. Other experimental results giving 40 W/m^2 as a typical value for the sensible heat generated at the ground (Papadakis *et al* 1989) support this estimate.

4. CFD SIMULATION OF THE VENTILATION FLOW IN A MEDITERRANEAN-TYPE GREENHOUSE AT ZERO WIND SPEED.

A plastic film covered greenhouse commonly used in the Southern European countries is the multi-span structure with arch-shape roof. 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 equipped with roof or side ventilators, or both roof and side ventilators. The number of spans in such a greenhouse is usually kept small in order to increase ventilation through side openings.

As an example of the prediction capabilities of the CFD method, the ventilation in a typical twin-span Mediterranean greenhouse with roof and side ventilators has been numerically studied at a wind speed of 0 m/s. The roof ventilators are located just above the gutter and open symmetrically with respect to the middle gutter. The opening part of the side walls is between 0.3 m and 1.3 m height. The side ventilators open by pivoting around their upper edge.

The cover is simulated by a material equivalent to a PE film 0.2 mm thick. Since the thickness of the cover in the numerical model is much larger than that of the plastic film due to the coarse grid used for the computation, the coefficient of thermal conductivity of the model material was selected so that the heat transfer coefficient fits the value corresponding to the plastic film. Similarly, the heat capacitance of the model covering material is selected so that its heat capacity per unit area fits that of the PE film. The long-wave-length emittance of the cover is taken equal to 0.5.

A typical early summer day of a Mediterranean country was simulated. The environmental temperature was set to 25°C. The boundary conditions of the simulations were selected following the argument of section 3. The convective heat flux transferred from the greenhouse ground to the air is 100 W/m^2, while the solar radiation absorbed by the cover was set equal to 150 W/m^2. The influence of the plants as a source or a sink of sensible heat was neglected, but the reduction of solar irradiance reaching the ground due to shadowing by the leaves was taken into account. In other words we assume that approximately all the solar radiation absorbed by the plants is either used for photosynthesis or is transformed into latent heat.

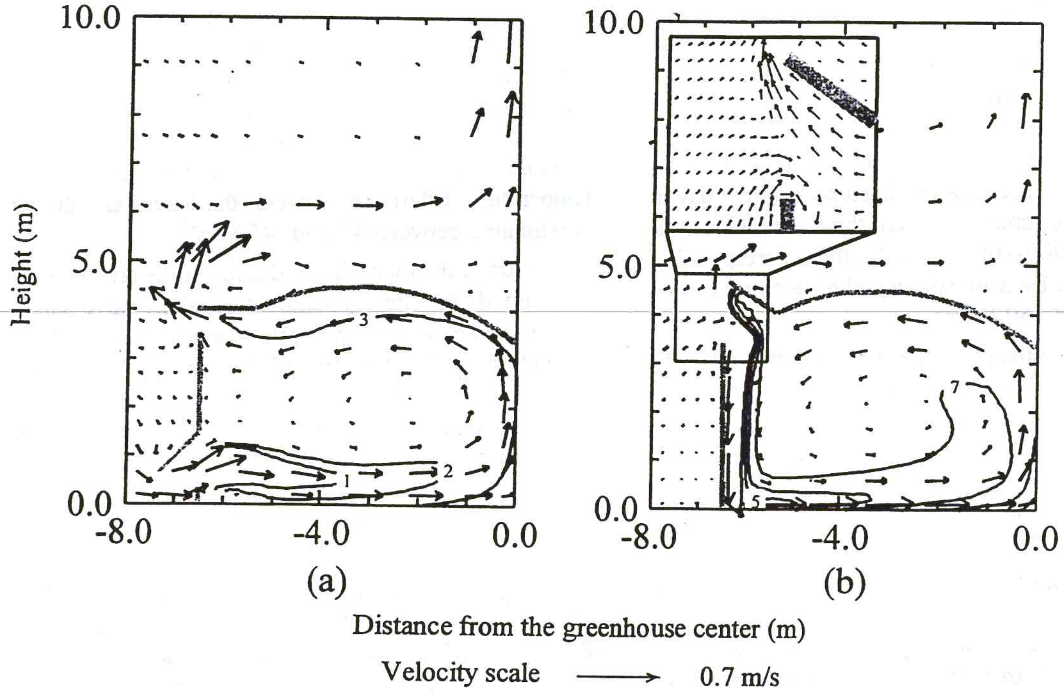

Fig 2: Ventilation flows in a twin-span Mediterranean type greenhouse with roof and side ventilators at zero wind speed: a) when both side and roof ventilators are open; b) when only roof ventilators are open. The solar energy absorbed by the cover is 150 W/m^2 and sensible heat generated at the ground is 100 W/m^2. The contours show temperature differences to the environment.

The effective sky temperature was set equal to 11.5 °C. Thermal radiation exchange was assumed between the cover and the sky. No thermal radiation exchange was considered between the cover and the ground since the temperature of the ground is expected to be considerably higher than that of the sky. The convective flow was calculated simultaneously with the thermal radiation exchange. The blocking effect due to the plants has been neglected. The air is assumed to be an ideal gas. The flow is considered symmetric with the respect to the middle of the greenhouse due to the symmetry of the structure.

Figure 2 shows the differences with respect to temperature distribution and flow characteristics between a situation where both side and roof ventilators are open (a) and the case where only roof ventilators are open (b), while the total opening area remains approximately the same. In the case (a), cool air enters through the side openings and pushes the indoor hot air through the roof ventilator. In case (b), the cool external air enters the greenhouse through the lower part of the roof window, drops fast along the side walls and after following a circulating path exits through the upper half of the roof window.

In the second case, the ventilation is clearly less efficient and results in more than 4 degrees higher temperature at the layer of the greenhouse used for cultivation (ground to 2.5 m height). This example CFD simulation demonstrates the need for side and roof ventilators in climates where high ventilation rates are required.

5. CONCLUSIONS

The ventilation behaviour of greenhouse structures when air temperature differences constitute the main driving force of the flow ("buoyancy effect") has been analysed with the use of Computational Fluid Dynamics.

The accurate experimental investigation of the buoyancy effect in greenhouses is a complicated task. The small air velocities induced by the buoyancy effect and the turbulent character of the corresponding convective flow make difficult accurate measurements in full scale experiments. However, laboratory experiments on model scaled structures such as the measurements of Sase *et al* (1984) can provide valuable information about the thermally driven ventilation performance of greenhouses.

Numerical (CFD) simulations are complementary to these experiments and offer a detailed picture of the temperature spatial distribution and the air flow field. These data can be used for analysing the contribution of every ventilator to the general ventilating performance of the greenhouse. As an example, in the present work, the great importance of both roof and side ventilators for an efficient thermally driven ventilation was demonstrated by the numerical simulations. The above results can provide useful hints to designers of greenhouse frames or greenhouse control systems.

Nevertheless, one must keep in mind that both the CFD results and the laboratory experiments concern empty greenhouses. Therefore, they offer only a rough picture of the ventilation flow in real greenhouses, where the plants and the internal structural elements alter the internal air flow. Further investigation is required for obtaining a simplified but realistic representation of these blocking elements in CFD simulations.

ACKNOWLEDGMENTS

The present work is partially supported by the EU Human Capital and Mobility Program (Contract ERBCHRXCT930384). One of the authors, A. Mistriotis is fully supported by the EU-TMR Individual Fellowship Program (Contract ERBFMBICT960972).

REFERENCES

Awbi H.B. (1991). *Ventilation in Buildings*. E & FN Spon, London, G. Britain. Chapter 7.

Bailey B.J. (1988). Principles of environmental control. in "*Energy conservation and renewable energies for greenhouse heating*" edited by C. von Zabeltitz, FAO/CNRE, Rome, Italy.

Bot G.P.A. (1983). *Greenhouse climate: from physical processes to a dynamic model.* Doctoral Thesis, Agricultural University of Wageningen, Wageningen, The Netherlands.

De Zwart H.F. (1993). Determination of direct transmission of a multispan greenhouse using vector algebra. *J Agric Engng Res.*, **56**, 39-49.

Fichera C.R., Cascone G., Arcidiacono C., (1996). Studio del regime del terreno sotto serra. Parte prima: Analisi dei rilievi sperimentali. Submitted to the *Journal Ingegneria Agraria* (in Italian).

Kittas C., Boulard T., Mermier M., and Papadakis G., (1996). Wind induced air exchange rates in a greenhouse tunnel with continuous side openings. *J. Agric. Engng Res.* **65**, 37-49.

Mistriotis A., Bot G.P.A., Picuno P., Scarascia-Mugnozza G., (1996). Analysis of the efficiency of greenhouse ventilation using computational fluid dynamics. To be published in *J of Agric. and Forest Meteorology.*

Mistriotis A., Arcidiacono C., Picuno P., Bot G.P.A., Scarascia-Mugnozza G., (1997). Computational analysis of ventilation in greenhouses at zero and low wind speeds. To be published in *J of Agric. and Forest Meteorology.*

Papadakis G., Frangoudakis A. and Kyritsis S. (1989). Soil energy balance analysis of a solar greenhouse. *J of Agric. Eng. Res.*, 43, 231-243.

Papadakis G., Frangoudakis A. and Kyritsis S. (1994). Experimental investigation and modeling of heat and mass transfer between a tomato crop and the greenhouse environment. *J of Agric. Eng. Res.*, **57**, 217-227.

Sase S., Takakura T. and Nara M. (1984). Wind tunnel testing on airflow and temperature distribution of a naturally ventilated greenhouse. *Acta Hortic.* **148**, 329.

Stanghellini C. (1987). *Transpiration of greenhouse crops: an aid to climate management.* Doctoral Thesis, Agricultural University of Wageningen, Wageningen, the Netherlands.