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WIND-CAUSED AIR TRANSPORT THROUGH GREENHOUSE SCREENS: A PHYSICAL MODELLING APPROACH

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Abstract. An understanding of the air exchange through screens is needed to optimise climate control strategies in greenhouses. An analysis of the airflow through porous screens due to wind pressure was performed, based on physical concepts and experiments. Firstly, a theoretical approach was presented describing the air exchange through porous screens. The mean and the root mean square wind velocity were proposed to model the wind pressure. Secondly, an experimental study was carried out in a screened greenhouse located in a windy field. The results of these measurements are in agreement with the predictions based on the given theoretical model.

Keywords: air exchange, porous screen, greenhouse, wind pressure, physical model

INTRODUCTION

Protected horticulture is an important contribution to the economy of several countries around the world. In the Netherlands [4], it represents a value of about 6.6% of total exportation (10^{10} US dollar per year) and about 70% of the total greenhouse area is equipped with screens.

There are three reasons for the use of screens in greenhouses:

- to reduce solar radiation in the greenhouse [6,9] and to prevent water stress, heat stress and quality reduction (shading screen);
- to reduce energy loss in the greenhouse [1,9] (thermal screen);
- to prevent the entrance the birds and insect in the greenhouse [5] (insect screen).

Traditionally, shading and thermal screens are used between the crop and the greenhouse roof, while insect screens are used to cover the greenhouse window openings. The characteristics of the screen depend on its purpose.

The use of screens has a considerable effect on the greenhouse climate. Several research projects were dedicated to the study of the effect of screens on convective heat transfer, solar radiation and thermal radiation [1,3,4,6,9]. The air movement through and around the screen is the less understood aspect of environmental design being usually described by empirical equations [5].

The aim of this study was to investigate the airflow transport through porous screens (shading, thermal and insect screens), by means of a physical model, and to validate this against measurements obtained in a full-scale greenhouse.

THEORY

The motion equation which describes the air exchange through a permeable material can be expressed as [2,8]:

$$(\rho/\varepsilon)\partial\vec{u}/\partial t+\left[\rho\left(Y/K^{1/2}\right)|\vec{u}|+(\mu/K)\right]\vec{u}+$$

$$\left(\rho/\varepsilon^{2}\right)\vec{u}\nabla\vec{u}=-\nabla p \qquad (1)$$

with

$$Y=4.36\ 10^{-2}\,\varepsilon^{-2.12}$$

where $\vec{u}$ is the air fluid velocity (ms^{-1}), ρ the air density (kg m^{-3}), μ the dynamic air viscosity (Pa s), Y the inertia factor (-), p the pressure (Pa) and t the time (s). The parameter ε (m^3m^{-3}) is the porosity and represents the volume fraction of fluid contained within the total volume of the medium, while parameter K(m^2) is the permeability of the medium, representing the ability of the medium to transmit the fluid through itself. The permeability is determined using the Darcy Law [2] and experimental data, obtained by means of forcing air through the material and measuring the pressure drop.

The physical significance of the terms of Eq. (1) is:

- the local acceleration of the fluid flow at fixed point (first left-hand side term);
- inertia and viscous deceleration of fluid on the pores (second left-hand side term);
- convective acceleration of fluid flow (third left-hand side term);
- pressure acceleration (right-hand side terms).

According to Bear and Bachmat [2], the flow can be considered incompressible for porous screen (∇u=0). Then the third left-hand term side of Eq. (1) can be discarded. For a unidimensional flow, Eq. (1) becomes:

$$(\rho/\varepsilon)\,du/dt+\rho\left(Y/K^{1/2}\right)|u|+$$

$$(\mu/K)\,u=-\Delta p/H \qquad (2)$$

where H is the characteristic depth of porous screen.

Since porous screens are always made of very thin materials, their porosity can be given by:

$$\varepsilon=A_a/A \qquad (3)$$

where A_a represents the area of space filled with air and A the area occupied by the solid matrix and the air.

The driving force which induces the airflow can be caused by temperature differences or wind. If the driving force is the wind velocity, the instantaneous value at time t can be written as the sum of a mean component and a fluctuating component (turbulence). The wind pressure p_w can be related to the wind velocity [3] by:

$$p_w=0.5\rho\left(\bar{u}_w^{2}+u_w'^{2}\right) \qquad (4)$$

where $\bar{u}_w$ is the mean wind velocity, u'_w the fluctuations in wind velocity [3] and ρ the air density.

As a large number of anemometers give direct readings of the mean velocity and the root mean square of the velocity, it is easier to have p_w as a function of these two quantities. Assuming u'_w to have a Gaussian probability distribution:

$$u_w'^{2}=2\pi^{-1}\,u_{rmsw}^{2} \qquad (5)$$

the wind pressure can be rewritten as:

$$p_w=0.5\rho\,\bar{u}_w^{2}+\rho\,\pi^{-1}\,u_{rmsw}^{2} \qquad (6)$$

where u_{rmsw} is the root mean square wind velocity [2,3].

EXPERIMENTAL STUDY

In an attempt to give experimental support to the model presented, a study was carried out in a twin-span glasshouse oriented E-W, with a window open in the windward side (Fig. 1). The greenhouse dimensions were: eaves height 4.5 m, roof angle 22°, width 4.1 m and length 6.6 m. The inside of the greenhouse was kept without any crop and hermetically sealed, except for the roof, where the window opening was located.

Two cases were considered: firstly a horizontal thermal screen was placed inside the greenhouse at 1 m from the roof; secondly an

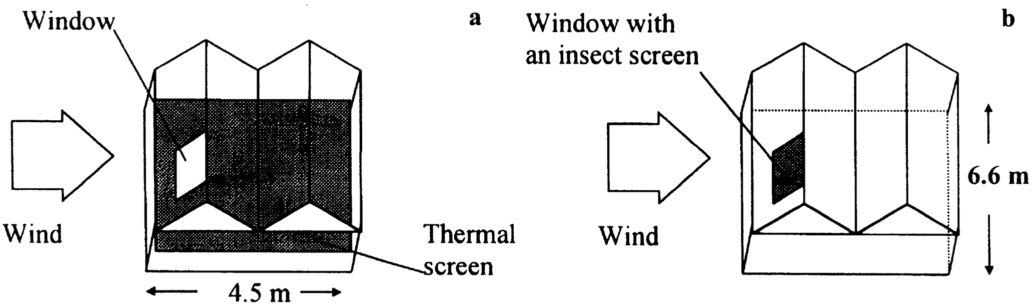

Fig. 1. Schematic representation of a glasshouse used in the experimental study: a) glasshouse with a horizontal thermal screen, b) glasshouse with an insect screen.

insect screen was placed in the greenhouse window (opened in the windward side). The greenhouse screen samples used in this experiment were: insect screen trade name "ECONET" (ε=0.34, K=6.59 10^{-9}m^2) [7] and thermal/shading screen trade name "EH/P" (ε=0.09, K=9.08 10^{-11} m^2) [7].

The wind velocity was measured outside of the glasshouse (at a distance of 0.20 m from the greenhouse window opening and 0.25 m above the greenhouse gutter), using hot-wire anemometers (response time of 9.5 Hz). The pressure inside the greenhouse was measured using membrane pressure transducers, distributed uniformly in different points of the greenhouse (Fig. 2). A computer with a DAS1600 board (maximum sampling frequency 1000 Hz) controlled these measurements.

Ten copper-constantan thermocouples were installed for measuring the temperature of the air within the greenhouse and the temperature of the outside air.

The airflow through the screens was measured by injecting a tracer gas (N_2O) inside the greenhouse and then measuring the rate of decay of the gas concentration (tracer gas decay rate method [3]). The airflow rate was assumed to be proportional to the rate of the loss of N_2O, being expressed by:

$$\eta = -V\, dc/dt \tag{7}$$

where η is the airflow rate (m^{3}s^{-1}), V the volume of greenhouse (m^3), c the concentration of N_2O (mg/kg) at any instant within the greenhouse, and t the time (s).

The tracer gas decay rate method is based on the principle that within the greenhouse there is a perfect mixing of the air. To prevent an imperfect mixing, a small fan was placed near the greenhouse ground and the air was sampled at 10 different locations inside the glasshouse. The N_2O concentration was measured by means of an infrared gas analyzer.

The airflow through the screens was measured as function of the wind velocity. To prevent the influence of stack pressure, the measurements were performed with a temperature

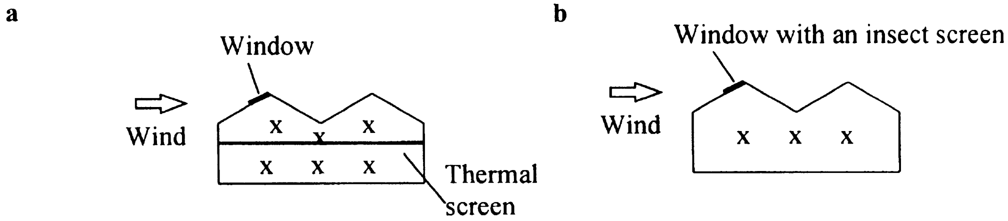

Fig. 2. Schematic representation of the distribution of pressure probes (x) in the glasshouse: a) glasshouse with a horizontal thermal screen, b) glasshouse with an insect screen.

(difference between the inside and the outside of the greenhouse) of less than 2 °C, and a wind velocity higher than 0.5 ms^{-1}.

RESULTS AND DISCUSSION

The wind pressure was determined from the wind velocity measurements, using Eqs (4) and (6). To allow for comparison between both predictions, the result is shown in Fig. 3. Over the range of predicted wind pressures (0.01 to 16 Pa), there is a good agreement between both equations. In general, differences between them were less than 4%.

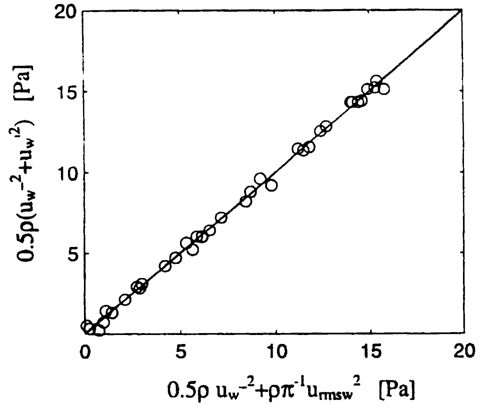

Fig. 3. Wind pressure predicted with Eq. (4) versus the wind pressure predicted with Eq. (6).

The measured value (using the tracer gas decay rate method) and predicted value (Eq. (2)) of air velocity through screens caused by wind were plotted as shown in Figs 4 and 5. Figure 4 shows the air velocity through a thermal screen (trade name "EH/P") versus the wind pressure. Figure 5 shows the air velocity through an insect screen (trade name "ECONET") versus the wind pressure.

In both Figs 4 and 5, measured and predicted values were in good agreement. The scatter occurring in the experimental data is due to the tracer gas technique used to measure the airflow. In spite of using a small fan near the greenhouse ground, to maintain an uniform N_2O concentration (basic for the tracer gas method), the N_2O is not always perfectly mixed with air within the glasshouse, and small gradients of N_2O concentration occur which, contributing to the scatter in the experimental data.

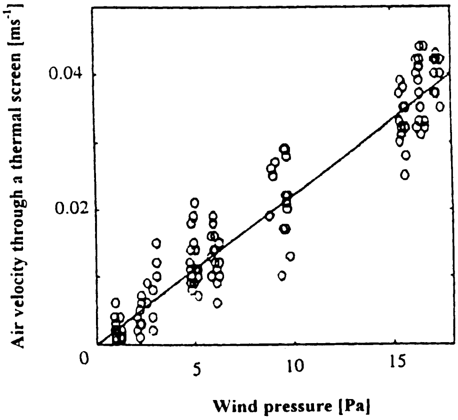

Fig. 4. Air velocity through a thermal/shading screen (trade name "EH/P") versus the wind pressure (o - measured data, solid line - data predicted with Eq. (2)).

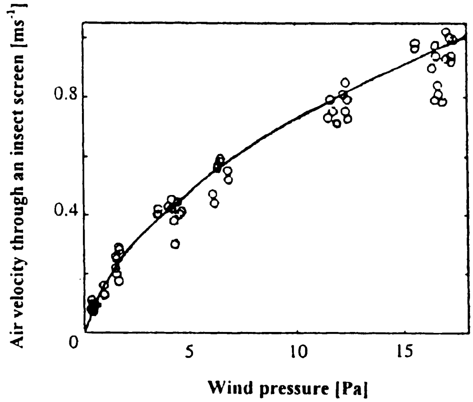

Fig. 5. Air velocity through an insect screen (trade name "ECONET") versus the wind pressure (o - measured data, solid line - data predicted with Eq. (2)).

CONCLUSION

The approach presented in this paper is simple in form, enabling the prediction of wind-caused airflow through porous screens. The results obtained through the theoretical approach agree well with experimental values.

Since screens are used, the present approach can be widely employed. Particularly, this description can be a useful tool in increasing a more sustainable use of greenhouse screens.

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