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Numerical study of wind-driven natural ventilation in a greenhouse with screens

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ABSTRACT

This paper is devoted to the CFD study of wind-driven ventilation in a greenhouse, with particular focus to the effect of screens on the inner airflow distribution. Although the use of shading screens to cover agricultural crops has been constantly increased to reduce high radiation loads, their effect on airflow distribution within the greenhouse is still not fully understood. In this paper, CFD simulations of the ventilation in a greenhouse with and without screens are performed, by means of a finite volume CFD code (Ansys-Fluent 17.2), with a standard k-ε turbulence model, together with proper user defined functions (UDF) for the inlet velocity and turbulent profiles. The screens have been modeled as porous surfaces and the porosity and the permeability have been obtained experimentally and set into the model. The code has been validated by a comparison with velocity measurements performed in a greenhouse owned by the University of Bologna. Comparisons between the airflow velocity patterns obtained within the greenhouse with screens and without screens have been obtained for different external airflow velocities. The cases with screens show a more uniform distribution of velocity field inside the greenhouse than the cases without screens, especially near the crops. All the cases show that screens strongly affect the airflow velocity distribution inside the greenhouse and the distribution of volume flow rates through the vents. This work shows how the characteristics of the screens and their positioning near the vents are critical for the ventilation within a greenhouse.

1. Introduction

The management of microclimate variables in a greenhouse is one of the most important tasks to maximize quantity and quality of crops production. Generally, temperature is the most important parameter considered and its optimal range has been evaluated to be between 17 °C and 27 °C for most plants (Fidaros et al., 2010; Bartzanas et al., 2004). A key role in modifying climate inside greenhouses is played by ventilation, which can be used to control all the important parameters involved, as temperature, humidity, oxygen concentration (Bartzanas et al., 2004). A non-uniform distribution of these variables inside the greenhouse can lower the growth of the plants and can give issues with pests and diseases (Piscia et al., 2012). The ventilation can be obtained by means of forced airflow inlet systems or by proper vents in the building walls, to achieve natural aeration. From a constructive point of view, the efficiency of natural ventilation depends on the disposition of vents and on their opening timing during the day. Such action, however, should be designed in an optimal way: for example, Bartzanas et al. (2004) underlined that the optimal timing could be effective in reducing the indoor temperatures and the type of opening (roll up or side opening) could directly affect the airflow. Boulard et al. (2002) studied airflow distribution obtained by side openings, roof vents, or both, in Mediterranean climate. In this regard, the natural airflow is a key factor which directly affects the transport of heat and mass between the inside and the outside environment (Rico-Garcia et al., 2011; Teitel et al., 2008). In fact, the goals of a ventilation system are to eliminate the excess of heat, besides to assure the exchange of CO_2 and O_2, necessary for crop efficiency and to establish acceptable levels of humidity and temperature (Fidaros et al., 2010; Teitel and Wenger, 2014). In most cases, aeration management is diversified upon the seasonal basis: in winter, it permits to eliminate the excess of humidity and to obtain appropriate climatic conditions for the plant growth, while in summer it is needed also to cool the air inside (Bournet and Boulard, 2010). Frequently, the ventilation in summer is not enough for cooling the greenhouse, so that other helpful systems are added, e.g. cooling panels, which are quite common because they are an economical solution, or

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other more powerful and costly devices (Norton, 2013). As delineated above, ventilation plays an important role in the control of climate inside a greenhouse for crop production at every step of the process, but it is strongly dependent on outside conditions, which are not easy to predict, due to the numbers of parameters involved and their mutual influences. Focusing on summer season, the most used technique to lower temperature and protect the crops is the use of shading screens. These devices are special tissues made with a weave of plastic fibers, located with different shade strategies (He et al., 2014). On one side these screens protect from the sun-radiation, on the other side they can act as an obstacle to the inlet of air from the vents (Montero et al., 2013). Many numerical studies of ventilation inside a greenhouse are available in the literature, but most of them do not consider the effect of the screens. Bournet and Boulard (2010) gave an extensive review of experimental and numerical studies on the ventilation processes inside the greenhouses. They showed the differences between natural ventilation induced by buoyancy forces and wind-driven ventilation inside the greenhouse and the influence of the geometry of the greenhouse on the ventilation process. Teitel and Wenger (2014) studied the effect of cross-openings in monospan greenhouses and they examined the effect of wind velocity on the air exchange and ventilation efficiency inside the greenhouse. Mistriotis et al. (1997) compared no-wind and low-wind-speed conditions on natural ventilation processes inside greenhouses by means of CFD, focusing on the importance of side-wall vents. Molina-Aiz et al. (2004) showed the differences between Finite Element Methods (FEM) and Finite Volume Methods (FVM) in the airflow in naturally ventilated greenhouses. They found that both methods give results in a good agreement with experiments, but FEM require much more computing time per cell and more memory storage than FVM. Only recently, He et al. (2014) and Montero et al. (2013) investigated the influence of horizontal shading screens on the temperature and airflow patterns, using 2D models. The numerical study of the effects of shading screens within a 3D model of a greenhouse involves the challenge of studying a complex geometry and to determine the fluid-dynamics properties of the screen, such as porosity and pressure-drop across the screen. In fact, in a natural ventilation configuration, the global air-dynamics within the greenhouse may change drastically if screens are set in proximity of vents, depending on their horizontal or vertical arrangement inside the structure (Kittas et al., 2002; Teitel, 2001). Therefore, the scientific literature points out the importance of further improving management and design criteria to optimize natural ventilation in greenhouses also through in-depth analyses of the effects of shading screens. In fact, they are widespread in greenhouses and have important functions for the control of indoor temperature, but at the same time they remarkably affect natural ventilation airflows. The aim of this work is to numerically investigate the effects of sun-shading screens on the ventilation processes within greenhouses adopting a 3D modeling approach. A specific aim is also to measure mechanical properties related to fluid-dynamics of a typical screen solution used in greenhouses.

2. Description of the methodology

The research has been developed through experimental trials and numerical models carried out over a case study. It consists in a three spans greenhouse of the Department of Agricultural Sciences of the University of Bologna, Italy (44.337340°N latitude, 11.718647°E longitude and 72 m altitude, about 30 km east of Bologna). The plant of the greenhouse is shown in Fig. 1. We set the axes of the Cartesian coordinate system parallel to the sides of the greenhouse plant. Three access doors are located on the NE wall of the building. The greenhouse covers an area of 304.8 m^2 and each span is 8 m wide, 12.7 m long, and 4 m high at eave, with 5.5 m maximum height (pitch slope is 40%). The pavement is in concrete, the structure in steel with a cover of 4 mm tempered glass. In each span, there are two roof vents (B) and (C) with opening angle of 25° and length of 1.5 m. Besides, there are two lateral openings (A), of the same size, on the SE and NW walls. These vents are continuous for all the length of the greenhouse. The area of each vent is 8.05 m^2, for a global opened area of 24.15 m^2. The dimensions of the vents, related to the ones of the structure, are important for an optimal design of a greenhouse. For mild climates, a significant parameter is the ratio between the openings area and greenhouse floor area, which, from literature, should be recommended between 0.18 and 0.29 but from experiences the ratio suggested is 0.18–0.25 (von Zabeltitz, 2011). In this case, the ratio is equal to 0.21 for the global structure and 0.21 for the studied span, both within the more restrictive range for a sufficient ventilation in a greenhouse.

The spans are indoor areas separated by glass walls and connected through internal doors. The investigations have been focused on the SE span, highlighted in Fig. 1. This span, the first shown by Fig. 2, is provided with three benches with an aluminum structure. This area is arranged to experimental and educational activities related to propagation, protection, nutrition, and programming of phenological phases of potted and soil less ornamental plants. Furthermore, it is applied to directly investigate the microclimate management in a protected environment, to test the interactions between climate parameters and plants growth and for the validation of CFD models (Benni et al., 2016; Benni et al., 2017). In fact, the equipment allows regulating independently the indoor conditions of the spans by means of a computer, which controls heating and cooling systems, vent opening, and shading curtains. As introduced before, this study focuses on a case of wind-driven natural ventilation, *i.e.* an internal ventilation induced by the external wind entering from the openings. Indoor temperature and relative humidity are monitored in each span with 10 min acquisition time; outdoor meteorological data of illuminance, temperature, wind speed and direction are collected with the same frequency. Data of wind direction, related to a period of 2 months (May and June), have been observed in order to evaluate the probability of SE wind, in specific $270^{\circ} \pm 30^{\circ}$ direction. It has been noticed that the wind was coming from SE for more than 50% of the data recorded. Moreover, the data recorded during the measurements campaign showed an 84% of wind direction values in the desired range, during the time of measurements, and a 52% during the entire day.

2.1. Computational model

The numerical simulations have been carried out by means of the Ansys-Fluent 17.2 code. The computational domain is a parallelepiped with dimensions 72 m by 50.7 m in the horizontal plane and 22 m in the vertical direction. The greenhouse numerical domain is adherent to the real geometry, in which there is a separation wall, dividing the spans in two, called front and back, as shown in Fig. 1.

The benches located in the first span in the cultivation zone have been modeled as parallelepipeds, with a distance of 1 m from the back wall, 1.49 m from the separation wall, at a high of 0.65 m. The greenhouse has been modeled as an empty building, in order to obtain results independently from the quantity or type of plants inside the structure, and on their arrangement. The benches have been modeled as obstacles for the fluid flow with the shape of parallelepipeds.

A neutral atmospheric boundary layer, with the following velocity profile has been set:

$$u(z) = \frac{u^{\star}}{\kappa} \log \frac{z + z_0}{z_0} \tag{1}$$

where $u(z)$ is the average wind speed at the height z above the ground, z_0 is the surface roughness, u_* is the friction velocity and κ (0.40) is the von Karman's constant. *Symmetry* boundary conditions have been considered on the top and lateral sides of the computational domain, to enforce a parallel flow. A the boundary downwind of the greenhouse, where the fluid leaves the computational domain, an *outflow* boundary condition has been used, to force all derivatives of the flow variables to vanish, corresponding to a fully developed flow (Gromke et al., 2008).