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Research Paper

Airflow characteristics and patterns in screenhouses covered with fine-mesh screens with either roof or roof and side ventilation

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In many countries fine mesh screens are used to protect agricultural crops. The low porosity of such screens impedes the exchange of mass, heat and momentum between the air around the crop and that occur in the atmosphere, thereby modifying the crop microclimate. Experiments were carried out aimed at determining the internal airflow characteristics and patterns of screenhouses. The results showed that screenhouses reduced air velocity compared to that in an open field. For a given windspeed the air velocity inside the screenhouse increased with height. The internal air velocity increased with external windspeed but it increased to a greater extent near to the roof. Flow patterns and characteristics were affected by whether the screenhouse was ventilated only via the roof or via the roof and sidewalls. When the screenhouse was ventilated from the roof and side panels the air velocity was higher than under roof ventilation alone, and the airflow direction, both within the canopy and above it, was usually in a similar direction to that of the outside wind. However, under roof ventilation alone the internal airflow direction was generally opposite to that of the external wind, resulting in outflow through the windward section of the roof and inflow through the leeward section. In the central region of the screenhouse the mean vertical velocity within the canopy was near zero and its fluctuations with time were relatively small. Near the roof, there was a mean net inflow and the velocity fluctuations were much larger.

1. Introduction

1.1. Use of screenhouses in agriculture

Since the beginning of this century screenhouses have become an important component of protected cultivation in mild climates. Depending on the screen material and its properties, screenhouses are used to fill various roles, such as: exclusion of insects and thereby reducing pesticide use; selective spectral absorption/transmission of solar radiation for pest control; reduction of hail and wind damage; extending the growing period and delaying fruit ripening; reducing

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Nomenclature

k	Turbulence kinetic energy, $m^2\ s^{-2}$
Re	Reynolds number
rms	Root mean square
U_0	Ambient mean windspeed at 6 m height, $m\ s^{-1}$
U_s	Ambient mean windspeed at air-velocity sampling height, $m\ s^{-1}$
u_i, v_i, w_i	Instantaneous velocity components, $m\ s^{-1}$
u, v, w	Mean velocity components, $m\ s^{-1}$
u', v', w'	Root mean square (rms) of velocity components, $m\ s^{-1}$
u_h	Instantaneous horizontal resultant air velocity, $m\ s^{-1}$
u_{hm}	Mean horizontal resultant air velocity, $m\ s^{-1}$
u^*	Normalised air velocity (u_h/U_0)
u_n	Normalised air velocity (u_h/U_s)
z_0	Aerodynamic roughness length, m
θ	Mean wind azimuth, degree
$\sigma_{\theta U}$	Standard deviation of wind azimuth, degree
$\sigma_{\theta u}$	Standard deviation of horizontal resultant air velocity, $m\ s^{-1}$

radiative heat loss and consequent night-time cooling; increasing water-use efficiency; and protecting against supra-optimal (i.e., excessive) radiation. Screenhouses enable the grower to achieve these above objectives at lower costs than by using fully climate-controlled greenhouses; therefore they are steadily increasing in use in several countries, worldwide.

1.2. *Studies on the determination of screenhouse microclimate*

Ventilation rate is one of the key factors in controlling greenhouse and screenhouse microclimates, and thereby influencing crop production at every growth stage (Bournet & Boulard, 2010). However, there is not sound knowledge of the effects of ventilation on the distribution of microclimate within the house.

A decade ago, Boulard, Kittas, Roy, and Wang (2002) indicated that although an analysis that considers the greenhouse as a perfectly stirred tank may be sufficient to solve most classical engineering problems related to describing the microclimate, it is necessary to develop and use tools specifically for the determination of the spatial distribution of microclimate. Boulard et al. (2002) suggested that given such knowledge, it would then be possible to control the climate at plant level with enhanced economy of means, materials, and energy, and with greatly improved efficiency, in order to satisfy the specific needs of each type of plant and/or other biotic agents. In light of the need to determine the detailed climate distribution, researchers in recent years have used experimental and modelling techniques that enable determination of temperature and water-vapour distributions, in addition to yielding a detailed description of the airflow patterns.

In contrast to the advances in measurement and modelling of the greenhouse microclimate distribution, very little was published with regard to the microclimate distribution in screenhouses. In particular, there is very little information on airflow patterns and flow characteristics in such enclosures.

In a recent review, Tanny (2013) summarised the past research and recent advances regarding microclimate and evapotranspiration of crops under horizontal flat screens and in screenhouses; his review covers the issues of radiation, air velocity, ventilation, turbulence, temperature, humidity, evapotranspiration and water-use efficiency; it shows that although screens reduce the transmission of total radiant energy, the effect on air temperature is complex and depends on additional factors. Tanny (2013) indicated that in attempting to characterise the effects of horizontal-screen covers or screenhouses on air velocity, several field measurements have established relationships between internal air velocity and external windspeed.

Möller, Tanny, Cohen, and Teitel (2003) and Tanny, Cohen, and Teitel (2003) conducted microclimate measurements in an insect-proof screenhouse in which pepper was grown. They reported that the central region of the structure was warmer and more humid than its northern edge. Air velocity measured under the screen along the windward half of the screenhouse was approximately in the opposite direction to that of the outside wind, and that along the leeward half was roughly in the same direction as external wind.

The vertical distribution of air velocity inside the screenhouse is of interest, as well as the absolute value of the mean air velocity at any specific level, but only a few studies have addressed this issue. Allen (1975) reported a uniform air-flow distribution across the air gap between the screen and the plants, a finding that is essentially different from that of Tanny, Dicken, and Cohen (2010) for a banana screenhouse, which showed that air velocity at a level closer to the plants was between 50 and 70% of that measured at a higher position, closer to the screen.

The effects of the screen on the mass, momentum, and energy-exchange rates of a uniform crop situated in a screenhouse were studied by Siqueira, Katul, and Tanny (2012); they used a newly proposed higher-order closure model to explore the effects of a shading screen on the mean flow field, turbulent stresses, and radiative and energy fluxes, as well as scalar sources, sinks, fluxes, and mean scalar concentrations within screenhouses. Their model results showed that the presence of a horizontal flat screen reduced the velocity statistics that accounted for turbulent transport, and also reduced the effective roughness of the surface. This model (Siqueira et al., 2012) also showed that air velocity increased with height and proximity to the screen, in agreement with the findings of Tanny et al. (2010).

1.3. *Gap of knowledge and expected contribution of present study*

The above literature review indicates that detailed data on screenhouse microclimate distribution are quite scarce and, furthermore, that temperature and humidity fields are non-uniform, and flow patterns are complex. Therefore, the major goal of this study was to extend the available data on airflow patterns and characteristics in the case of a crop grown in a screenhouse fitted with either screened or impermeable sidewalls and a roof comprising a horizontal flat