Energy and Buildings 87 (2015) 293–301

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A simple model for ventilation rate determination in screenhouses

N. Rigakis[a], N. Katsoulas[a,b], M. Teitel[c], T. Bartzanas[b], C. Kittas[a,b,*]

[a] University of Thessaly, Dept. of Agriculture Crop Production and Rural Environment, Fytokou Str., 38446 Volos, Greece
[b] Centre for Research and Technology Hellas, Institute for Research and Technology of Thessaly, Dimitriados 95 & P. Mela, 38333 Volos, Greece
[c] Institute of Agricultural Engineering, Agricultural Research Organization, the Volcani Center, PO Box 6, Bet Dagan 50250, Israel

ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form
17 November 2014
Accepted 20 November 2014
Available online 26 November 2014

Keywords:
Screen
Shading
Insect proof
Porosity
Discharge coefficient
Wind effect coefficient

ABSTRACT

The objective of this work was to study and model the ventilation rate in screenhouses. Thus, microclimate variables and crop transpiration as well as the air velocity were measured in three screenhouses covered by different screens: (i) a clear insect-proof screen, (ii) a white insect proof screen and (iii) a green shade screen, with values of shading factors to solar radiation measured in the lab of about 13%, 34% and 36%, respectively. The porosity of the screens was found 0.46 for the insect proof and 0.63 for the shading screen. The ventilation rate was estimated using the decay rate 'tracer gas' method, using the water vapour as tracer gas. The results showed that the insect proof screens reduced at the same rate the inside screenhouse air velocity, since they had the same geometrical characteristics. The internal air velocity in the insect proof and the shading screenhouses was about 20% and 44%, respectively, of that measured outside. The ventilation rate data obtained were used to calibrate a model that can be used for the prediction of ventilation rate in screenhouses, taking into account the geometrical characteristics of the screens used and of the screenhouse and the outside wind speed.

1. Introduction

Screenhouses are steadily spreading around Mediterranean regions and especially in Israel, southern regions of Spain, Italy and Greece. Those low cost structures protect covered crops from environmental (wind, hail, excessive radiative loads during hot period of the year) and biological (pests, birds, bats) pressure factors, while reduce pesticide applications (case of insect-proof screenhouses) and irrigation water needs, increasing in this way the water use efficiency [1–3]. Using screens to protect horticultural crops improves the microclimate, promoting crop productivity and fruit quality [4–6].

Screen physical and optical properties are the main factors that affect the resulting microclimate inside an enclosure i.e., screenhouse or greenhouse with screened openings. The optical properties of screens affect the construction's transmission to solar and thermal radiation and accordingly determine their heat load [7–10], while the physical properties of screens affect the natural ventilation performance of the enclosures [10–17], which is the only means of removing the excessive heat load in screenhouse structures, which negatively affects the productivity and quality of open field-grown crops [12,18]. Concerning the physical properties of screens, their geometrical characteristics strongly affect screens' permeability to air flow. The pressure drop through screens is related to screen porosity and geometry and can be determined either by Forchheimer's or by Bernoulli's equation [19–21]. The porosity of a woven screen that is made of a monofilament thread and that has a simple texture was determined by 2-D or 3-D geometric analysis [22,23] or with specifically developed software [24], while, for the case of screens with complex texture, the image analysis is proposed (microscope or image processing software) [7,25]. Determination of the aerodynamic characteristics of screens can be done through wind tunnel measurements [19,26,27].

Several studies have been devoted to the relationship between inside and outside air velocity in screenhouses [1,8,11,12,28–31]. Tanny [13], in his review presented a summary of literature data on the effect of screen covers and screenhouses on air velocity. The ratio between inside to outside air velocity referred was ranging between 0.2 and 0.7. Furthermore, Tanny et al. [11,31] studied the ventilation performance of various commercial screenhouses of different size (covered ground area ≈0.66 and 8 ha; Height = 3.2 m and 6 m). The air exchange rate was found to range between 7 and 33 h^{-1} for wind speed between 1.5 and 3.5 $m\,s^{-1}$. Tanny et al. [31] who studied the volume flow rate in a banana screenhouse compared their results with those obtained by Tanny et al. [11] in a pepper screenhouse and by Demrati et al. [32] in a banana

---

* Corresponding author at: University of Thessaly, Dept. of Agriculture Crop Production and Rural Environment, Fytokou St., 38446 Volos, Greece.
Tel.: +0030 2421093012; fax: +0030 2421093234.
E-mail address: ckittas@uth.gr (C. Kittas).

http://dx.doi.org/10.1016/j.enbuild.2014.11.057
0378-7788/

Nomenclature

A_T	ventilation opening area (m^2)
A_g	screenhouse/greenhouse covered ground area (m^2)
A_s	screenhouse cover area (m^2)
C_d	discharge coefficient (dimensionless)
C_{ds}	discharge coefficient of a screen (dimensionless)
C_{ds*}	discharge coefficient of a screen multiplied by its porosity (dimensionless)
C_w	global wind—effect ventilation coefficient (dimensionless)
$G_{sc,o}$	screenhouse air volume flow rate at zero wind velocity ($m^3\,s^{-1}$)
G_{sc}	screenhouse air volume flow rate ($m^3\,s^{-1}$)
D_{air}	vapour pressure deficit (kPa)
Tr_i	transpiration rate ($kg\,m^{-2}\,s^{-1}$)
h	height of screenhouse (m)
K	permeability of a screen (m^2)
N	screenhouse air exchange rate (h^{-1})
P	pressure (Pa)
Q	volume flow rate ($m^3\,s^{-1}$)
T_{air}	air temperature (°C)
v	air velocity through the pores of a screen ($m\,s^{-1}$)
u_{in}	air velocity inside the screenhouse ($m\,s^{-1}$)
u_o	outside wind speed ($m\,s^{-1}$)
V_{sc}	screenhouse volume (m^{-3})
Y	inertial factor of a screen (dimensionless)
x_o	absolute humidity outside the screenhouse ($g\,m^{-3}$)
x_i	absolute humidity inside the screenhouse ($g\,m^{-3}$)
Δx	thickness of a screen (m)
ε	porosity (dimensionless)
ρ	density of air ($kg\,m^{-3}$)

greenhouse. The flow rate in the banana screenhouse was much larger than those in the banana greenhouse of and the pepper screenhouse, while the reported air exchange rates were of the same order of magnitude [13].

The air exchange rate and its correlation to buoyancy and wind forces has been extensively studied in greenhouses and several models have been developed to predict greenhouse air exchange rate as a function of vent opening characteristics, vent opening area, inside to outside air temperature difference and outside air velocity [17,33–35]. The screenhouse air exchange rate could be estimated as a wind driven air flow through an opening [36]. Generalizing the latter method for both wind pressure effect and temperature difference effect and assuming the ideal condition of unidirectional flow, Desmarais et al. [8] defined the air exchange rate of small experimental screenhouses. However, to the best of our knowledge, there is no model available to be used for the simulation of screenhouse air exchange rate as a function of screen physical properties, screenhouse covering area and wind velocity.

Thus, the objective of the current work was to develop a model for screenhouse air exchange simulation as a function of screen physical properties and outside climate variables, using measurements of screenhouse microclimate performed in three screenhouses covered with different screens.

2. Materials and methods

Measurements of screenhouse and outside microclimate variables were performed during a cultivation period. The vapour fluxes measured were used for the calculation of screenhouse ventilation rate, by means of the water vapour balance technique [37,38]. Finally, the calculated values of the screenhouse ventilation rate were used for the calibration of a model for screenhouse ventilation rate simulation.

2.1. Screenhouse facilities and plant material

The experiments were performed in three experimental flat roof screenhouses, located at the University of Thessaly near Volos (Velestino: Latitude 39°22′, longitude 22°44′, altitude 85 m), on the continental area of Eastern Greece, during summer and autumn of 2012. The geometrical characteristics of the screenhouses were as follows (Fig. 1): length of 20 m (oriented North-South, 36° declination from North), width of 10 m and height h of 3.2 m, screenhouse covered area A_g of 200 m^2; screen cover area A_s of 392 m^2, screenhouse volume V_{sc} of 640 m^3. The distance between two adjacent screenhouses was 8 m.

Three different screens were tested. Two were insect-proof (IP) screens (Fig. 2a and b) manufactured by Meteor Ltd., Israel: (1) a clear 50 mesh (10/20) AntiVirus^{TM} screen with a mean light transmittance in lab measurements (400–1100 nm) of 87%, that is, a shading factor of 13% (hereafter, IP-13); and (2) a white 50 mesh (10/20) BioNet^{TM} with a mean light transmission of 66% (hereafter IP-34). The third one (Fig. 2c) was a green shade screen (Thrace Plastics C S.A. Xanthi, Greece) with a mean light transmission of 64% (hereafter S-36). The insect proof has a regular mesh netting with a hole size of 0.75 × 0.25 mm and thread diameter of 0.24 mm, while the green shading screen, due to its different knitting (Fig. 2c), present meshes that are irregular in size and arrangement and mean thread diameter of 0.25 mm. Screens porosity (ε) was measured by image processing using an image analysis software (ImageJ). The calculated values of porosity for the screens IP-13 and IP-34 were of 0.46, as also reported by Möller et al. [7], while the porosity of S-36 was of 0.63.

The transmission measurements referred above were carried out prior to installation of screens, in the laboratory by means of a spectroradiometer (model LI-1800, LI-COR, Lincoln, NE, USA) equipped with a 10 W glass halogen lamp and an external integrating sphere (model LI-1800-12S, LI-COR, Lincoln, NE, USA).

Sweet pepper plants (*Capsicum annuum* L., cv. Dolmi) were transplanted on May 8, 2012. Plants were laid out 0.5 m apart in the row, in five double rows with a distance between the double rows of 1.2 m and a distance between the two rows of a double row of 0.5 m, resulting in a plant density of 1.8 plants per m^2. The plants were supported vertically by cords hanging from cables attached longitudinally to the frame of the screenhouses. Cropping techniques (fertigation, pruning, chemical treatments) were identical in all treatments.

Plant height was not considerably changed during the period of measurements in the different treatments varying from 0.9 m (mid of August) to 1.1 m (mid of September). The screenhouse soil was totally covered by black polypropylene (water permeable) mulch, primarily deployed against weeds and secondly in minimizing soil water evaporation.

Irrigation water was supplied through drip-laterals with one drip-line per row and one dripper per plant. The dripper flow rate was 2 L h^{-1}. In all treatments, irrigation scheduling was based on the concept of crop coefficient, K_c, as described in Katsoulas et al. [39].

2.2. Measurements

The following climatic data were recorded:

(a) wet and dry bulb temperature by means of aspirated psychrometers (type, Delta-T Devices, Cambridge, U.K.), at the centre of