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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

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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 Bernouli'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).

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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™ 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™ 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

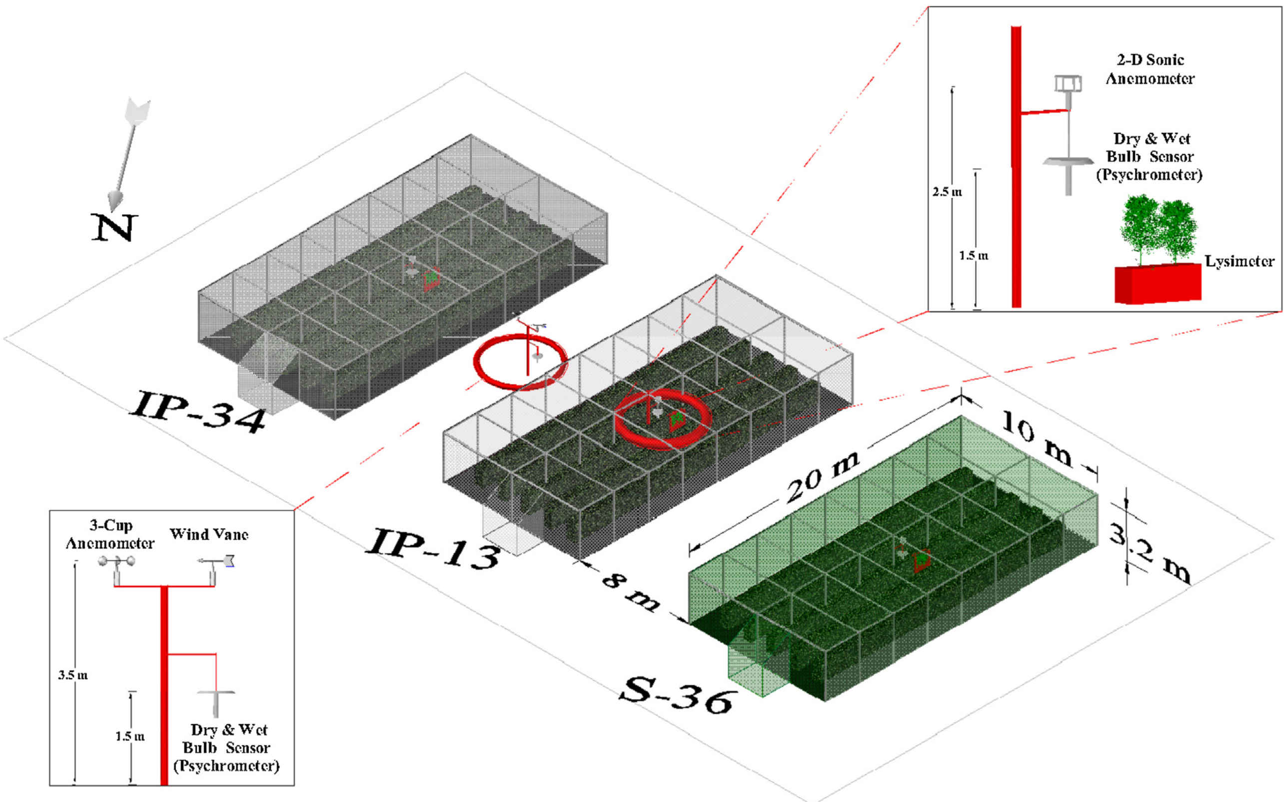

Fig. 1. Configuration of experimental facilities: screenhouses constructions and sensors deployment.

each screenhouse (at 1.5 m height aboveground) and outside at 1.5 m height aboveground,

(b) wind speed (u_{0-10}) and direction outside the screenhouses by means of a cup anemometer (A100R Switching Anemometer, Campbell Scientific Ltd., U.K.) and a wind vane (W200P Windvane, Vector Instruments Ltd., U.K.) located at a height of 10 m above ground in a nearby (75 m) meteorological station and by means of the same type of sensors located outside the screenhouses at 3.5 m above ground ($u_{0-3.5}$),

(c) wind speed (u_{in}) and direction at the centre of each screenhouse, 2.5 m above ground, by means of 2-D sonic anemometers (WindSonic^{TM}, Gill Instruments Ltd, U.K.). Two 2-D anemometers were available and therefore the anemometers were moved in the different screenhouses in sequence in appropriate time intervals.

The crop transpiration rate (Tr_i) was measured every 10 min using weighing lysimeters located in a central row of each screenhouse. The device included an electronic balance (model 60000 G SCS, Presica, Dietikon, Switzerland, scale capacity = 62 kg, resolution ± 1 g) equipped with a tray carrying two plants grown in a container (1 m long, 0.4 m wide and 0.4 m deep) and an independent system of water supply and drainage. The soil surface of the container was covered with the same black PP mulch as the screenhouse soil. The weight loss measured by the electronic balance was assumed to be equal to crop transpiration.

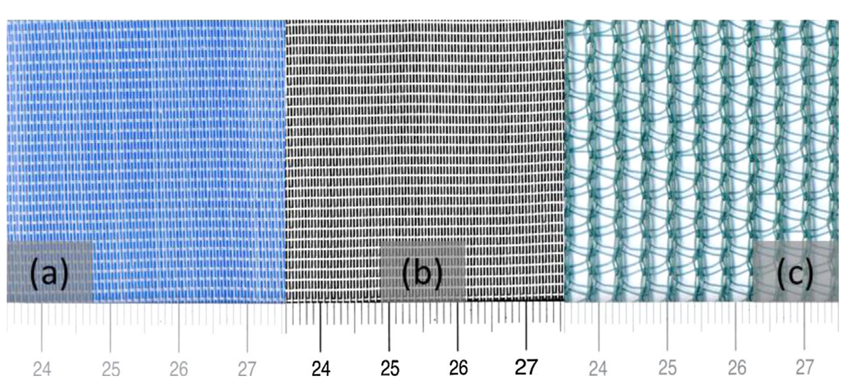

Fig. 2. Screenhouse covering materials with rank indication as in the text: (a) IP-13, (b) IP-34 and (c) S-36. The ruler indicates measurement scale in cm. Background colours: (a) blue, (b) black and (c) white. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Measurements took place every 30 s and 10-min average values were recorded in a data logger (model DL3000, Delta-T Devices, Cambridge, U.K.).

2.3. Calculations

2.3.1. Air flow characteristics of porous screens

Wind tunnel tests were conducted in order to determine the aerodynamic properties of the screens. The screen samples were fitted in the wind tunnel and an air flow of a vertical angle attack was forced to the samples' surface. The pressure drop (ΔP) through screens' surface was measured over a range of upstream air velocities u. The discharge coefficient C_{ds} of the screens was estimated by fitting the data of ΔP and u to Bernoulli's equation [40]:

$$\Delta P = 0.5\frac{\rho v^2}{C_{ds}^2} = 0.5\frac{\rho u^2}{\varepsilon^2 C_{ds}^2} = 0.5\frac{\rho u^2}{C_{ds^*}^2} \qquad (1)$$

using Marquardt's algorithm [41].

2.3.2. Ventilation rate estimates applying the water vapour balance technique

The screenhouse ventilation rate was determined using the water vapour balance technique, using the water vapour as tracer gas [37,38]. Assuming homogeneity of the water vapour within the air, the following relation holds:

$$\rho V_{sc} = \frac{dx_i}{dt} = -\rho Q(t)\left[x_i(t) - x_o(t)\right] + Tr_i(t) \qquad (2)$$

where ρ is the air density (kg m^{-3}), Q is the ventilation rate (m^3 s^{-1}), V_{sc} is the screenhouse volume (m^3), $x_i(t)$ and $x_o(t)$ are the inside and outside concentrations (air absolute humidity) of water vapour (tracer gas) (kg m^{-3}), and $Tr_i(t)$ is the rate of supply of water vapour within the screenhouse by means of the crop transpiration process (kg m^{-2} s^{-1}).

The air flow rate (G_{sc}; m^3 s^{-1}) of the screenhouse can be calculated as follows [11]:

$$G_{sc} = A_g\frac{Tr_i(t) - h(d\bar{x}_i/dt)}{(\bar{x}_i - x_o)} \qquad (3)$$

where h is the screenhouse height (m). Then, the screenhouse air exchange rate (N, in h^{-1}) is calculated as follows:

$$N = 3600\frac{G_{sc}}{V_{sc}} \qquad (4)$$

where V_{sc} (m^3) is the screenhouse volume.

2.3.3. Screenhouse ventilation modelling

Based on the application of Bernoulli's equation, G_{sc} can be also derived by taking into account the two main driving forces of natural ventilation: the wind and stack effects [34,35,42]. However, since the air velocity in the screenhouses is relatively high and inside to outside air temperature differences are low, the stack effect could be ignored [43,44].

Thus, following the modelling procedure used in greenhouse, the ventilation rate could be expressed by the following equation [35,44]:

$$G_{sc} = \frac{A_T}{2}C_d\sqrt{C_w}u + G_{sc,o} \qquad (5)$$

where A_T is the ventilation area, C_d the discharge coefficient of the screenhouse, C_w is the wind related coefficient and $G_{sc,o}$ the ventilation rate observed at zero wind velocities. Fitting the ventilation rate calculated by Eq. (3) and the wind velocity measured to Eq. (5), the dual coefficient $C_d\sqrt{C_w}$ for each screenhouse was estimated.

In greenhouses with screened vent openings, the total pressure drop coefficient indicates the pressure drop across both the inlet opening and the screen [17,45]. In screenhouses, the total cover area can be considered as a screened vent opening. Therefore, it could be assumed that the total pressure drop coefficient is equal to the pressure drop coefficient across the screen, alone. Thus, the total discharge coefficient C_d of the screenhouse construction (or "vent") is considered to be equal to the discharge coefficient of the covering screen ($C_d = C_{ds^*}$).

Table 1
Estimated values (95% confidence) of the discharge coefficient (C_{ds}) by means of Eq. (1), for the insect proof (IP-13 and IP-34) and shade (S-36) screens.

Screen	Estimate	Std. error	R^2 [a]	DF [b]
IP-13	0.991	0.015	0.92	27
IP-34	1.035	0.017	0.91	27
IP screens (pooled data)	1.013	0.011	0.91	55
S-36	1.262	0.029	0.76	27

[a] R^2: Models coefficient of determination.
[b] DF: Degrees of freedom.

3. Results

3.1. Air flow characteristics of porous screens

The discharge coefficient C_{ds} of the screens was estimated by fitting the data of ΔP and u measured in the wind tunnel to Eq. (1) using Marquardt's algorithm [41]. The mean estimated values of the discharge coefficient C_{ds} from the different screen samples tested are presented in Table 1. In order to test if the C_{ds} values of the two insect proof screens were statistically different, the t-test was used [46]:

$$t = \frac{1.03 - 0.99}{\sqrt{(0.017)^2 + (0.015)^2}} = 1.97 < 2.00(t_{0.05;54}) \qquad (6)$$

The t value estimated (1.97) was lower than 2.00, which is the corresponding t-value for 95% of confidence and 54 degrees of freedom (the sum of the degrees of freedom for each fit). Accordingly, the C_{ds} values estimated for the two insect proof screens were not significantly different and thus, the data were pooled and a unique value was estimated. The C_{ds} value estimated by means of Eq. (1) was 1.01 (±0.011) with R^2 of 0.91.

The corresponding C_{ds^*} values were 0.465 and 0.795 for IP and S-36 screens, respectively.

3.2. Screenhouse microclimate

3.2.1. Air temperature and vapour pressure deficit

The average daytime (08:00–20:00, local time) mean values of the internal air temperature (Table 2) in all three screenhouses were about 0.2 °C lower than the outside air temperature, while the air temperature values observed in the three screenhouses were similar. The maximum air temperature recorded under screenhouse conditions was about 0.7 °C lower than the corresponding outside. A similar trend was also observed for the air vapour pressure deficit values (Table 2). The maximum air vapour pressure deficit values observed in the screenhouses were about 40% higher than the mean values observed outside during the 12 h period.

The diurnal (08:00–20:00, local time) inside to outside air temperature difference (Fig. 3) followed similar trends for all three screenhouses, with the minimum air temperature difference observed during noon to reach about −0.7 °C and the minimum vapour pressure deficit difference to reach about −0.4 kPa. The lower vapour pressure deficit values observed inside the three screenhouses could be attributed to the enrichment of screenhouse air by air vapour through crop transpiration. Comparing the three screenhouses, the lower air temperature and vapour pressure

Table 2
Average of daytime (08:00–20:00) mean and max air temperature (T_{air}; °C) and vapour pressure deficit (D_{air}; kPa) over 6-day intervals.

Period	Treatment	T_{air} (°C)			D_{air} (kPa)		
		Mean	Stdev	Max	Mean	Stdev	Max
(1st) 20–25 Aug.	Out	31.6	1.52	36.4	3.2	0.41	4.6
	IP-13	31.6	1.48	36.2	3.0	0.38	4.3
	IP-34	31.6	1.27	36.1	3.1	0.40	4.3
	S-36	31.1	1.23	35.6	2.9	0.34	4.3
(2nd) 26–31 Aug.	Out	29.3	2.08	33.7	2.7	0.45	3.6
	IP-13	29.2	2.01	32.7	2.5	0.43	3.3
	IP-34	28.8	2.60	32.0	2.5	0.55	3.3
	S-36	28.9	2.06	32.0	2.5	0.43	3.3
(3rd) 1–6 Sept.	Out	27.5	0.51	31.8	2.1	0.11	3.1
	IP-13	27.5	0.47	31.7	1.9	0.09	2.8
	IP-34	27.4	0.53	31.4	1.9	0.10	2.8
	S-36	27.0	0.51	30.9	1.9	0.10	2.8

deficit values during the most part of the day were observed in the S-36 screenhouse.

3.2.2. Screenhouse air velocity and direction

The wind velocity observed inside the three screenhouses was highly correlated to that measured outside the screenhouses (Fig. 4). It was found that the air velocity measured inside (u_{in}) the IP screenhouses was about 50% lower than that observed under the green shading screen and about 20% of the outside (u_o). The regression lines obtained between inside and outside air velocity values for the three screenhouses were:

$$u_{in_{IP\text{-}13}} = 0.195(\pm 0.007)u_o + (2.80 \times 10^{-4})(\pm 0.008), \quad \text{with} \quad R^2 = 0.80,$$
$$u_{in_{IP\text{-}34}} = 0.205(\pm 0.007)u_o + (1.53 \times 10^{-4})(\pm 0.008), \quad \text{with} \quad R^2 = 0.82,$$
$$u_{in_{S\text{-}36}} = 0.437(\pm 0.013)u_o + (1.04 \times 10^{-4})(\pm 0.015), \quad \text{with} \quad R^2 = 0.84,$$

for IP-13, IP-34 and S-36, respectively. The values given in parenthesis correspond to the standard error of slope and intercept, respectively. The slope for all cases was statistically significant ($a = 0.05$), while the intercept was not statistically significant and could be excluded without any statistical error. A t-test was performed to compare the slope of the correlations for IP-13, IP-34 and was found that the values were not statistically different (data not shown), and thus the data from the two screenhouses were pooled and the new correlation found between inside and outside air velocity for the insect proof (IP) screenhouses was:

$$u_{in_{IP}} = 0.201(\pm 0.005)u_o - (7 \times 10^{-4})(\pm 0.005), \quad \text{with} \quad R^2 = 0.81$$

The value of the intercept was not statistically significant and can be ignored without any statistical error.

The air direction inside the IP-13 and S-36 screenhouses (hourly mean values) as a function of the external wind direction is presented in Fig. 5. It was found that the inside wind direction was correlated with that of the outside air with data points in S-36

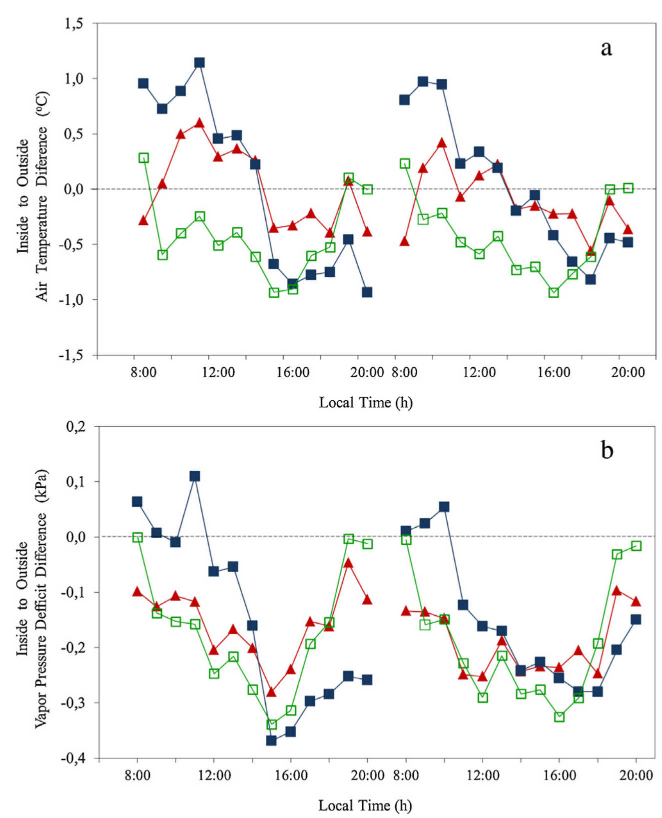

Fig. 3. Diurnal (08:00–20:00, local time) inside to outside (a) air temperature difference (T_{air}; °C) and (b) vapour pressure deficit (D_{air}; kPa) during two consecutive days (30–31August, 2012). Triangles: IP-13; closed squares: IP-34; open squares: S-36.

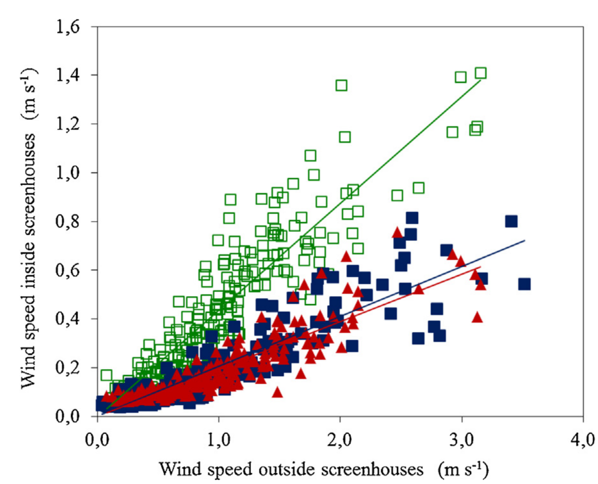

Fig. 4. Wind speed inside the screenhouses as a function of the external wind speed. The data presented for IP-13 (triangles) and S-36 (open squares) correspond to the period from August 25 to August 31, 2012 while the data presented for IP-34 (closed square), correspond to the period from October 26 to November 5, 2012. Solid lines present the best fit regression lines.

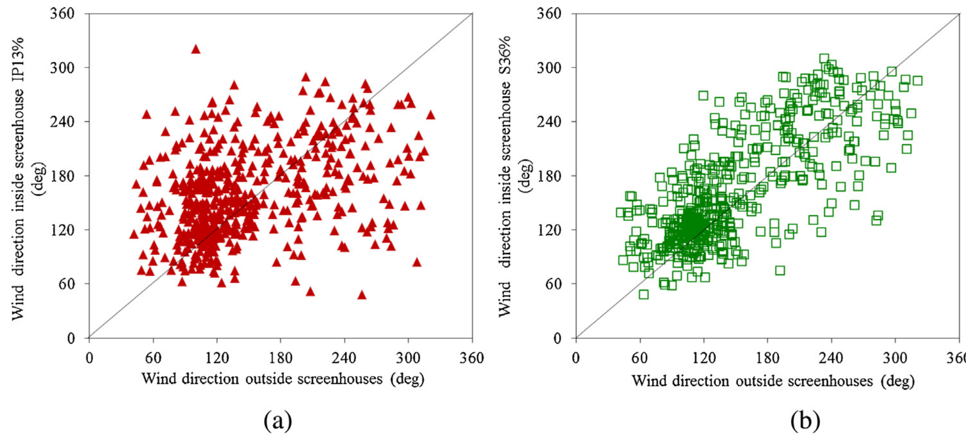

Fig. 5. Wind direction inside the screenhouses as a function of the external wind direction. (a) IP-13 (triangles); (b) S-36 (squares). The data presented correspond to the period from August 25 to September 15, 2012. The solid lines are the 1:1 lines.

screenhouse uniformly distributed around the 1:1 line. The same type of distribution was less uniform in the case of IP screenhouses, something that could be attributed to the differences in the texture of the shading and insect proof screens tested. The IP screens that were denser than the shading screen seem to affect in a higher degree the wind direction, compared to the less dense shading screen. The IP screenhouses presented similar relation between the inside and outside wind direction and that is why the data from IP-34 screenhouse are not shown.

3.3. Crop transpiration

The evolution of the crop transpiration rate in the three screenhouses are shown for consecutive days (30–31 August 2012) in Fig. 6. The higher values of crop transpiration rate were observed in the screenhouse with the higher transmittance to solar radiation (IP-13) while the screenhouses with the lower transmittance (IP-34 and S-36) presented similar values of crop transpiration rate.

3.4. Screenhouse ventilation modelling

In the results presented below, the analysed data correspond to the main wind direction of the region (E-SE 115° ± 25°). Data from different directions were not included in the analysis. Moreover, the ventilation analysis was conducted in 30-min average climate values with stable wind direction, in order to fulfil the steady state conditions during measurements period.

The volume air flow rate observed during the period of measurements in the two IP screenhouses was similar with an average daytime value of 0.06 $m^3\,m^{-2}\,s^{-1}$ while the respective values observed in the S-36 screenhouse were about double (0.11 $m^3\,m^{-2}\,s^{-1}$) of those observed in the IP screenhouses.

The hourly mean air exchange rate (N, h^{-1}) values observed during the period of measurements in the S-36 screenhouse and the IP screenhouses (pooled data) are shown in Fig. 7, as a function of the outside air velocity.

The regression lines obtained between the air exchange rate and the outside air velocity for the two IP screenhouses and the S-36 screenhouse, respectively, were:

$$N_{IP} = 23.8(\pm 3.2)u_o + 28.5(\pm 5.5), \quad \text{with} \quad R^2 = 0.66, \tag{7}$$

$$N_{S\text{-}36} = 66.6(\pm 7.7)u_o + 14.4(\pm 13.4), \quad \text{with} \quad R^2 = 0.79 \tag{8}$$

The air exchange rate was ranging between 35–80 h^{-1} and 55–180 h^{-1}, for the case of the insect-proof (IP-13 and IP-34) and the S-36 screenhouses, respectively, for wind speed values ranging between 1 $m\,s^{-1}$ and 2.5 $m\,s^{-1}$. The slope of the regression line presented above for S-36 is about 2.8 times higher than that of the IP screenhouses.

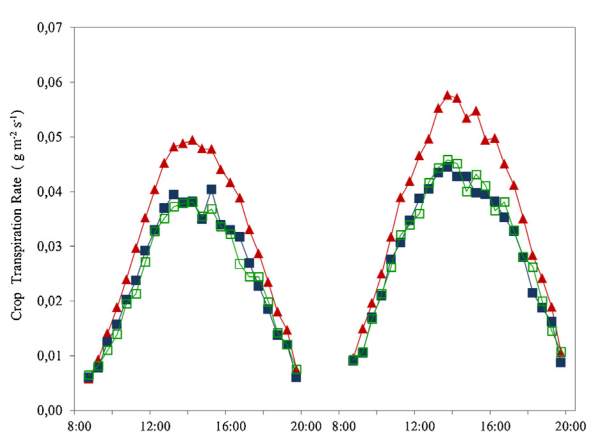

Fig. 6. Diurnal (08:00–20:00, local time) crop transpiration rate ($g\,m^{-2}\,s^{-1}$) inside the screenhouses during 2 consecutive days (August 30 and 31, 2012). Triangles: IP-13; closed squares: IP-34; open squares: S-36.

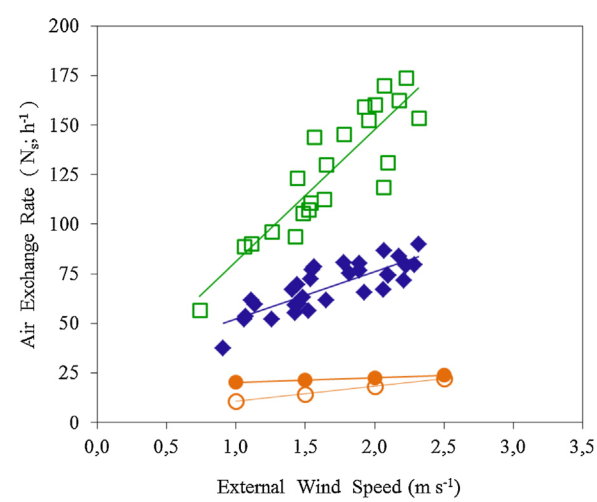

Fig. 7. Screenhouse air exchange rate (h^{-1}) as a function of measured external wind speed, during August 30 until 31, 2012. Diamond: pooled data IP-13 and IP-34; squares: S-36; closed circle: 8 ha banana screenhouse [11] open circle: 0.66 ha pepper screenhouse [31]. Solid lines present the best fit regression line.

Table 3
Regression coefficients estimates (95% confidence) of the overall pressure drop and wind effect coefficient $\left(C_d\sqrt{C_w}\right)$ and of the ventilation rate at zero wind velocity ($G_{sc,o}$) for groups of data (G_{sc}, A_T and u_{ext}), for screenhouses IP (pooled data for IP-13 and IP-34) and S-36.

Screenhouse	$C_d\sqrt{C_w}$		$G_{sc,o}$		[a]R^2	[b]DF
	Estimate	Std. error	Estimate	Std. error		
IP (pooled data IP-13 and IP-34)	0.026	0.003	5.064	0.978	0.66	30
S-36	0.072	0.008	2.532	2.385	0.79	21

[a] R^2: Models coefficient of determination.
[b] DF: Degrees of freedom.

Fitting the measured values of the ventilation flow rate (G_{sc}) for the two type of screenhouses to Eq. (5), using Marquardt's algorithm [41], allowed the estimation of model parameters ($C_d\sqrt{C_w}$ and $G_{sc,o}$) shown in Table 3. The ventilation area A_T considered in Eq. (5) was the sum of the windward and leeward side walls ($2 \times 64 = 128\,m^2$) and the roof surface ($20 \times 10 = 200\,m^2$).

The estimated value of the overall pressure drop and wind effect coefficient $\left(C_d\sqrt{C_w}\right)$ for the insect proof screenhouses (pooled data IP-13 and IP-34) was 0.026 (±0.003), while the value estimated for the S-36 screenhouse (0.072 ± 0.008) was three times higher than that of the IP screenhouses.

Assigning to Eq. (5) the C_{ds^*} values estimated by means of the wind tunnel measurements (Table 1) and following the same calibration procedure [41], the C_w values estimated for the IP and S36 screenhouses were 0.003 (±0.001) and 0.008 (±0.002), respectively.

4. Discussion

4.1. Air velocity reduction

The screens used for screenhouse covering created a barrier between the screenhouse environment and the outside environment and significantly reduced screenhouse air velocity (Fig. 4). Tanny [13] using data from Desmarais et al. [8] who reported wind measurements inside and outside several types of screenhouses, elaborated a rough linear regression between the inside and outside air velocity as following:

$$u_{in} = 0.2(u_o - 1.16) \quad (9)$$

This relationship is similar to the one found in the present study for the insect proof screenhouses. Furthermore, Möller and Assouline [1], for a 30% black knitted shade screen found a relationship between inside and outside air velocity as following (as shown by Tanny [13]):

$$u_{in} = 0.5016(u_o - 0.119) \quad (10)$$

that is in agreement with the presented reduction rate of S-36 screenhouse found in the present study.

4.2. Effect of screens' and screenhouse size on ventilation

Harmanto et al. [47] presented values for the discharge coefficient (C_{ds^*}) of different anti-insect screens. A 52-mesh (anti-whiteflies and larger pests; hole size: 0.80 mm × 0.25 mm; d: 0.31; ε: 0.38) and a 40-mesh (Econet M®, anti-leaf miners and larger pests; hole size: 0.44 mm × 0.39 mm; d: 0.25; ε: 0.41) had C_d values of 0.28 and 0.31, respectively. For the IP-13 and IP-34 screenhouses, the C_{ds^*} values observed in the case of the present study were higher, something that could be attributed to the higher porosity and the different yarn and hole dimensions of the IP screens of the present study.

Teitel [40] reported that for a woven/knitted 22% shading screen (tape threaded; ε: 0.49) the discharge coefficient observed was 0.73 which is close to the C_{ds^*} value observed in the present study for the S-36 screen ($C_{ds} \times \varepsilon = 1.262 \times 0.63 = 0.795$).

Wind tunnel measurements of the present work were fitted into the Forchheimmer equation to estimate the permeability (K) and the inertial factor (Y) of the screens that were used, following the procedure presented by several authors [21,19,48,49]. The estimated K values were 2.93×10^{-9} and 1.98×10^{-8}, while Y values were 0.120 and 0.065 for IP and S-36 screenhouse, respectively.

Knowing the geometrical characteristics (ε; Δx) of a screen it could be possible to calculate (i) its aerodynamic characteristics (K and Y), (ii) the resulting pressure drop through its matrix (using Forchheimmer equation) and consequently (iii) the discharge coefficient (C_{ds^*}) of the screen [26,40]. Finally, using the calculated C_{ds^*}, the ventilation rate of a screenhouse could be estimated using Eq. (5). Several authors have reported equations relating the aerodynamic properties with their porosity [21,40,48,49]. Calculating the K and Y of the screens of the present work using the equations reported by Valera et al. [48,49] resulted in a good agreement between the calculated values of C_{ds^*} coefficients (IP: 0.401; S36: 0.838) and those estimated using the wind tunnel measurements (IP: 0.465; S36: 0.795).

However, using the equations proposed by Miguel [21] we did not find an agreement between the calculated values (IP: $K = 9.93 \times 10^{-10}$ and $Y = 0.225$; S-36: $K = 1.64 \times 10^{-10}$ and $Y = 0.115$) and the estimated values from the wind tunnel tests. Similar results were also found by Teitel [40] who also did not found a good agreement using the values calculated after Miguel [21].

The ventilation rate values observed in the experimental screenhouses of the present study (IP-13, IP-34, and S-36) were much higher than the ventilation rate values observed in large scale (≈0.66 ha pepper screenhouse and ≈8 ha banana screenhouse) commercial screenhouses (Fig. 7), as those reported by Tanny et al. [11,31].

Tanny et al. [31], comparing the ventilation performance of a greenhouse against a screenhouse, stated that for a large enough naturally ventilated structure with a well-developed dense canopy, the air exchange rate in the middle of the structure is less dependent on its size and vent area, since the latter represents only a small percentage of the total covered area. In the present work the size of the screenhouses seems that strongly influenced their air exchange rate. Comparing the ventilation performance of small scale screenhouses ($200\,m^2$) against that of two large commercial constructions (≈8 ha and 0.66 ha) presented by Tanny et al. [11,31], it can be seen that the air exchange rates of the large screenhouses (≈7.4–33.3 h^{-1} for a pepper screenhouse and 10–45 h^{-1} for a banana screenhouse) were much lower than the small scale screenhouses (≈35–160 h^{-1}) of the present work.

4.3. Comparison between screenhouses and greenhouses

In the present work, apart from the C_{ds^*} values of the screens, the values of the dual coefficient $\left(C_d\sqrt{C_w}\right)$ of the screenhouses and of the wind related coefficient C_w, were also estimated. To the best of our knowledge, there are no previous works reporting the $C_d\sqrt{C_w}$

or the C_w coefficients in screenhouses and that is why the observed values will be compared to those observed in greenhouses.

Teitel [45] reported that the presence of an insect screen in the vent openings of a greenhouse reduces the $C_d\sqrt{C_w}$ coefficient by about 50%, depending the porosity of the screen used, resulting in reduction of greenhouse ventilation rate. Katsoulas et al. [50] reported values of the $C_d\sqrt{C_w}$ coefficient of 0.078 for a small greenhouse (ground covered area of 160 m^2) without screens in the side vents and of 0.096 for the same greenhouse with screened side + roof vents. These values are close to the $C_d\sqrt{C_w}$ values estimated for the S-36 screenhouse of the present work (0.072). The same authors reported a value for the dual coefficient for screened roof vent which is about the same with the estimate of the $C_d\sqrt{C_w}$ coefficient of the insect proof screens of the present work (0.026). Kittas et al. [17] measured the ventilation rate of a small greenhouse (A_g = 200 m^2) with only a roof vent and estimated the $C_d\sqrt{C_w}$ to be about 0.132 for a screened vent opening, which is about double of the corresponding value for the S-36 screenhouse. A $C_d\sqrt{C_w}$ value of 0.14 was reported for a large Canarian-type greenhouse, for wind directions perpendicular to the side openings [51]. Perez Para et al. [52] estimated the dual coefficient for a Paral-type greenhouse and for the case of rolling roof + side walls vents reported a value of 0.025 which is similar to the $C_d\sqrt{C_w}$ value of the insect proof screenhouses presented in this work (0.026).

Considering that C_w is related to the pressure distribution around the structure, and taking into account that the IP-34 screenhouse could be considered as windward and the S-36 as leeward screenhouse, the lower values of the parameter in the case of IP screenhouses could be explained by the differences in the created pressure profile along the wind direction blowing the screenhouses. The so called 'side wall effect' [34,53] induces an inflow in the leeward side of the screenhouses' complex, something that could explain the higher values of C_w observed in the leeward screenhouse (S-36). Fatnassi et al. [54] reported, for a 922 m^2 screened greenhouse a C_w value of 0.0009, which is one order of magnitude lower than the values estimated for the screenhouses of the present work. The C_w values of the screenhouse constructions estimated in the present study are at least on order of magnitude lower than the corresponding values reported for greenhouses [26,35,38,55]. Screenhouses are constructions covered with highly permeable materials unlike greenhouses which are perfectly closed constructions. Consequently, screenhouses may not disturb the wind profile as the greenhouses do, which promotes a different pressure distribution pattern around a screenhouse construction. Thus, the lower values of the C_w coefficient estimated for the screenhouses of the present study (IP: 0.003; S-36: 0.008) compared to most of those reported for greenhouses may be due to lower pressure differences between the leeward and windward sides of the screenhouse construction.

Based on previously published data for other screenhouses, an effort was made to estimate the $C_d\sqrt{C_w}$) for the pepper and the banana screenhouses reported by Tanny et al. [11,31]. Furthermore, knowing the characteristics of the screens, their C_d values were also estimated (Bionet: C_{ds^*} = 0.465; Crystal Shade Net: C_{ds^*} = 0.616) as described in Section 4.2. Then the C_w of the constructions referred in Tanny et al. [11,31] were also estimated and found equal to 0.0001 for the pepper screenhouse of 0.68 ha and 0.0002 for the banana screenhouse of 8 ha. In an effort to generalise the results and estimate the C_w values for different constructions and based on the C_w values of the present study and those estimated for Tanny et al. [11,31], the following relationship was found between the C_w and the screenhouse volume:

$$C_w = 0.166 \quad V_{sc}^{-0.59} \tag{11}$$

with a value for the determination coefficient R^2 of 0.78.

Thus, based on Eq. (11) that correlates a geometrical parameter of the screenhouse construction with the C_w, on the C_d coefficient of the screen, which is related to its geometrical characteristics, and using the ventilation model proposed in this study (Eq. (5)), it could be possible to calculate the ventilation performance of any flat roof screenhouse.

5. Concluding remarks

A good correlation was observed between the inside and outside air velocity measurements in the three screenhouses. The reduction of air velocity was higher in the case of insect proof screenhouses compared to the screenhouse covered by the shading screen, something that was in agreement with the differences in the porosity and permeability of the screens. The internal air velocity in the insect proof and the shading screenhouses was about 20% and 44%, respectively, of that measured outside. The discharge coefficient C_{ds^*} of the screens was estimated by means of wind tunnel experiments and was found to be 0.465 and 0.795, for the insect proof and shading screen, respectively.

A good correlation was found between the air exchange rate values calculated using the tracer gas method and the air velocity measured outside the screenhouses. The data were used to calibrate a model for the prediction of screenhouse ventilation rate related to the discharge (C_d) and the wind effect (C_w) coefficients. The value of the overall pressure drop and wind effect coefficient $\left(C_d\sqrt{C_w}\right)$ coefficient observed for the insect proof screenhouses was 0.026 while the respective value estimated for the shaded screenhouse was 0.072.

Finally, it was found that the ventilation rate observed in the experimental, small scale screenhouses was much higher to that observed in commercial, large scale screenhouses. A generalisation of the results was attained and a method for estimating the ventilation performance for screenhouses with different volume and screens was proposed.

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