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RESEARCH ARTICLE

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Effect of material ageing and dirt on the behaviour of greenhouse insect-proof screens

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Abstract

The present work examines the variations in the aerodynamic characteristics of four insect-proof screens by means of wind tunnel tests and digital image processing. The tested insect-proof screens were examined in three different conditions: (i) in their new, unused state; (ii) under conditions of accumulated dust and dirt after a period of 3 to 4 years of use; and (iii) under clean conditions after a period of 3 to 4 years of use and a cleaning treatment with high-pressure water. The deterioration of the screens caused the mesh to become less tense, therefore increasing its thickness and improving its aerodynamic behaviour despite a slight increase of the thread diameter and a subsequent decrease of the 2-dimensional porosity. The pressure drop coefficient, F_φ, of the used but clean screens was 1.5% to 8.8% lower (for u=1.0 m/s) than that of the new ones, thus increasing the discharge coefficient, $C_{d,\varphi}$, by between 0.8% and 4.8% as a result of the presence of the screens. On the other hand, comparison of the used screens in their clean and unclean states showed that the accumulation of dirt has a major bearing on their aerodynamic characteristics: F_φ increased by between 16.5% and 61.2% (for u=1.0 m/s) for the unclean screens, resulting in a $C_{d,\varphi}$ reduction of between 7.5% and 21.3% and therefore a lower natural ventilation capacity of the greenhouse. A regular cleaning treatment of the insect-proof screens is a simple measure that improves the natural ventilation capacity of the greenhouse.

Additional keywords: anti-insect screens; aerodynamic characterisation; accumulation of dust and dirt; deterioration.

Abbreviations used: *a*, *b* and *c* (second-order polynomial regression coefficients); *e* (thickness [μm]); *u* (air velocity [m/s]); *x* (direction of airflow); $C_{d,\varphi}$ (discharge coefficient due to the presence of insect-proof screens); CFD (computational fluid dynamics); D_h (diameter of the threads [μm]); D_{hx} (diameter of the weft threads [μm]); D_{hy} (diameter of the warp threads [μm]); D_i (diameter of the inside circumference of the pore [μm]); D_r (thread density measurement [threads/cm^2]); F_φ (pressure drop coefficient due to the presence of an insect-proof screen); HDPE (high density polyethylene); K_p (screen permeability [m^2]); L_{px} (length of the pore in the direction of the weft [μm]); L_{py} (length of the pore in the direction of the warp [μm]); *P* (pressure [Pa]); R^2 (coefficient of determination); Re_p (Reynolds number based on the screen's permeability); S_p (area of the pore [mm^2]); S_t (reference surface area [mm^2]); *Y* (inertial factor). **Greek letters:** μ (dynamic viscosity of air [kg s^{-1} m^{-1}]); φ (porosity [m^{-2} m^{-2}]); φ^* (estimated imaging porosity [m^{-2} m^{-2}]); ρ_a (air density [kg m^{-3}]); ΔP (pressure drop due to the presence of an insect-proof screen [Pa]).

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Introduction

Insect-proof screens are a widespread means of preventing the entrance of harmful insects into greenhouses. Insect-proof screens are commonly manufactured with HDPE monofilament-woven fabrics of different densities of warp and weft threads (threads/cm^2). In the Mediterranean Basin, the use of insect-proof screens in greenhouse vents is a standard crop management practice; in the Province of Almería, Spain, insect-proof screens are employed in the side and roof vents in 99.1% and 95.4% of the greenhouses, respectively (Valera *et al.*, 2016). These screens are installed to reduce the incidence of harmful insects inside the greenhouse (Baker & Jones, 1989; Teitel, 2007) and to impede the exit of biological-control insects that are beneficial for the crop (Teitel, 2007).

A number of research works have highlighted the negative effect of insect-proof screens on the greenhouse ventilation capacity and, by extension, on the greenhouse microclimate. Screens of low porosity increase both the temperature and the humidity inside the greenhouse (Fatnassi *et al.*, 2002), decrease air velocity inside the greenhouse (Kittas *et al.*, 2008) and increase the vertical temperature gradient (Soni *et al.*, 2005), all of which have negative repercussions on crop growth and development (Teitel, 2010). Teitel (2007) published a review describing the negative effects of insect-proof screens in greenhouses, namely: (i) a reduction of the discharge coefficient of the vents, of the air velocity and of the turbulent kinetic energy of the air inside the greenhouse, resulting in a decrease of the capacity of the greenhouses to be cooled by natural ventilation; (ii) a reduction of light transmission; and (iii) an increase of temperature and humidity inside the greenhouse. A more detailed description of the negative effects of the use of insect-proof screens in greenhouses was presented in a previous work by López *et al.* (2013), where the effect of ageing and the accumulation of dirt on the geometrical characteristics of screens was studied. Other studies have analysed the geometric characteristics of insect-proof screens (Álvarez *et al.*, 2012) and their aerodynamic behaviour by means of wind tunnel experiments (Miguel *et al.*, 1997; Dierickx, 1998; Valera *et al.*, 2005, 2006) or Computational Fluid Dynamics (CFD) simulations (Valera *et al.*, 2005; Teitel, 2010).

In addition to determining the geometric and aerodynamic characteristics of the insect-proof screens, it is of great interest to quantify the influence of both the deterioration of the screens and the accumulation of dirt over time on these characteristics and thus on the natural ventilation capacity of the greenhouse. Among the few research works in this field of study, Linker *et al.* (2002) found that two months after installing a 50-mesh screen (porosity of 0.36) in a 50 m^2 greenhouse in Israel, the pressure drop coefficient of the screen can increase by a factor of up to 20 (from 12 to 200). López *et al.* (2013) studied the effect of the deterioration of the screen over time and of the accumulation of dirt on the geometric characteristics of 4 insect-proof screens. The authors found that the thread diameter increased by between 2.1 and 3.9% and resulted in a reduction in the two-dimensional porosity φ of between 4.9 and 10.4% and a reduction of the porosity by up to 21.2% as a result of the accumulation of dust.

The effect of material aging and the accumulation of dirt on the geometrical and aerodynamic characteristics of insect-proof screens is of great research interest since their placement in the greenhouse vents negatively affects the ventilation capacity of the greenhouses (Kittas *et al.*, 2008; Molina-Aiz *et al.*, 2009) and, as a consequence, its microclimate (Fatnassi *et al.*, 2002; Soni *et al.*, 2005) and crop yield (Teitel, 2010). Moreover, the determination of the geometrical and aerodynamic characteristics of the insect-proof screens is necessary in energy balance models (Reyes-Rosas *et al.*, 2017) and CFD simulations (Chu *et al.*, 2017; Molina-Aiz *et al.*, 2005) in order to predict climatic conditions in space and/or time in greenhouses in a variety of situations. The change of the characteristics of insect-proof screens as a result of their use over time is also a topic of interest for future research.

Kitta *et al.* (2014) studied the effect of the optical properties of greenhouse covers on pepper productivity. Three types of screens were analysed in this study: a pearl insect-proof screen (transmittance to photosynthetically active radiation PAR of 78%), a white insect proof screen (59%) and a green shade screen (62%). The best agronomic results were obtained with the pearl insect-proof screen. Sangpradit (2014) analysed the effect of the material ageing and the accumulation of dirt on the optical characteristics of greenhouse cover materials. The influence of the accumulation of dust and dirt on the solar radiation transmissivity of polyethylene plastic films and of a variety of cleaning methods (jet cleaning, water jet cleaning and hand washing) was analysed in the study. Results showed that the average light transmissivity after 6 months decreased between 36% and 50% but that the mean transmission loss dropped to only 1% after the plastic film was cleaned. However, notable differences between cleaning methods were also apparent: the use of jet air with no additional treatment hardly improved the light transmissivity, whereas water jet cleaning improved the transmissivity drastically.

The aim of this work was to analyse the effect of material aging and the accumulation of dirt on the aerodynamic characteristics of the HDPE monofilament-woven fabrics that are employed as insect-proof screens in greenhouses. Variations in the aerodynamic behaviour of screens affect the ventilation capacity of greenhouses and therefore crop production. As a result, knowledge of the effect of material ageing and of the accumulation of dirt on the screen permeability is fundamental for an accurate estimation of ventilation capacity in greenhouse modelling. This work complements the information presented in the previous study by López *et al.* (2013), in which the geometric characteristics of used insect-proof screens were analysed.

Material and methods

In this study, wind tunnel experiments were performed on samples from four screens with the objective of determining the effect of material aging and of the accumulation of dirt on the aerodynamic characteristics of insect-proof screens. Insect-proof screens were assessed in three different conditions: (i) newly installed, (ii) after 3 to 4 years of use with no cleaning treatment, and (iii) after 3 to 4 years of use after a high-pressure water cleaning treatment.

Experimental setup

The four insect-proof screens manufactured with HDPE monofilament-woven fabrics were installed in the side vents of two multi-span, naturally-ventilated greenhouses located at the agricultural research station of the University of Almería in south-eastern Spain (36° 51′ N, 02° 16′ W and 87 masl). Both Greenhouse 1 (24×45 m) and Greenhouse 2 (18×45 m), were divided in half by a polyethylene sheet. Natural ventilation consisted of two side vents (18×45 m) and three roof vents in Greenhouse 1, and of two side vents and two roof vents in Greenhouse 2 as described in López *et al.* (2013). The screen samples used for analysis were randomly taken from the side vents. The dimensions of the vents were 1.05×17.5 m and 1.05×22.5 m for the western and eastern half of the greenhouses, respectively, except for the northern side vents of Greenhouse 2, whose vents had a dimension of 1.05×15.0 m and 1.05×20.0 m for the western and eastern half, respectively.

Screens 1 and 2 were installed in August 2007 (date of purchase July 2007), and screens 3 and 4 in September 2008 (date of purchase August 2008). The mechanisms used to hold the insect-proof screens in the side vents did not affect the integrity of the screens over time: U-shaped (omega) metal frames were attached to the vent structure, and the screen was then inserted and held in place by polyethylene stoppers, ensuring that the screens were not subjected to movements that may have affected their structure during usage, according to the method described in López *et al.* (2013). The four screens were removed from the greenhouses in September 2011.

Estimation of the porosity of unwashed insect-proof screens

Screen 1 had a thread density of 13×30 threads/cm^2 and was designed by the Engineering Department of the University of Almería. Screens 2, 3 and 4 are commercial models with a thread density of 10×20 threads/cm^2. The two-dimensional geometric characteristics of the new screens and the cleaned and uncleaned used screens (Table 1) were determined using specific software (Álvarez *et al.*, 2012). For each screen, three samples of approximately 2.04 cm^2 were analysed. Twenty-four images were taken of each sample with a microscope that incorporated a Motic DMWB1-223 digital camera (MoticSpain S.L., Barcelona, Spain) with a 4× lens and a resolution of 10.5 µm/pixel. The analysis of each image included the geometric characteristics of 30 pores, 2 wefts and 9 warp threads (mesh 1) and 12 pores, 1 weft

Table 1. Geometric characteristics of the new screens (New) and the clean used screens. Average value and standard deviation of: D_r, thread density [threads/cm^2], determined with specific software; φ, porosity [m^2/m^2]; L_{px} and L_{py}, the lengths of the pore [µm] in the direction of the weft and warp, respectively; D_{hx} and D_{hy}, diameter [µm] of the weft and warp threads, respectively; D_h, diameter of the threads [µm]; D_i, diameter of the inside circumference of the pore [µm]; S_p, area of the pore [mm^2]. N: number of the screen. Extracted from López *et al*. (2013).

N		D_r	φ^*	L_{px}^{**}	L_{py}^{**}	D_{hx}^{***}	D_{hy}^{****}	D_h^{**}	D_i^{**}	S_p^{**}
1	New	13.1×30.5	0.390±0.006 ^{b}	164.6±9.3 ^{b}	593.3±19.0 ^{b}	168.6±6.6 ^{a}	163.1±6.3 ^{a}	165.5±7.0 ^{a}	167.4±9.6 ^{b}	0.098±0.006 ^{b}
	Old and washed	13.4×30.7	0.371±0.006 ^{a}	156.5±10.7 ^{a}	574.6±19.3 ^{a}	170.5±6.0 ^{b}	169.3±6.0 ^{b}	169.8±6.0 ^{b}	159.7±10.8 ^{a}	0.090±0.007 ^{a}
2	New	9.9×19.7	0.335±0.011 ^{b}	233.7±23.9 ^{b}	734.0±29.2 ^{b}	276.4±11.2 ^{a}	273.4±10.7 ^{a}	274.5±11.0 ^{a}	236.6±24.0 ^{b}	0.171±0.019 ^{b}
	Old and washed	10.0×20.2	0.300±0.011 ^{a}	208.3±23.8 ^{a}	719.9±41.2 ^{a}	283.0±9.7 ^{b}	286.6±10.4 ^{b}	285.3±10.3 ^{b}	212.2±23.9 ^{a}	0.150±0.019 ^{a}
3	New	9.2×20.7	0.375±0.007 ^{b}	234.9±16.1 ^{b}	838.7±27.0 ^{b}	245.8±7.1 ^{a}	248.0±8.3 ^{a}	247.2±7.9 ^{a}	238.7±16.4 ^{b}	0.197±0.015 ^{b}
	Old and washed	9.2×20.7	0.355±0.004 ^{a}	225.8±16.2 ^{a}	828.4±22.5 ^{a}	257.0±5.3 ^{b}	256.9±8.7 ^{b}	256.9±7.6 ^{b}	231.6±16.5 ^{a}	0.187±0.014 ^{a}
4	New	10.1×20.0	0.379±0.007 ^{b}	256.6±14.3 ^{b}	736.4±17.1 ^{b}	256.8±8.3 ^{a}	243.7±8.2 ^{a}	248.6±10.4 ^{a}	259.8±14.4 ^{b}	0.189±0.011 ^{b}
	Old and washed	10.3×20.2	0.359±0.011 ^{a}	244.1±15.6 ^{a}	716.0±23.0 ^{a}	256.7±11.2 ^{a}	252.3 ± 9.4 ^{b}	253.9±10.3 ^{b}	246.7±15.8 ^{a}	0.174±0.013 ^{a}

Statistical analysis made with 3 samples of each screens with 24 images (*72 data) and 12 or 30 pores per image in function of the screen (**864 or 2160; ***432 or 1440; ****720 or 1944 data). ^{a,b} denote that there were statistical differences at the 99.0% confidence level between the different geometric parameters measured for the new and the clean used screens.

and 5 warp threads (meshes 2, 3 and 4). The following steps were performed for each color digital image of the fabric: (i) the images were converted to grayscale; (ii) a gray colour was manually assigned to the areas of the pores to be analysed; (iii) the gray areas corresponding to the pores were converted to white by the software, leaving the rest of the image black; (iv) the vertices of each pore were automatically identified by the software; (v) the correct identification of the vertices was verified by the user, who could then correct any potential errors caused by the software; and, finally, (vi) the relevant geometric parameters were calculated by the software. The following parameters were obtained: thread density D_r (weft × warp) [threads/cm^2]; porosity φ [m^2/m^2]; weft pore length L_{px} and warp pore length L_{py} [m]; weft diameter D_{hx} and warp diameter D_{hy} [m]; mean thread diameter D_h [m]; pore circumference diameter D_i [m]; and pore surface area S_p [mm^2]. Further details on the methodology used for the digital image processing can be found in Álvarez *et al.* (2012). In addition, the effect of the deterioration of the screen and of the accumulation of dirt on its two-dimensional geometric characteristics was analysed in a previous work (López *et al.*, 2013).

Statistically significant differences were found between all the geometric parameters of the new screens and of the clean used screens, except for the D_{hx} of the 4 mesh (Table 1). The two-dimensional geometric methodology cannot provide a complete analysis of the unclean used screens due to the fact that the dirt particles observed in the mesh (Fig. 1) are highly heterogeneous and, as such, hinder an accurate measurement of the real geometry of the pore with our specific software (López *et al.*, 2013). This software calculates the porosity of the mesh φ (m^2/m^2) by comparing the calculated surface of the pores S_p and a total reference surface S_t, maintaining the correct proportion between pores surface area and the solid surface area (threads) (Álvarez *et al.*, 2012). Proportional allocation was performed by relating the surface area of every hole of the screen to a reference surface area defined by the longitudinal axes of the threads that define the associated hole (Álvarez *et al.*, 2012). As this software could not determine the porosity φ of the unclean used screens, the imaging porosity (φ^*) was estimated based on black and white digital images of the insect-proof screens. This procedure compares the number of white pixels (corresponding to the pores) with the total number of pixels in each image, resulting in a certain degree of error due to the difficulty of maintaining the correct proportion between pores and threads (López *et al.*, 2013).

Wind tunnel tests

The effect of time on the geometric characteristics on the insect-proof screens as described by López *et al.* (2013) was analysed in the present study by measuring the pressure drop caused by the screens. To this end, experiments were performed in a wind tunnel (Fig. 2) designed and developed at the University of Almería (Molina-Aiz *et al.*, 2006; Valera *et al.*, 2006). This wind tunnel was provided with an auto-tuning PI automatic control system and an open hardware and software platform as described in Espinoza *et al.* (2015). The pressure drop ΔP produced by the screen in the wind tunnel was measured by two Pitot tubes and a differential pressure transducer, whereas air velocity was measured by a hot-film anemometer. The wind tunnel had a length of 4.74 m and an experimental section diameter of 38.8 cm. Further details on the methodology for the tests and the characteristics of the wind tunnel can be found in Molina-Aiz *et al.* (2006), Valera *et al.* (2006), Espinoza *et al.* (2015) and López *et al.* (2016). The four insect-proof screens were tested under three different conditions: (i) the original, new screen, before installation in the greenhouse; (ii) the unclean screen after 3 to 4 years of use in the greenhouse; and (iii) the used screen after a cleaning treatment with a water jet. In all cases experiments were carried out on three randomly taken samples from each screen.

Although the wind tunnel allows testing at speeds of up to 10 m/s, the experiments were carried out at 0

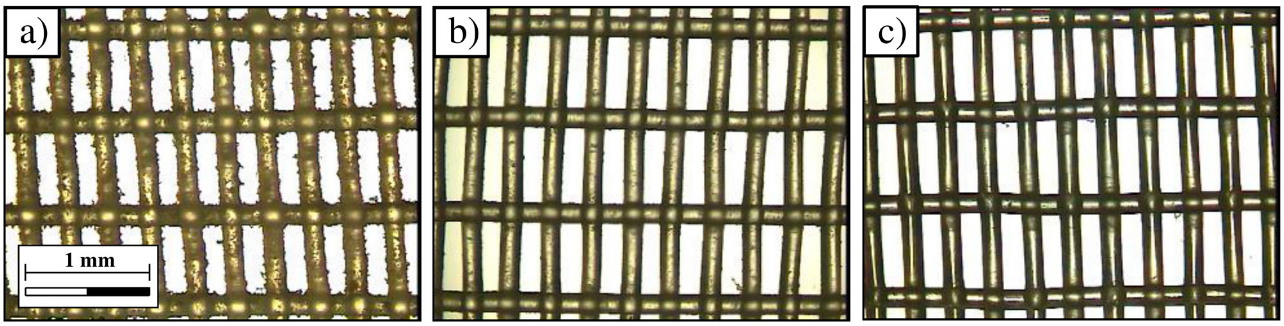

Figure 1. Images corresponding to insect-proof screen 1: microscope image of the unclean used screen (a), of the clean used screen (b) and of the original new screen (c).

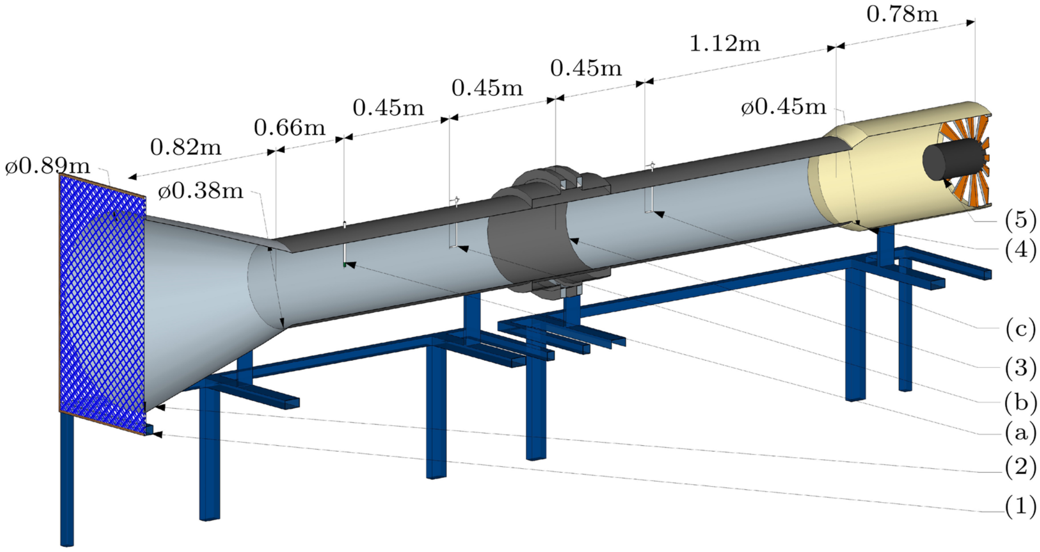

Figure 2. Wind tunnel used for the aerodynamic characterisation of the insect-proof screens: (1) flow conditioner; (2) contraction; (3) test section; (4) diffuser; (5) elastic joint clamp and fan. (a) hot-film anemometer and temperature probe; (b and c) Pitot tubes.

to 3 m/s to ensure that no damage to the sensors and wind tunnel components was caused when testing the unclean used screens. Once the screen is in place in the greenhouse, it is highly unlikely that the air velocity through it reaches the maximum tested speed of 3 m/s. In fact, the maximum air velocity registered at the vents in Greenhouse 1 with natural ventilation and with an insect-proof screen of 0.39 porosity was around 1.0 m/s in the study performed by López *et al.* (2012).

The wind tunnel experiments allow the determination of the pressure drop ΔP [Pa] caused by each insect-proof screen as a function of the air velocity through the porous medium u [m/s]. Thus, it is possible to determine the parameters that characterise the aerodynamic behaviour of the screens: K_p, the screen permeability [m^2], a coefficient that is independent of the nature of the fluid and dependent on the geometry of the porous medium (Nield & Bejan, 1998); Y, the inertial factor, a dimensionless drag constant that is dependent on the characteristics of the porous material; F_φ, the pressure drop coefficient; and, lastly, $C_{d,\varphi}$, the discharge coefficient that results from the presence of insect-proof screens.

The airflow through the porous medium (the insect-proof screen) can be described by modifying Darcy's equation (Forchheimer, 1901):

$$\frac{\partial P}{\partial x} = -\left(\frac{\mu}{K_p}\mathrm{u} + \rho_a\left(\frac{Y}{K_p^{1/2}}\right)|\mathrm{u}|\,\mathrm{u}\right) \tag{1}$$

where P is the pressure [Pa], x the direction of airflow, u the air velocity [m/s], μ is the dynamic viscosity of air [kg s^{-1} m^{-1}] and ρ_a is the air density [kg/m^3]. A second-degree polynomial can be used (Miguel *et al.*, 1997; Dierickx, 1998; Muñoz *et al.*, 1999) to adjust the experimental values of each pressure drop as a function of the air that passes through the porous medium (Molina-Aiz *et al.*, 2006; Valera *et al.*, 2006):

$$\Delta P = au^2 + bu + c \tag{2}$$

The zero-order term c can be neglected compared with the other terms a and b (Miguel *et al.*, 1997; Molina-Aiz *et al.*, 2009; López *et al.*, 2014, 2016). K_p and Y is then determined by equalling the first- and second-order coefficients of Eq. (2) with Eq. (1) (Molina-Aiz *et al.*, 2009):

$$K_p = e\,\frac{\mu}{b} \tag{3}$$

$$Y = \frac{a\,K_p^{0.5}}{\rho_a\,e} \tag{4}$$

The thickness e of the insect-proof screens was introduced in Eqs. (3) and (4) and was determined by using a TESA-VISIO 300 non-contact optical measurement device (TESA SA, Switzerland; resolution of 0.05 µm; uncertainty in measurement of (3+10·e/1000) [µm]). For the magnitude of the measurements taken the uncertainty was <10 µm.

Bernoulli's equation provides an alternative way of describing the relationship between the pressure drop caused by the insect-proof screens and the air velocity through the screens (Kosmos *et al.*, 1993; Montero *et al.*, 1997; Teitel & Shklyar, 1998):

$$\Delta P = -\tfrac{1}{2} F_\varphi \rho_a u^2 \tag{5}$$

where F_φ is the pressure drop coefficient as a result of the presence of an insect-proof screen, and can be obtained from Eqs. (1) and (5) for $\partial P/\partial x=\Delta P/e$ (Molina-Aiz *et al.*, 2009):

$$F_\varphi = \frac{2\,e}{K_p^{0.5}}\left(\frac{1}{\mathrm{Re}_p}+Y\right) \qquad (6)$$

The coefficient F_φ can be used to predict the pressure drop caused by the screens below a certain limit of the Reynolds number (Teitel, 2001). This limit is established at $\mathrm{Re}_p<10^5$ (Molina-Aiz *et al.*, 2009) when using a Reynolds number Re_p based on the permeability of the screen. Re_p can be obtained as follows (Nield & Bejan, 1998):

$$\mathrm{Re}_p = \frac{\sqrt{K_p}\,u\rho_a}{\mu} \qquad (7)$$

In addition, the discharge coefficient due to the presence of insect-proof screens $C_{d,\varphi}$ can be calculated as (Molina-Aiz *et al.*, 2009):

$$C_{d,\varphi} = 1/F_\varphi^{0.5} \qquad (8)$$

A similar discharge coefficient has been used in the literature for monofilament-woven fabrics (Wang *et al.*, 2007).

Statistical analysis

Regression analyses were carried out to study the relationship between different parameters (statistically significant for $p<0.05$), and in order to determine the statistical differences between geometric parameters. Multiple range tests were carried out applying Fisher's least significant difference (LSD) to determine the statistical differences between geometric parameters, establishing the confidence level at 99%. Statgraphics Plus (Manugistics Inc., Rockville, MD, USA) was used for all of these computations.

Results and discussion

The porosity values φ and the estimated imaging porosity φ^* were obtained for the four analysed screens. The following results show the pressure drop curves produced by the screens under three different conditions: (i) new, unused screens, (ii) unclean used screens, and (iii) clean used screens. The pressure drop coefficient F_φ, and the discharge coefficient that results from the presence of the insect-proof screens $C_{d,\varphi}$ are then presented, in both cases including an analysis of the effect of time and the accumulation of dirt on these values.

Porosity of unwashed old insect-proof screens

Table 2 presents the values of porosity φ and estimated imaging porosity φ^* for the four screens analysed under the three testing conditions. Based on these data, it has been found that the two parameters are related as follows: $\varphi = 0.941\cdot\varphi^* + 0.045$ ($R^2 = 0.85$ and $p = 0.001$), with statistical significance at the 95% confidence level. This expression differs from the one presented in López *et al.* (2013), as the present work analyses porosity data (φ and φ^*) of the new screens and the clean used screens for determining this expression, whereas the latter study only used the porosity data of the clean used screens. The values of the calculated porosity φ are higher than the estimated imaging porosity φ^* (Table 2) as a result of the reduction of the boundary areas of the images with incomplete pores. The interest of the above-mentioned equation that establishes the relationship between φ and φ^*, is that it allows the determination of the values of φ for the unclean used screens in those cases where the geometrical analysis for the identification of the pore vertices is not possible.

Compared to the new screens, the unclean used ones caused a reduction of the porosity φ of 16.4%, 26.6%, 15.7% and 25.3% for meshes 1 to 4, respectively.

Table 2. Average values (average value ± standard deviation) of the *estimated imaging porosity*, φ^* [m²/m²], and the porosity, φ [m²/m²], determined by the software.

N	φ^*			φ		
	Old and dirty	**Old and washed**	**New**	**Old and dirty**[1]	**Old and washed**	**New**
1	0.299±0.031 a	0.347±0.008 b	0.363±0.007 c	0.326	0.371±0.006 d	0.390±0.006 e
2	0.214±0.011 a	0.289±0.012 b	0.289±0.009 b	0.246	0.300±0.011 d	0.335±0.011 e
3	0.288±0.011 a	0.333±0.006 b	0.349±0.008 c	0.316	0.355±0.004 d	0.375±0.007 e
4	0.253±0.021 a	0.347±0.016 b	0.347±0.006 b	0.283	0.359±0.011 d	0.379±0.007 e

N: screen number. [1]: estimated with $\varphi = 0.941\,\varphi^* + 0.045$ ($R^2 = 0.85$ and $p = 0.001$). a,b,c indicate that there were statistical differences at the 99.0% confidence level between the values of the estimated imaging porosity φ^* for the new, clean used, and unclean used screens. d,e denote that there were statistical differences at the 99.0% confidence level between the values of the porosity φ for the new and clean used screens. Statistical analysis made with 3 samples of each screen with 24 images (72 data).

This reduction is the result of two effects, namely, the accumulation of dust and dirt and the deterioration of the threads. The separate consideration of both effects is a more useful indicator than the total reduction of porosity. Comparison of the new with the used screens, cleaned ones provided the following values for the reduction in porosity φ as a result of the deterioration of the screen: 4.9%, 10.4%, 5.3% and 5.3% for meshes 1 to 4, respectively.

The following values of reduction in porosity φ due to the accumulation of dust and dirt were obtained by comparing the cleaned and uncleaned used screens: 12.1%, 18.0%, 11.0% and 21.2% for meshes 1 to 4, respectively. These data differ from those presented by López *et al.* (2013) due to the modification of the expression [$\varphi = 0.941\ \varphi^* + 0.045$] that is used to estimate the porosity values φ of the unclean used screens.

In summary, deterioration of the screen mesh over time lead to a slight decrease in the two-dimensional porosity of the screen but the accumulation of dust and dirt produced a far greater reduction in this parameter. It could be argued that a reduction of the porosity of the screens should produce a reduction in the air permeability. However, this does not always hold true due to the fact that a variation in porosity produced by material ageing can also be associated with a modification in the tri-dimensional shape of the pore. This reinforces the need to perform aerodynamic analyses when determining the effect of material ageing and dirt on the screen permeability.

Variation in the pressure drop curves

Figure 3 shows the curves of pressure drop ΔP *vs.* air velocity u obtained from the wind tunnel experiments. Table 3 presents coefficients a, b and c of the fit obtained for Eq. (2), as well as parameters K_p, Y and the coefficient F_φ expressed as a function of Re_p, for screens 1, 2, 3 and 4. Baker & Shearin (1994) provided values for the maximum pressure drop that an insect-proof screen should allow, namely, 8 Pa for a clean screen and 24.9 Pa for an unclean one. For air velocities of between 1 and 1.5 m/s, all the samples of new screens and clean and unclean used ones showed values close to the above-mentioned limit of 8 Pa, while the clean and unclean used screens were both above this limit (screens 1, 2 and 3) (Fig. 3). Linker *et al.* (2002) found that the pressure drop caused by a 50-mesh insect-proof screen (porosity 0.36) increased from 3 Pa (original sample) to 30 Pa (2 months after its installation in the greenhouse) for air velocity values of u=0.65 m/s, *i.e.* a 10-fold increase in pressure drop. In the present study, for the same air velocity, comparison of the unclean used samples and the new ones at the same air velocity revealed a maximum pressure drop increase of ×1.5 for screen 4, well below the findings of Linker *et al.* (2002).

The pressure drop caused by the clean used screens was slightly lower to that caused by the new ones (Figs. 3b, 3c and 3d), except for screen 1 (Fig. 3a). The porosity values obtained for the new screens are higher than those

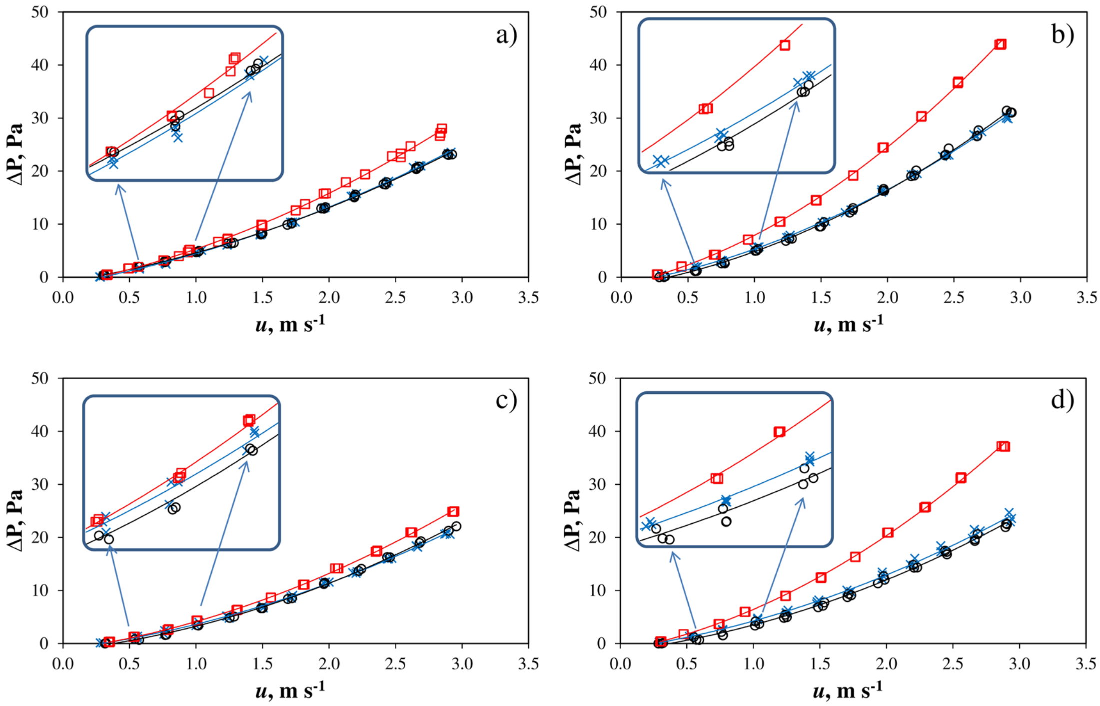

Figure 3. Pressure drops for insect-proof screens 1 (a), 2 (b), 3 (c) and 4 (d) in function of air velocity. ×, new; ○, clean used; □, unclean used.

Table 3. Aerodynamic characteristics of the insect-proof screens number 1–4: *e*, thickness [μm]; a, b and c are the coefficients of the polynomial fit from the wind tunnel tests (Eq. [2]); R^2, the fit determination coefficient; K_p, screen permeability [m^2]; *Y*, inertial factor; F_φ, pressure drop coefficient due to the presence of an insect-proof screen expressed as function of Re_p.

N		*e*	a	b	c	R^2	K_p	*Y*	F_φ
1	New	391.7±5.3 [a]	1.469	4.351	-1.375	0.999	1.631×10^{-9}	0.126	$19.40\times(Re_p^{-1} + 0.126)$
	Old and washed	415.6±41.7 [b]	1.480	4.092	-0.983	0.999	1.839×10^{-9}	0.127	$19.39\times(Re_p^{-1} + 0.127)$
	Old and dirty	*	1.921	4.757	-1.377	0.999	1.592×10^{-9}	0.154	$20.83\times(Re_p^{-1} + 0.154)$
2	New	563.8±5.7 [a]	2.301	4.281	-1.287	0.999	2.398×10^{-9}	0.167	$23.03\times(Re_p^{-1} + 0.167)$
	Old and washed	586.8±31.1 [b]	2.496	4.082	-1.760	0.999	2.585×10^{-9}	0.178	$23.08\times(Re_p^{-1} + 0.178)$
	Old and dirty	*	3.649	5.686	-1.436	1.000	1.881×10^{-9}	0.226	$27.06\times(Re_p^{-1} + 0.226)$
3	New	525.9±27.6 [a]	1.549	3.119	-1.050	0.999	3.057×10^{-9}	0.135	$19.02\times(Re_p^{-1} + 0.135)$
	Old and washed	627.9±38.2 [b]	1.768	2.794	-1.311	0.999	4.095×10^{-9}	0.151	$19.63\times(Re_p^{-1} + 0.151)$
	Old and dirty	*	1.882	3.430	-1.181	1.000	3.337×10^{-9}	0.145	$21.74\times(Re_p^{-1} + 0.145)$
4	New	480.2±11.2 [a]	1.698	3.580	-1.040	0.996	2.449×10^{-9}	0.147	$19.41\times(Re_p^{-1} + 0.147)$
	Old and washed	559.1±50.8 [b]	1.808	3.072	-1.383	0.997	3.283×10^{-9}	0.153	$19.52\times(Re_p^{-1} + 0.153)$
	Old and dirty	*	3.063	4.711	-1.347	0.999	2.163×10^{-9}	0.213	$24.04\times(Re_p^{-1} + 0.213)$

N: number of the screen. *The thickness of the unclean used screens is considered the same as that of the clean ones. It was not determined independently on criteria of safety and hygiene in the metrology laboratory. [a,b] denote that there were statistical differences at the 99.0% confidence level between the thickness measured for the new and clean used screens. Statistical analysis made with 3 samples of each screens with 10 thickness measurements (30 data).

of the clean used ones (Table 2), which does not explain why the latter produced a lower pressure drop than the former. The aerodynamic behaviour of the insect-proof screens depends not only on their porosity, but also on the geometry and thickness of the threads (López *et al.*, 2016). During manufacture the weft and warp threads are tensed, which may give rise to threads with an elliptic cross-section as opposed to a circular one (Wang *et al.*, 2007). Wang *et al.* (2007) found that for the same value of orthogonal or two-dimensional porosity, the discharge coefficient of the screens ($C_{d,\varphi}$) was lower for threads with an elliptic cross-section than for those with a circular one. In the present work, the values of thread diameter and thickness were greater for the clean used screens than for the new ones, with significant statistical differences at the 99.0% confidence level (Tables 1 and 3). The initial tensing of the mesh may relax with time, and this, together with the deterioration of the threads, may cause the cross-section of the threads to increase, resulting in a more circular cross-section in the used screens, as compared to a more elliptic cross-section in the new ones. The difference in the thread cross-section and the fact that the mesh is less tense would explain the increase registered in the thickness of the screens over time (Table 3). The greater thickness and the more circular cross-section of the threads are the reasons why the pressure drop recorded is lower in the clean used screens than in the new ones.

The values determined for K_p and *Y* do not depend solely on the screens' porosity of the screens, but also on other geometric characteristics (thread diameter, thread geometry, thickness, etc.) (López *et al.*, 2016) which vary over time. Although Miguel *et al.* (1997) and Teitel (2001) indicated that K_p increases with porosity, in the present study this was not the case. The permeability K_p of the new screens was inferior to that of the clean used ones (Table 3), which were less porous but thicker. The accumulation of dust and dirt implied that the permeability K_p of the unclean used screens was the lowest. As regards inertia *Y*, Teitel (2001) found that it increased with the porosity of the screen, whereas Miguel *et al.* (1997) did not find such a relationship. In the present study, no clear link between *Y* and porosity or any other of the screens' geometric parameters of the screens was found.

It should be highlighted that the passage of time, together with the exposure to environmental conditions, produces two contrasting effects on the aerodynamic behaviour of the screens. On the one hand, the deterioration of the mesh causes it to become less tense, resulting in a lower pressure drop (Figs. 3b, 3c and 3d). On the other hand, the accumulation of dust and dirt in the mesh leads to a much greater pressure drop through the screen.

Comparison of the screens by analysis of the parameters K_p and *Y* is difficult. Due to the fact that there is no clearly observable tendency, it is considered more suitable to analyse the effect of the deterioration and the accumulation of dirt in the screens on the pressure drop coefficient $F_{d,\varphi}$ and on the discharge coefficient due to the presence of insect-proof screens $C_{d,\varphi}$ as a result of the presence of insect-proof screens.

Variation in the pressure drop coefficient F_φ

The pressure drop coefficient F_φ was clearly greater for the unclean used screens than for the new ones and the clean used ones (Table 4). On the other hand, F_φ was slightly lower for the clean used screens than for the new ones. As commented above, this difference may be due to the deterioration and the tension loss, which increase the thickness of the mesh and the spherical shape of the threads. To compare the F_φ values of the different screens, the following air velocity *u* values were considered: 0.25, 0.5 and 1.0 m/s. It is considered that the maximum values of air velocity through the vents of a commercial greenhouse using natural ventilation are unlikely to exceed 1.0 m/s, as was observed in the literature by using sonic anemometry (López *et al.*, 2012).

Comparison of the unclean used screens and the new ones revealed increases in F_φ of between 36.0% (screen 2 for *u*=0.25 m/s) and 47.0% (screen 4 for *u*=1.0 m/s). The cleaning treatment on the used screens caused the value of F_φ to decrease with respect to the new screens, although this decrease is only relevant in the case of screen 4 (8.8% for *u*=1.0 m/s). Studying the effect of the accumulation of dirt in isolation, comparison of the unclean and clean used screens reveals an increase in F_φ of between 16.5% (screen 3) and 61.2% (screen 4), for *u*=1.0 m/s (Table 4). From Eqs. (6) and (7) we can deduce a linear relation between the pressure drop coefficient F_φ and the inverse of air velocity, whose slope is $2e\mu$ / $(K_p\rho)$. Since the thickness *e* was considered the same for the unclean and clean used screens, and the permeability of the clean used screens was always greater than that of the unclean used screens (Table 3), the above-mentioned slope was always greater for the unclean used screens than for the clean used screens. As a consequence, the difference between F_φ values increases as the air velocity drops (and therefore 1/*u* increases), as we can observe in Fig. 4. Thus, the greater differences in F_φ are produced when air velocity thought the greenhouse screens is lower than 0.3 m/s, (1/*u* > 3.3 s/m). This situation corresponds when greenhouse ventilation is deficient and the effect of the screen on the greenhouse microclimate is more important.

Variation in the discharge coefficient due to the presence of insect-proof screens $C_{d,\varphi}$

Once the values of F_φ are known, the values of the discharge coefficient $C_{d,\varphi}$ for each screen can be derived from Table 4 by using Eq. (8). Comparison of the unclean used screens with the new ones reveals a reduction in $C_{d,\varphi}$ of between 5.3% (screen 3 for *u*=0.25 m/s) and 17.6% (screen 4 for *u*=1.0 m/s). When comparing the clean used screens with the new ones to study the effect of the deterioration of the mesh in isolation, it can be noticed that there is a slight increase in $C_{d,\varphi}$ of between 0.8% (screen 3 *u*=1.0 m/s) and 7.3% (screen 4 for *u*=0.25 m/s). When studying the effect of the accumulation of dirt in isolation by comparing the clean and unclean used screens, the reduction in $C_{d,\varphi}$ is between 7.5% (screen 3) and 21.3% (screen 4), in both cases for *u*=1.0 m/s (Table 4).

Table 4. Values of the pressure drop coefficient F_φ and of the discharge coefficient due to the insect-proof screen $C_{d,\varphi}$ for *u* equal to 0.25, 0.5 and 1.0 m/s, for the new screens, clean used screens, and unclean used screens.

u	Screen	F_φ			$C_{d,\varphi}$		
		New	Washed old screen	Unwashed old screen	New	Washed old screen	Unwashed old screen
0.25 m/s	1	31.36	29.63	35.06	0.179	0.184	0.169
	2	32.48	31.00	44.17	0.175	0.180	0.150
	3	23.32	21.66	26.11	0.207	0.215	0.196
	4	26.87	23.30	36.66	0.193	0.207	0.165
0.5 m/s	1	16.90	16.05	19.14	0.243	0.250	0.229
	2	18.16	17.55	25.14	0.235	0.239	0.199
	3	12.95	12.31	14.63	0.278	0.285	0.261
	4	14.86	13.15	20.90	0.259	0.276	0.219
1 m/s	1	9.67	9.25	11.18	0.322	0.329	0.299
	2	11.00	10.83	15.62	0.301	0.304	0.253
	3	7.76	7.63	8.89	0.359	0.362	0.335
	4	8.85	8.07	13.01	0.336	0.352	0.277

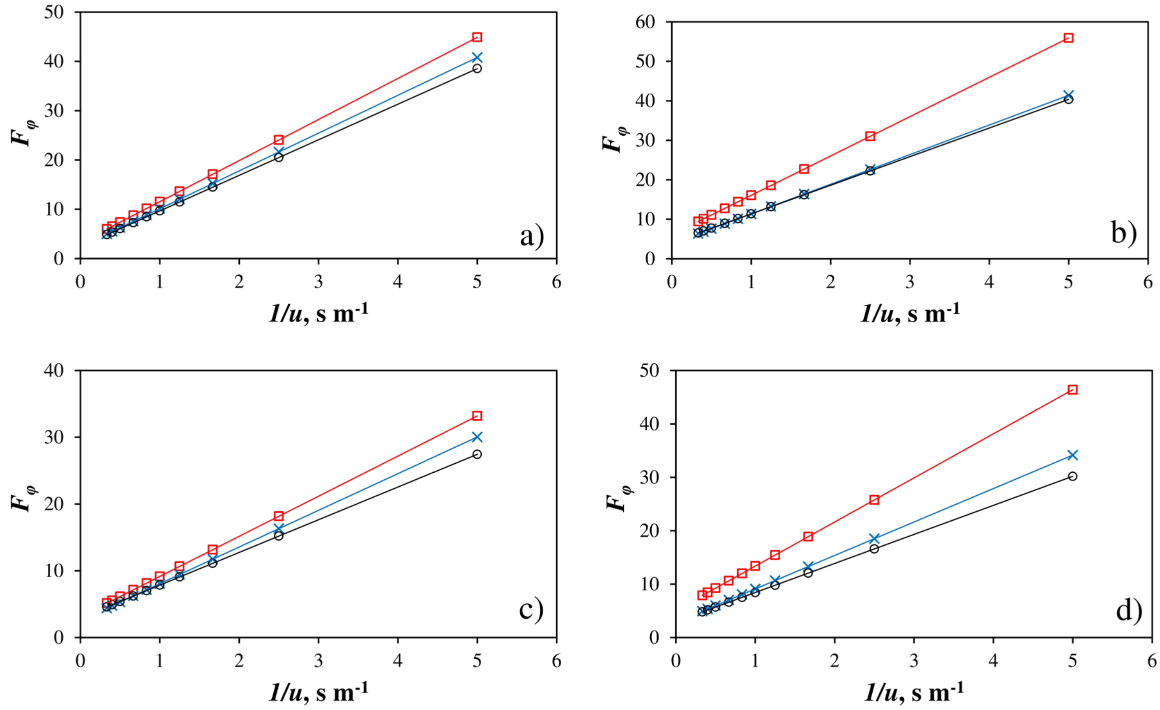

Figure 4. Pressure drop coefficient Fφ of the insect-proof screens 1 (a), 2 (b), 3 (c) and 4 (d) in function of the inverse of air velocity (1/u). ×, new; ○ clean used; □, unclean used.

Fatnassi *et al.* (2002) found that the ratio between the air renewal rate (h^{-1}) in a greenhouse with and without insect-proof screens can be considered proportional to the ratio between the discharge coefficients at the vents. In turn, the discharge coefficient at the vents depends on the coefficient $C_{d,\varphi}$. The reduction observed in the coefficient $C_{d,\varphi}$ due to the accumulation of dust and dirt on the insect-proof screens results in a reduction of the natural ventilation capacity of the greenhouse.

Conclusions

The comparison of clean used screens with new ones showed a reduction of the pressure drop coefficient F_φ of up to 8.8% (screen 4 for u=1.0 m/s). The maximum increase in the discharge coefficient $C_{d,\varphi}$ was 7.3% (screen 4 for u=0.25 m/s). This may be due to the deterioration of the insect-proof screens over time as it causes the mesh to become less tense, therefore increasing its thickness and improving its aerodynamic behaviour.

In addition, the accumulation of dirt on the screens has a major bearing on their aerodynamic characteristics. Comparison between the clean and unclean used screens showed an increase in F_φ of up to 61.2% (screen 4 for u=1.0 m/s) and a decrease in $C_{d,\varphi}$ of up to 21.3% (screen 4 for u=1.0 m/s), with a concomitant reduction of the natural ventilation capacity of the greenhouse.

In view of the results obtained in the present work, it is recommended that insect-proof screens are manufactured with geometrical and aerodynamic characteristics that avoid approaching the limit of 8 Pa established by Baker & Shearin (1994) at an air velocity of between 1 and 1.5 m/s. Furthermore, it is advisable to incorporate anti-static properties in order to avoid the accumulation of dirt as much as possible. From an experimental point of view, it is also important to take into account the differences between the aerodynamic characteristics of new insect-screen and deteriorated, unclean insect-proof screens in order to avoid significant errors in the CFD simulation or in the climatic greenhouse models.

Lastly, we can conclude that the mechanical deformation of screens over time produces a reduction of the resistance to airflow throughout the insect-proof screens installed in the greenhouse openings, whereas ventilation is hindered by the dirt accumulation. A regular cleaning treatment of the insect-proof screens is a simple measure that improves ventilation inside the greenhouse and avoids major reductions in the natural ventilation capacity of the greenhouse, as quantified in the present study. Future research will focus on the study of the effect of material degradation and accumulation of dust on the optical properties of the insect-proof screens and on crop productivity.

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References

Álvarez AJ, Oliva RM, Valera DL, 2012. Software for the geometric characterisation of insect-proof screens. Comput Electron Agr 82: 134-144. https://doi.org/10.1016/j.compag.2012.01.001

Baker JR, Jones RK, 1989. Screening as part of insect and disease management in the greenhouse. NC Flower Growers' Bulletin 34: 1-9. https://hortscans.ces.ncsu.edu/uploads/s/c/screenin_53e4f3cf4132a.pdf [10 April 2017]

Baker JR, Shearin EA, 1994. An update on screening for the exclusion of insect pests. NC Flower Growers' Bulletin 39 (2): 6-11. http://hortscans.ces.ncsu.edu/library/floriculture/doc_id/3625/An-Update-on-Screening-for-the-Exclusion-of-Insect-Pests.pdf [10 April 2017]

Chu CR, Lan TW, Tasi RK, Wu TR, Yang CK, 2017. Wind-driven natural ventilation of greenhouses with vegetation. Biosyst Eng 164: 221-234. https://doi.org/10.1016/j.biosystemseng.2017.10.008

Dierickx IE, 1998. Flow reduction of synthetic screens obtained with both a water and airflow apparatus. J Agr Eng Res 71: 67-73. https://doi.org/10.1006/jaer.1998.0299

Espinoza K, Valera DL, Torres JA, López A, Molina-Aiz FD, 2015. An auto-tuning PI control system for an open-circuit low-speed wind tunnel designed for greenhouse technology. Sensors 15: 19723-19749. https://doi.org/10.3390/s150819723

Fatnassi H, Boulard T, Demrati H, Bouirden L, Sappe G, 2002. Ventilation performance of a large Canarian-type greenhouse equipped with insect-proof nets. Biosyst Eng 82 (1): 97-105. https://doi.org/10.1006/bioe.2001.0056

Forchheimer P, 1901. Wasserbewegung durch Boden [Water movement from ground]. Z Ver Dtsch Ing 45: 1782-1788.

Kitta E, Baille AD, Katsoulas N, Rigakis N, González-Real MM, 2014. Effects of cover optical properties on screenhouse radiative environment and sweet pepper productivity. Biosyst Eng 122: 115-126. https://doi.org/10.1016/j.biosystemseng.2014.04.001

Kittas C, Katsoulas N, Bartzanas T, Mermier M, Boulard T, 2008. The impact of insect screens and ventilation openings on the greenhouse microclimate. T ASABE 51 (6): 2151-2165. https://doi.org/10.13031/2013.25396

Kosmos SR, Riskowski GL, Christianson LL, 1993. Force and static pressure resulting from airflow through screens. T ASAE 36 (5): 1467-1472. https://doi.org/10.13031/2013.28487

Linker R, Tarnopolsky M, Seginer I, 2002. Increased resistance to flow and temperature-rise resulting from dust accumulation on greenhouse insect-proof screens. Proc ASAE Annu Int Meet, Jun 28-31; Chicago (USA); Paper 024040; 9 pp.

López A, Valera DL, Molina-Aiz FD, Peña A, 2012. Sonic anemometry measurements to determine airflow patterns in multi-tunnel greenhouse. Span J Agric Res 10 (3): 631-642. https://doi.org/10.5424/sjar/2012103-660-11

López A, Valera DL, Molina-Aiz FD, Peña A, Marín P, 2013. Field analysis of the deterioration after some years of use of four insect-proof screens utilized in Mediterranean greenhouses. Span J Agric Res 11 (4): 958-967. https://doi.org/10.5424/sjar/2013114-4093

López A, Valera DL, Molina-Aiz FD, Peña A, Marín P, 2014. Microclimate evaluation of a new design of insect-proof screens in a Mediterranean greenhouse. Span J Agric Res 12 (2): 338-352. https://doi.org/10.5424/sjar/2014122-4956

López A, Molina-Aiz FD, Valera DL, Peña A, 2016. Wind tunnel analysis of the airflow through insect-proof screens and comparison of their effect when installed in a Mediterranean greenhouse. Sensors 16: 690. https://doi.org/10.3390/s16050690

Miguel AF, Van de Braak NJ, Bot GPA, 1997. Analysis of the airflow characteristics of greenhouse screening materials. J Agr Eng Res 67: 105-112. https://doi.org/10.1006/jaer.1997.0157

Molina-Aiz FD, Valera DL, Peña AA, Gil JA, 2005. Optimisation of Almería-type greenhouse ventilation performance with computational fluid dynamics. Acta Hortic 691: 433-440. https://doi.org/10.17660/ActaHortic.2005.691.52

Molina-Aiz FD, Valera DL, Álvarez AJ, Madueño A, 2006. A wind tunnel study of airflow through horticultural crops: determination of the drag coefficient. Biosyst Eng 93 (4): 447-457. https://doi.org/10.1016/j.biosystemseng.2006.01.016

Molina-Aiz FD, Valera DL, Peña AA, Gil JA, López A, 2009. A study of natural ventilation in an Almería-type greenhouse with insect screens by means of tri-sonic anemometry. Biosyst Eng 104: 224-242. https://doi.org/10.1016/j.biosystemseng.2009.06.013

Montero JI, Muñoz P, Antón A, 1997. Discharge coefficients of greenhouse windows with insect-proof screens. Acta Hortic 443: 71-77. https://doi.org/10.17660/ActaHortic.1997.443.8

Muñoz P, Montero JI, Antón A, Giuffrida F, 1999. Effect of insect-proof screens and roof openings on greenhouse ventilation. J Agr Eng Res 73: 171-178. https://doi.org/10.1006/jaer.1998.0404

Nield DA, Bejan A, 1998. Convection in porous media. Springer, NY, USA.

Sangpradit K, 2014. Study of the solar transmissivity of plastic cladding materials and influence of dust and dirt on greenhouse cultivations. Energy Procedia 56: 566-573. https://doi.org/10.1016/j.egypro.2014.07.194

Soni P, Salokhe VM, Tantau HJ, 2005. Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. Biosyst Eng 92 (4): 469-482. https://doi.org/10.1016/j.biosystemseng.2005.08.005

Reyes-Rosas A, Molina-Aiz FD, Valera DL, López A, Khamkure S, 2017. Development of a single energy balance model for prediction of temperatures inside a naturally ventilated greenhouse with polypropylene soil mulch. Comput Electron Agr 142: 9-28. https://doi.org/10.1016/j.compag.2017.08.020

Teitel M, 2001. The effect of insect-proof screens in roof openings on greenhouse microclimate. Agr Forest Meteorol 110: 13-25. https://doi.org/10.1016/S0168-1923(01)00280-5

Teitel M, 2007. The effect of screened openings on greenhouse microclimate. Agr Forest Meteorol 143 (3-4): 159-175. https://doi.org/10.1016/j.agrformet.2007.01.005

Teitel M, 2010. Using computational fluid dynamics simulations to determine pressure drops on woven screens. Biosyst Eng 105: 172-179. https://doi.org/10.1016/j.biosystemseng.2009.10.005

Teitel M, Shklyar A, 1998. Pressure drop across insect-proof screens. T ASAE 41 (6): 1829-1834. https://doi.org/10.13031/2013.17336

Valera DL, Molina FD, Álvarez AJ, López JA, Terrés-Nicoli JM, Madueño A, 2005. Contribution to characterization of insect-proof screens: experimental measurements in wind tunnel and CFD simulation. Acta Hortic 691: 441-448. https://doi.org/10.17660/ActaHortic.2005.691.53

Valera DL, Álvarez AJ, Molina FD, 2006. Aerodynamic analysis of several insect-proof screens used in greenhouses. Span J Agric Res 4 (4): 273-279. https://doi.org/10.5424/sjar/2006044-204

Valera DL, Belmonte LJ, Molina-Aiz FD, López A, 2016. Greenhouse agriculture in Almería. A comprehensive techno-economic analysis, Cajamar Caja Rural, Almería, Spain. http://www.publicacionescajamar.es/series-tematicas/economia/greenhouse-agriculture-in-almeria-a-comprehensive-techno-economic-analysis/ [10 April 2017]

Wang Q, Mazé B, Tafreshi HV, Pourdeyhimi B, 2007. On the pressure drop modeling of monofilament-woven fabrics. Chem Eng Sci 62 (17): 4817-4821. https://doi.org/10.1016/j.ces.2007.06.001