Europ.J.Hort.Sci., **69** (5). S. 235–243, 2004, ISSN 1611-4426. © Verlag Eugen Ulmer GmbH & Co. Stuttgart

Test of Insect Screens – Measurement and Evaluation of the Air Permeability and Light Transmission

F. Klose and H.-J. Tantau
(Institute of Horticultural and Agricultural Engineering, University of Hannover, Germany)

Summary

The air permeability and light transmission of 15 screens were evaluated at the Institute of Horticultural and Agricultural Engineering, University of Hannover. The air permeability of the screens was tested by fixing each screen on a frame and placing it on an open end of a wooden box (2×2×2 m) connected to a wind tunnel with a fan on the other end. From the measured data, the pressure loss coefficient (F_s) of the screen was computed. The light transmission was tested with an "Ulbricht-sphere", while the mesh size and thread thickness were investigated under a microscope. Insect screens have a well-defined structure that is characterised by the diameter (or width) of the thread (or fibre used), and the dimensions of the pores (BAILEY et al. 2003), hence the correlating pressure loss coefficient of the different insect screens was calculated.

The tested screens show a clear dependence of air speed on screen loss coefficient and Reynolds number. Moreover, the flow regime depends on the Reynolds number (Re). While porous materials have Reynolds numbers Re < 1, the investigated insect screens had Reynolds numbers 3.4 < Re < 144 at air velocities up to 1.1 m s^{-1}. The screen loss coefficient can only be expected to be constant at Reynolds numbers Re > 200.

As expected, the screens with the smallest mesh size (group 1) had the highest-pressure drop, while the opposite was observed for the screens with the biggest mesh size (group 4). However, this was not the case with the screens in the other groups. Therefore, when choosing a screen, it is important to include the open area (porosity), since it contains the thickness of the threads. Screens with a larger open area should be used, because of their better air permeability. However, in order to accurately determine the open area of a screen and thereby calculate the screen's pressure drop from the air speed, the information about the mesh size and thickness of the threads must be correct.

The screens with the biggest mesh size had the highest light transmission, but the screens with the smallest mesh size did not have the lowest transmission. Hence light transmission was influenced by other parameters such as the structure of the threads (wool threads) and, of course, contamination of the threads by dirt.

Zusammenfassung

Untersuchung von Insektenschutznetzen – Messung und Bewertung der Luft- und Lichtdurchlässigkeit. Am Institut für Technik in Gartenbau und Landwirtschaft wurde die Luft- und Lichtdurchlässigkeit von 15 Insektenschutznetzen bewertet. Die Luftdurchlässigkeit wurde mit einer Versuchsanlage untersucht, die aus Ventilator, Durchflussmessstrecke und Holzkasten (2×2×2 m) bestand, der an einer Seite offen war. In diese Öffnung wurde das jeweilige Netz, das auf einem Rahmen befestigt wurde, geschoben. Aus den ermittelten Ergebnissen wurden die netzspezifischen Druckverlustkoeffizienten (F_s-Werte) errechnet. Die Lichtdurchlässigkeit wurde mit Hilfe einer Ulbricht-Kugel bestimmt. Zusätzlich wurden die Maschenweiten und Fadenstärken der Netze unter dem Mikroskop ermittelt. Da Insektenschutznetze eine geordnete Struktur aufweisen, lassen sich mit Ansätzen aus der Literatur (BAILEY et al. 2003) die Druckverlustkoeffizienten berechnen. Die Strömung durch die Maschen des Netzes hängt entscheidend von der Reynoldszahl ab. Poröse Materialien haben Reynoldszahlen < 1. Für die untersuchten Netze ergeben sich Reynoldszahlen zwischen 3,4 und 144 (Luftströmungen bis ca. 1 m s^{-1}). In diesem Bereich ist der Druckverlustkoeffizient nicht konstant. Ab Re > 200 kann man mit konstanten Druckverlustkoeffizienten rechnen.

Wie erwartet, konnte festgestellt werden, dass die Netze mit den kleinsten Maschenweiten (Gruppe 1) die höchsten Drücke und Druckverlustkoeffizienten aufweisen. Das Gegenteil trifft für die Netze mit den größten Maschenweiten (Gruppe 4) zu. Bei den Netzen, die zwischen diesen Gruppen liegen, stimmte diese Aussage nur teilweise. Das liegt z. T. daran, dass die Angaben der Hersteller bezüglich der Maschenweite nicht genau genug sind und z. B. unterschiedliche Fadenmaterialien im selben Netz (Wollfäden) nicht mit angegeben werden. Es erscheint sinnvoll, die offene Fläche bei der Auswahl eines Netzes mit einzubeziehen, da dort die Fadenstärke mit eingeht. So sollten Netze mit höheren Werten für die offene Fläche (Porosität) ausgewählt werden, da diese eine bessere Luftdurchlässigkeit aufweisen. Jedoch müssen für eine genaue Bestimmung der offenen Fläche die Angaben für die Maschenweite und Fadenstärke exakt sein. Die ist auch die Voraussetzung für eine korrekte Berechnung des Druckverlustes in Abhängigkeit von der Strömungsgeschwindigkeit.

Key words. insect screens – air permeability – light transmission – pressure loss coefficient

Für die Lichtdurchlässigkeit konnte festgestellt werden, dass die Netze mit den größten Maschenweiten (Gruppe 4) die höchste Lichtdurchlässigkeit aufwiesen, jedoch die Netze mit den kleinsten Maschenweiten (Gruppe 1) nicht die geringste Lichtdurchlässigkeit besaßen. So wird die Lichtdurchlässigkeit z. B. durch andere Fadenstrukturen (z. B. Wollfäden), und insbesondere durch die Verschmutzung vermindert.

Introduction

The use of insect screens on greenhouse doors and vents is becoming more and more popular, since they reduce the entry of insects such as thrips, leaf miners, aphids and whiteflies into a greenhouse (BAKER and JONES 1989, 1990; BERLINGER et al. 1991, 1993), and keep organisms used for biological control within. Reduction in pesticide application due to the use of screens is an effective precaution in integrated pest management to protect the health of the workers and the environment (BAKER and JONES 1991, 1993). Another advantage of using screens is the reduction in production costs resulting from the use of fewer pesticides. Additionally, insect pests have become more and more resistant against pesticides, thus other pest-control methods must be used. In warmer climates, tunnels and greenhouses can entirely be covered with screens or have screens used in the window openings.

Generally, the type of screen to use depends on the insects that the grower intends to keep out of the greenhouse. Therefore the mesh size is important in determining the pests that will be repelled. For instance; thrips require the use of screens with smaller mesh size than whiteflies. However, the use of screens with small mesh sizes results in the reduction of air exchange (the smaller the mesh size, the less air exchange). This results in high temperatures and possibly higher air humidity in the greenhouse especially in summer. It is therefore important to know extend to which the screen reduces the air exchange, in order to take precautions that guarantee air exchange and thereby prevent excess temperatures. Although screens reduce light transmission, this can be an advantage in summer because it can help to protect the crops from sunburn.

Several authors have been involved in studying this subject before. BELL and BAKER (1995) realized the necessity to evaluate screens for their air exchange rate, and tested them for their efficiency to keep insect pests away. FUCHS et al. (1997) discovered that screens reduce the efficiency of fans, by causing more air resistance and higher pressure drop. All authors agree that screens reduce the air exchange, but they differ on the parameters describing the air resistance. BRUNDRETT (1993) found that the porosity of screens is affected by the structure of the threads, local damages, and the screen tension. After experimental testing with air and water, DIERICKX (1998) described a coefficient of air resistance for screens. He discovered a relationship between the open area and the air resistance. According to VON ZABELTITZ (2002) it is necessary to describe the screens with the mesh and the open area, because the open area includes the thickness of the threads. SASE and CHRISTIANSON (1990) and KAMARUDDIN et al. (2000) computed for various screens, a coefficient of discharge (C_d), which decreases with decreasing mesh size. When a screen is dirty, the C_d is drastically reduced. The pressure on the screen increases with decreasing mesh size, and rises by the square of the air velocity. KAMARUDDIN et al. (2000) described an apparatus for testing the light transmission and open area of screens. To compute the $C_{d,}$ he used an apparatus similar to the one used in this study. KOSMOS et al. (1993) discovered in different experiments that the air resistance and static pressure of screens rose exponentially with increasing air velocity. The air resistance and static pressure are affected by the mesh size, the structure, and the dimensional properties of a screen. The C_d varied more by low air velocities (with higher C_d) than by high velocities (with low C_d). MIGUEL et al. (1997) investigated the permeability of different screens (both theoretically and with an apparatus similar to the one in used this article), and reported that the pressure rose exponentially, with increasing air velocity. The shapes of the yarns and the mesh geometry have a negligible influence on the airflow characteristics of screening materials (MIGUEL et al. 1998). MIGUEL and SILVA (2000) found that under low air velocities the efficiency of the screen increased with the window area.

Some authors investigated the influence of screens with computer programs, and occasionally with a small apparatus. According to BARTZANAS et al. (2001) and FATNASSI et al. (2001a, b), the airflow and air velocity of a screen are reduced when the temperature rises, but the air distribution is better. DESMARAIS and RAGHAVAN (1996) tested alternative types of greenhouses and screens. They discovered that the type of greenhouse, as well as the screen, affects the temperature inside the greenhouse. By considering the pressure, air volume and air velocity, BAKER and SHEARIN (1994, 1995) developed a clear description of the steps to follow when choosing the right screen, including computing the required area needed when the screens are retrofitted. Diagrams for some screens show that with increasing air velocities, the pressure increases exponentially. BAKER and SHEARIN (1995) developed a computer program, to simplify the procedure for finding the right screen. BAILEY et al. (2003) used a test facility to determine the pressure differences required to create airflows through five insect screens and developed a correlation equation. This equation was shown to compare well with the majority of values derived from five publications, which reported data on 27 nets and screens. ROB-

ERTS (1995), MUÑOZ (1999) and MEARS and BOTH (2000, 2001) described, the constructions that can be used to enlarge the area of the screen. TAYLOR et al. (2001) investigated, whether or not it is economical to use screens.

The aim of this study was to investigate the light transmission and air permeability of 15 screens and evaluate the results. It was necessary to know the air velocity v_s (m s^{-1}) and the pressure difference p_s (Pa) from the static pressure both in front of and behind the screen.

Material and Methods

Measurements

15 different insect screens, (from the Netherlands (10), Israel, Germany and Thailand), were tested for their air permeability and light transmission. The thickness of the threads and the mesh size were measured under a microscope, after which all results were evaluated.

The air permeability was measured with an apparatus (Fig. 1) consisting of a wind tunnel with a fan at one end. The tunnel was connected to a wooden box (2×2×2 m), open at one side. The screens to be tested were attached to a frame, which was then fixed within the opening. The dynamic pressures for each screen were measured at different air velocities, with an inclined tube manometer (connected with a measuring rake to the wind tunnel). The dynamic pressure resulted from the total pressure p_{ges} in the wind tunnel and the static pressure p_{st} (atmospheric pressure). The pressure difference between the static pressure behind the screen and the room atmosphere was measured with a "Betz-Manometer". To get these values, two tubes were attached to the "Betz-Manometer": one led into the wooden box and the other hung "in the room". The air velocities and air volumes were determined for each screen by measuring the dynamic pressures in a wind tunnel attached to the wooden box.

Since it was not possible to adjust the motor of the fan in constant stages (in order to produce equal. air velocities), the pressure was regulated at the "Betz-Manometer" by increasing the air velocities in steps of 0.05 and 0.01 m s^{-1} for each screen. This was done for a better comparison of the screens later on. For each screen, four measurements were taken and the mean value was computed.

The distribution of pressure behind the screen was measured with a "Prandl-tube" on a slat mounted on one side of the wooden box. This was to ascertain whether the pressure was (nearly) constant and if the air at the edges of the wooden box flowed without turbulence. When this was not the case, an attempt was made to reduce the turbulence by mounting half of a tube on the edges of the wooden box. The difference between the total and static pressure (the dynamic pressure) was measured with the "Prandl-tube". Two screens were tested, with four repetitions each. The light transmission was tested with an "Ulbricht-sphere".

Computation of the physical values from the ascertained pressures

From the measured pressure differences of the inclined tube manometer (ten tubes), the mean value for each adjusted pressure difference (p_s) of the "Betz-Manometer" was computed. This mean value was then multiplied with the angle of the inclined tube manometer (sin 30°), in order to calculate the real. mean value (H_d). The following formula was used to compute the air velocity v_d (m s–1) in the wind tunnel (BOHL 1991):

$$V_d(m/s) = \sqrt{\frac{2 \cdot g \cdot \Delta p}{p_{air}}} \qquad (1)$$

$$g = 9.81 \frac{kg}{s^2 \cdot m} \qquad (=1 \text{ mm water column})$$

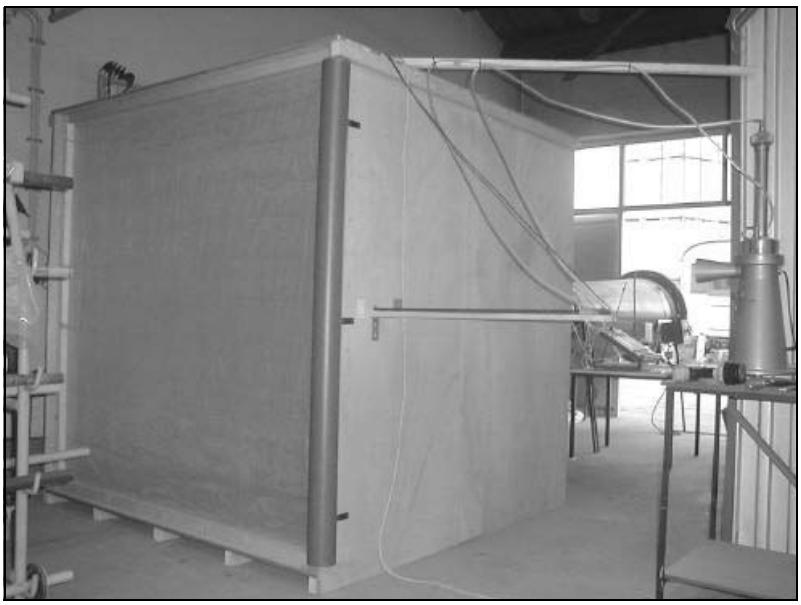


Fig. 1. Apparatus for testing the air permeability.

$\Delta p (=Hd)$ = pressure difference $p_{ges} - p_{st}$ (mm WS) (Dynamic pressure)

p_{ges} = total pressure
p_{st} = static pressure

The stream of air volume in the wind tunnel, $\dot{V}_d$ ($m^3\ s^{-1}$) was calculated by multiplying the air velocity v_d ($m\ s^{-1}$) with the sectional area of the wind tunnel, A_d (m^2). The sectional area of the wind tunnel, A_d (m^2) was computed as follows:

$$A_d = r^2\pi \qquad (2)$$

$$r = 0.25\ m$$

The outcome of this A_d is 0.19 m^2.

From the continuity equation (3) (BOHL 1991), the stream of air volume behind the screen $\dot{V}_s$ ($m^3\ s^{-1}$) is equal to the one in the wind tunnel $\dot{V}_d$ ($m^3\ s^{-1}$):

$$\dot{V} = A_s v_s = A_d v_d = Av = \text{const.} \qquad (3)$$

where $\dot{V}$ is the stream of air volume ($m^3\ s^{-1}$); A_s is the area of the screen (m^2); v_s is the air velocity behind the screen in ($m\ s^{-1}$); A_d is the sectional area of the wind tunnel in (m^2) and v_d is the air velocity in the wind tunnel in ($m\ s^{-1}$).

The area of the screen A_s is 1.90 m × 1.90 m (= 3.61 m^2). The air velocity behind the screen v_s can be obtained from shifting (3):

$$v_s = \frac{A_d \cdot v_d}{A_s} \qquad (4)$$

Computation of a loss coefficient

The pressure lost by the airflow when passing through a screened opening can be calculated using the following equation:

$$\Delta p = F_{o;s} p / 2 v_s^2 \qquad (5)$$

Thus a screened opening will have a loss coefficient $F_{o;s}$. This coefficient is considered as the sum of the loss coefficient for the air flow passing through the unscreened opening F_o, and for the air flow passing through the screen F_s. It is given by:

$$F_{o;s} = F_o + F_s \qquad (6)$$

The loss coefficients for the screens were obtained by subtracting the loss coefficient of the unscreened opening from the measured values.

A structural property of insect screens is porosity, which is expressed as the ratio of the volume of the pores to the total volume. The weave texture is also important if the spacing between two adjacent threads of the screen is small in comparison to the thread diameter.

The flow regime depends on the Reynolds number. While porous materials have Reynolds numbers Re < 1, the investigated insect screens had Reynolds numbers 3.4 < Re < 144 at air velocities up to 1.1 m s^{-1}. Only at Reynolds numbers Re > 200 can the loss coefficient be expected to be constant. BRUNDRETT (1993) reviewed information on the pressure difference required to create airflow through wire mesh screens. Based on the analysis of six sets of published loss coefficients for screens F_s, it was shown that all the values could be correlated using the following equation:

$$F_s = g(Re)h(e) \qquad (7)$$

where the function g(Re), which introduces the influence of Reynolds number, is given by

$$g(Re) = p/Re + q/\log(Re + 1.25) + r\log(Re) \qquad (8)$$

where p, q and r are empirical coefficients, and the function h(e) defines the influence of the screen porosity ∈ and was represented by

$$h(e) = (1 - \varepsilon^2)/\varepsilon^2 \qquad (9)$$

In this case, the Reynolds numbers were based on the diameter of the threads forming the screen. The first term in Eqn (8) dominates when Re < 1, the third provides the nearly constant value at high Reynolds numbers (Re > 200) and the second provides the transition between the first and third term. In principle, Eqn (7) should be applicable to a wide range of flow regimes since it accounts for the influence of Reynolds number on the flow.

There is a clear dependence of screen loss coefficient on air speed and hence Reynolds number. The wire screens reviewed by BRUNDRETT (1993) are similar to insect screens in that both have a well-defined structure that can be characterised by the diameter (or width) of the wire (or fibre), and the dimensions of the pores. BAILEY et al (2003), used Eqn (7) as the basis for calculating the loss coefficients of the insect screens. The resulting equation, based on the loss coefficients of the five insect screens, was

$$F_s = \left[\frac{18}{Re} + \frac{0.75}{\log(Re+1.25)} + 0.055\log(Re)\right]\left[\frac{1-\varepsilon^2}{\varepsilon^2}\right] \qquad (10)$$

The pressure drop of the different screens can be calculated using the following equation:

$$\Delta p = F_S p / 2 v_s^2 \qquad (11)$$

Classification of the screens in groups according to the mesh size

For easier comparison, the different screens were classified in groups. Table 1 shows the mesh sizes (in mm and mm^2) of the screens and their arrangement in groups ac-

Table 1. Distribution of screens in groups according to the mesh size.

Name of material	Group (information of the manufacturer)	Mesh size				Fibre thickness	
		Manufact. (mm)	Manufact. (mm^2)	Measured (mm)	Measured (mm^2)	Manufact. (mm)	Measured (mm)
Econet B	4	4.0 x 1.0	4.00	3.70 x 1.56	5.77		0.25
Brinkman M	4	1.05 x 0.95	1.00	1.13 x 1.03	1.16	–	0.30 / 0.28
Econet L	3	0.60 x 0.60	0.36	0.62 x 0.56	0.35	0.15	0.21 / 0.20
Econet F	3	0.78 x 0.45	0.35	0.81 x 0.42	0.34	–	0.24 / 0.21
FVG-screen	3	0.79 x 0.42	0.33	0.82 x 0.27	0.22	0.22	0.24
Thailand-screen 1	2	–	–	0.63 x 0.39	0.25	–	0.20 / 0.18
Econet SF	2	0.78 x 0.28	0.22	0.72 x 0.25	0.18	–	0.25 / 0.26
Antivirus	2	0.78 x 0.28	0.22	0.82 x 0.28	0.23	0.24	0.23 / 0.24
Bionet	2	0.82 x 0.26	0.21	0.85 x 0.26	0.22	0.24	0.22
Brinkman W	2	0.77 x 0.27	0.21	0.80 x 0.28	0.22	–	0.22 / 0.23
Econet M	2	0.45 x 0.40	0.18	0.49 x 0.42	0.21	0.22	0.26
Thailand-screen 2	2	–	–	0.48 x 0.37	0.18	–	0.25
Brinkman T	1	0.31 x 0.22	0.07	0.54 x 0.25	0.14	–	0.21 / 0.19
Econet T	1	0.35 x 0.15	0.05	0.38 x 0.17	0.06	0.15	0.14
Econet S	1	0.14 x 0.14	0.02	0.22 x 0.18	0.04	0.15	0.14 / 0.10

Group 1: ≤ 0.10 mm^2; Group 2: ≤ 0.25 mm^2; Group 3: ≤ 0.40 mm^2; Group 4: ≥ 1 mm^2
Manufact. = Manufacturer; – = No information of the manufacturer

Table 2. Measured values of the light transmission compared to the information of the manufacturer (%) and their absolute and relative deviation (%).

Nr.	Name of material	Light transmission		Deviation of the measured light transmission from the information of the manufacturer	
		Information of the manufacturer (A) direct (%)	Measured (B) direct (%)	absolute (%) (C=B–A)	relative (%) (D=C*100/A)
1	Brinkman M	–	93.3	–	–
2	Econet B	90	90.5	+0.5	0.6
3	Brinkman T	–	87	–	–
4	Econet M	90	87	–3.0	3.3
5	Thailand-screen 2	–	86–88 (dirty)	–	–
6	Econet F	90	85.7	– 4.3	4.8
7	Antivirus	80* (85)	88.5	+8.5 (+3.5)	10.6 (4.1)
8	Econet SF	88	82.6	–5.4	6.1
9	Econet T	85	86	+1.0	1.2
10	Econet S	85	82	–3.0	3.5
11	Econet L	84	77.5	–6.5	7.7
12	FVG-screen	80	87.5	+7.5	9.4
13	Bionet	65–68	66.5	+1.5 bis –1.5	2.2 – 2.3
14	Brinkman W	–	89.5	–	–
15	Thailand-screen 1	–	70 (dirty)	–	–

* = Information of the seller
– = No information of the manufacturer

cording to the information from the manufacturer. The measured mesh sizes are also included in the table.

Results

Light measurements

Table 2 shows the results for light transmission of the screens, measured with an "Ulbricht-sphere". All results deviated from the information given by the manufacturer. Because of the inaccuracy of the "Ulbricht-sphere" of 1 %, the relative deviation of 0.6 % by Econet B was tolerable. Econet M, Econet S, Econet T and Bionet screens showed relative deviations between 1.2 and 3.5 %. The Antivirus (information from the manufacturer) and Econet F screens had differences up to 4.8 %. The largest relative differences, between 6.1 and 10.6 %, were shown by Econet L, Econet SF, the FVG and the Antivirus-screens (information from the seller).

Values between 70 and 93.3 % were measured for the four screens, where there was no information from the manufacturer. The Thailand-screen was dirty hence its light transmission is not mentioned in the discussion (it is necessary to test clean screens again).

Pressure measurements

The pressure measurements with the "Prandtl-tube" showed that there was a pressure-gradient over the backside of the screen. The pressure varied from 1 Pa at 1 cm distance from the edge to 0.3 Pa at 6 to 8 cm distance going up again to 1 Pa at a distance of 86 cm, remaining at this level until the centre of the screen (without figure). The curves for the pressure with respect to the distance from the edge of the screen, with and without a plastic tube at the edge of the wooden box, were not very different. Therefore further measurements were carried out without a tube at the edge of the box.

Fig. 2 shows the measured pressure difference for all screens as a function of air velocity. As expected the pressure drop is increasing with increase in air velocity. The curves are no square functions as it can be expected for Reynolds numbers larger than 200. The range of air velocity up to 1.1 m s–1 can be expected at ventilation openings of greenhouses, when free ventilation is used.

Econet S had the highest-pressure drop with values about two times higher than Econet T or Brinkman T. Both screens can be used against thrips. The screens Econet T, Brinkman T and Econet SF are close together. This is similar with Econet L, FVG screen, Brinkman W and Econet M. The Antivirus screen shows a different curve. The results of Brinkman M and Econet B with the largest mesh size are not logical as the pressure drop is negative. This means that the total pressure (Po + Ps) is smaller than the pressure of the opening without any screen (P_o). The Reynolds numbers for the unscreened opening are much higher than for a screened opening resulting in a different flow regime. The reason for this difference could be inaccuracies in the measurements. It is difficult to measure a pressure difference less than 1 Pa. Furthermore the pressure behind the screen (in the wooden box) was measured at one position only.

The pressure differences and the different air velocities for all screens were calculated using Eqn. 10 and Eqn 11. The results in comparison with the measured values are shown in Fig. 3.

For most of the screens a good agreement can be seen, showing that Eqn 10 is valid for a large range of different screen materials. Most of the deviations can be explained by differences in the mesh and thread size. It is however important to note that fixing a screen with strain can influence the mesh size. The measured pressure drop of Econet S was about 60 % higher than calculated. When using the thread size given by the manufacturer (0.15 mm instead of 0.12) and a smaller mesh size (0.18 x 0.19 instead of 0.18 x 0.22) the conformity was good as shown in Fig. 3. Moreover, only the Antivirus screen does not fit (Fig. 3.) and the calculated pressure drop is higher than that measured. Changing the mesh size from measured values to values given by the manufacturer did not have a

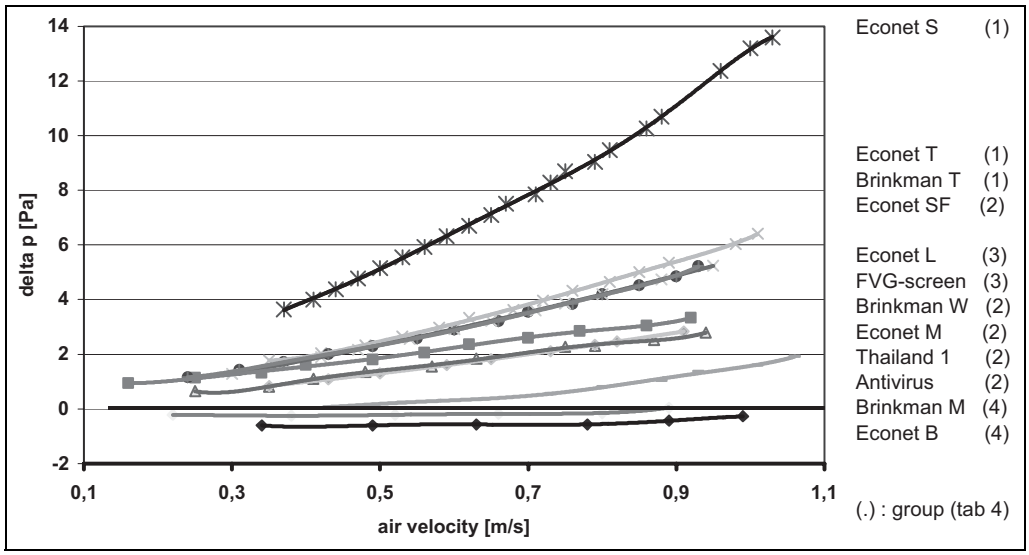


Fig. 2. Pressure difference of different screens P_s as a function of air velocity.

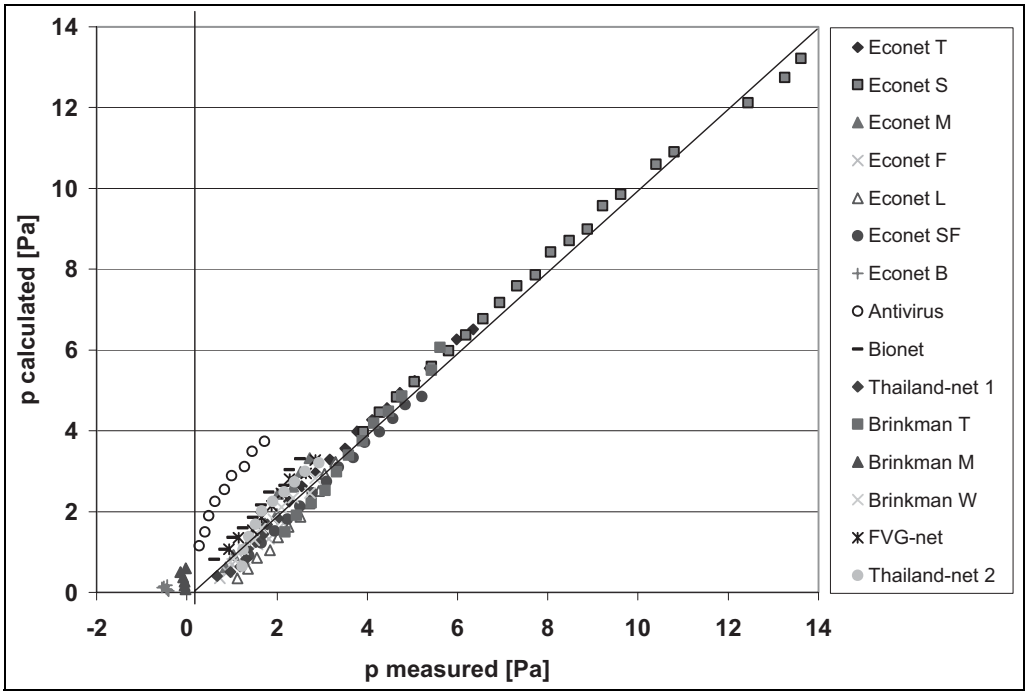


Fig. 3. Pressure difference measured and calculated for all screens using Eqn. 10 and 11.

real influence on the results. These deviations cannot be explained by inaccuracies of the measuring equipment, as the pressure drop is higher when compared with Econet B and Brinkman M. The measured pressure drop of these screens is negative, that is, lower than an opening without screens. But in Fig. 3, it can be seen that the differences are quite small, (less than 1 Pa).

Discussion

Fig. 2 shows that – as expected – the screens with the smallest mesh size (group 1) have the highest pressure drop. The opposite is true for the screens with the largest mesh sizes (group 4). The screens of group 2 should be closer to the screens of group 1, but that is true only for Econet SF. The screens of group 3 are orientated more to group 4, but this proved to be incorrect for all screens. The reason for this deviation could be inaccuracies in the measurement, lack of exact information of the mesh size from the manufacturer and/or the presence of different thread materials, which were not mentioned (e.g. wool threads in one screen). Therefore, it is sensible to include the open area of a screen since this includes the thickness of the threads (Von Zabeltitz 2002) as it is done using the porosity (s. Eqn 10). Screens with a larger open area (higher porosity) should be used, because they have better air permeability. In order to determine the porosity of a screen and to calculate the correct pressure loss coefficient (Fs), the information about the mesh size and thickness of the threads must be correct.

It is surprising that the control (opening without screens) did not have the lowest pressure drop, although there was no resistance of a screen. Inaccuracies in the measurement are the only possible explanation why the results of Econet B and Brinkman M were negative (better than the control). Moreover, for Econet B, Brinkman M and the control, the water columns in both "Manometers" varied very much and the pressure difference was less than 1 Pa, hence within the error range.

The correlation equation developed by BAILEY et al. (2003) was used to calculate the loss coefficients and the pressure drop of all screens. The results are encouraging, showing that this equation can be used for quite different screen materials. The Antivirus screen was the only one giving a larger deviation between measured and calculated values, which can not be explained by differences in the mesh and thread size. When using the measured mesh and thread size for Econet S, the measured pressure drop was about 60 % lower than calculated. This example shows the importance of a correct estimation of these values. The mesh size may vary within a screen giving different pressure drops.

It is possible to combine the screens from group 2 and 3 into one group, because their respective curves are very close to each other. From this group, the Antivirus-screen (or any other screen), with small values of pressure loss in respect to the permeability of air, should be used. If a screen from group 1 is to be chosen, then Econet T should be taken, because it has a lower pressure loss.

Considering all screens, it is noticeable that the screens with large mesh sizes had the highest light transmission, but it cannot be claimed that the screens with the smallest mesh size had the lowest light transmission.

When screens with high air permeability and high light transmission are to be chosen, the following screens should be used: Brinkman W or Econet B, the Antivirus-screen, Econet F, the FVG-screen and Econet M. Screens like Bionet or Econet L should be

chosen, when the screen is to be used for shading with relatively high air permeability.

The article from BETHKE (1994) was used to evaluate the ability of the screens to keep insects away. This article mentions, the sizes of a few leaf miners, aphids, thrips, and whiteflies and the screen that kept the specific insect away. According to this article, a user who would like to keep thrips away, have a high light transmission, and compensate for the high air resistance should choose for example Brinkman T. When whiteflies or leaf miners are to be kept off at high air permeability and light transmission, Antivirus-screen, Econet F, Econet M, FVG-screen or Brinkman W should be chosen. When shading is needed, the Bionet-screen should be used. If the main problem is aphids and larger insects, combined with the aim of small air resistance and high light transmission, then the screens from group 4 should be chosen.

Solutions must be found to compensate for the obstruction of the air permeability caused by all screens. The window openings must be enlarged, the efficiency of the fans must be increased or additional fans, and other cooling systems must be used (BETHKE et al. 1994). BAKER and SHEARIN (1994, 1995) gave an exact method for choosing the right screen and computing the needed area. It is also important to clean the screens when they are too dirty, because of the otherwise resulting high air resistance (BAKER and SHEARIN 1994). Finally, it is possible to calculate the pressure drop of a screen using Eqn 10 and 11. This offers the possibility to design the ventilation openings of a greenhouse in order to meet all requirements according to the outside climate conditions.

Acknowledgements

This work was supported by the DFG.

References

BAILEY, B. J., J. I. MONTERO, J. Perez PARRA, A. P. ROBERTSON, E. BAEZA and R. KAMARUDDIN 2003: Airflow resistance of greenhouse ventilators with and without insect screens. Biosystems Engineering **86**, 217–229.

BAKER, J. R. and R. K. JONES 1989: Screening as part of insect and disease management in the greenhouse. North Carolina (N.C.) Flower Growers' Bulletin **34** (6), 1–9.

BAKER, J. R. and R. K. JONES 1990: An update on screening as part of insect and disease management in the greenhouse. North Carolina (N.C.) Flower Growers' Bulletin **35** (6), 1–3.

BAKER, J. R. and E. A. SHEARIN 1994: An update on screening for the Exclusion of insect pests. North Carolina (N.C.) Flower Growers' Bulletin **39** (2), 6–11.

BAKER, J. R. and E. A. SHEARIN 1995: Screening greenhouses for insect exclusion. Ohio Florists' Association Bulletin No. **786**, 6–9.

BARTZANAS, T., T. BOULARD and C. KITTAS 2001: Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. Proceedings of the international symposium on design and environmental control of tropical and subtropical greenhouses, National Taiwan University, Taichung, Taiwan, April 15–18.

BERLINGER, M. J., S. MORDECHI and A. LEEPER 1991: Application of screens to prevent Whitefly penetration into greenhouses in the Mediterranean basin. WPRS Bulletin **14** (5), 105–110.

BERLINGER, M. J., S. Lebiush-Mordechi D. FRIDJA and N. MOR 1993: The effect of types of greenhouse screens on the presence of Western Flower Thrips: a preliminary study. WPRS Bulletin **16** (2), 13–16.

BELL, M. L. and J. R. BAKER 1995: Greenhouse screening: comparison of materials for excluding Thrips and Whiteflies. North Carolina (N.C.) Flower Growers' Bulletin **40** (2), 3–8.

BETHKE, J. A. 1994: Considering installing screening? This is what you need to know. Greenhouse Manager **13** (1), 34–38.

BETHKE, J. A., R. A. REDAK and T. D. PAINE 1994: Screens deny specific pests entry to greenhouses. California Agriculture **48** (3), 37–40.

BOHL, W. 1991: Technische Strömungslehre. Kamprath-Reihe, Vogel Verlag und Druck KG, Würzburg, 9. Aufl..

BRUNDRETT, E. 1993: Prediction of pressure drop for incompressible flow through screens. Journal of Fluid Engineering; Transactions of the ASME (American Society of Mechanical Engineers) **115**, 239–242.

DESMARAIS, G. and G. S. V. RAGHAVAN 1996: Thermal characteristics of screenhouse configurations in a west-african tropical climate. Greenhouse Technologies 39–46.

DIERICKX, W. 1998: Flow reduction of synthetic screens obtained with both a water and airflow apparatus. Journal of Agricultural Engineering Research **71**, 67–73.

FATNASSI, H., T. BOULARD, L. BOUIRDEN and G. SAPPE 2001a: Ventilation performances of a large canarian type greenhouse equipped with insect-proof nets. Proceedings of the international symposium on design and environmental control of tropical and subtropical greenhouses, National Taiwan University, Taichung, Taiwan, April 15–18.

FATNASSI, H., T. BOULARD and L. BOUIRDEN 2001b: Simulation of air flux and temperature patterns in a large scale greenhouse equipped with insect proof nets. Proceedings of the international symposium on design and environmental control of tropical and subtropical greenhouses, National Taiwan University, Taichung, Taiwan, April 15–18.

FUCHS, M., E. DAYAN, D. SHMUEL and I. ZIPORI 1997: Effects of ventilation on the energy balance of a greenhouse with bare soil. Agricultural and Forest Meteorology **86**, 273–282.

KAMARUDDIN, R., B. J. BAILEY and M. P. DOUGLASS 2000: Physical properties of covering materials for naturally ventilated tropical greenhouses. Journal of Tropical Agriculture and Food Science **28** (1), 55–69.

KOSMOS, S. R., G. L. RISKOWSKI and L. L. CHRISTIANSON 1993: Force and static pressure resulting from airflow through screens. Transactions of the ASAE (American Society of Agricultural Engineers) **36**, 1467–1472.

MEARS, D. R. and A. J. BOTH 2000: Insect exclusion from greenhouses. New Jersey Agricultural Experiment Station Publication P-03130-23-00.

MEARS, D. R. and A. J. BOTH 2001: Insect exclusion from greenhouses. New Jersey Agricultural Experiment Station Publication P-03130-06-01.

MIGUEL, A. F., N. J. VAN DE BRAAK and G. P. A. BOT 1997: Analysis of the airflow characteristics of greenhouse screening materials. Journal of Agricultural Engineering Research **67** (2), 105–112.

MIGUEL, A. F. 1998: Airflow through porous screens: from theory to practical considerations. Energy and Buildings **28**, 63–69.

MIGUEL, A. F. and A. M. SILVA 2000: Porous materials to control climate behaviour of enclosures: an application to the study of screened greenhouses. Energy and Buildings **31**, 195–209.

MUÑOZ, P., J. I. MONTERO, A. ANTÓN and F. GIUFFRIDA 1999: Effect of insect-proof screens and roof openings on greenhouse ventilation. Journal of Agricultural Engineering Research **73**, 171–178.

ROBERTS, W. J., L. VASVARY and S. KANIA 1995: Screening for insect control in mechanically ventilated greenhouses. ASAE (American Society of Agricultural Engineers) Paper No. NABEC **95-09** resp. **95-4541**, 1–13.

SASE, S. and L. L. CHRISTIANSON 1990: Screening greenhouses – some engineering considerations. ASAE (American Society of Agricultural Engineers) Paper No. NABEC **90–201**, 1–13.

TAYLOR, R. A. J., S. SHALHEVET, I. SPHARIM, M. J. BERLINGER and S. LEBIUSH-MORDECHI 2001: Economic evaluation of insect-proof screens for preventing tomato yellow leaf curl virus of tomatoes in Israel. Crop Protection **20**, 561–569.

VON ZABELTITZ, C. 2002: Insektenschutznetze für Gewächshäuser. Taspo Magazin **5**, 42–43.

Received February 16, 2003 / Accepted July 8, 2004

Addresses of authors: F. Klose and H.-J. Tantau (corresponding author), University of Hannover, Faculty of Horticultural Sciences, Institute of Horticultural and Biosystems Engineering, Herrrenhäuser Str. 2, D-30419 Hannover, Germany,
e-mail: tantau@itg.uni-hannover.de.