TEST RESULTS AND EMPIRICAL CORRELATIONS TO ACCOUNT FOR AIR PERMEABILITY OF AGRICULTURAL NETS

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Abstract

Fifteen HDPE agricultural nets were tested inside a micro wind tunnel (0.1345 m diameter) to establish their characteristic air flow rate vs pressure drop curves with velocities > 4 m s^{-1}. The air pressure drop through the net was accounted for, with reference to the Bernoulli scheme, by means of the loss coefficient. Experimental results confirmed those available in the literature, in terms of the dependence of the pressure drop on the velocity squared and the net porosity, ε, by means of the function $h(\varepsilon) = (1-\varepsilon^2)/\varepsilon^2$. The influence of the orifice geometry was investigated and an effect equivalent to the increase in net porosity was identified in textile pores with elongated shapes. As with previous studies, the loss coefficient trend was found to fit the product of two functions, one depending on the porosity, and the other on the Reynolds number defined using the pore equivalent diameter. The calculated values of the loss coefficient show deviations from experimental results in the range of 19.9 to 41.1%. In addition, a new formulation for the loss coefficient, dependent only on the porosity and wet perimeter was proposed. Except for higher porosity nets the simplified formulation, showed the best match with the experimental data. The two formulations of the loss coefficient proposed here were compared with those found in the literature.

Keywords: airflow, porous media, loss coefficient, discharge coefficient, plastic nets, wind tunnel

Nomenclature

Abbreviations	
HDPE	High Density Polyethylene
Variables and parameters	
C_d	discharge coefficient, -
D	diameter of the micro wind tunnel, m
d_{warp}	diameter of the warp, mm
d_{weft}	diameter of the weft, mm
F_s	loss coefficient, -
$h(\varepsilon)$	function of the porosity ε
$g(Re)$	function of the Reynolds number Re
K	permeability parameter of the net, m^2
l_{eq}	equivalent diameter of the pores, mm
l_{warp}	length of the empties into the warp direction, mm
l_{weft}	length of the empties into the weft direction, mm
p	pressure, Pa
P_w	wetted perimeter of the orifice per square centimetre, mm cm^{-2}
Q	volumetric flow rate, m^3 s^{-1}
R	coefficient of correlation, -
R^2	coefficient of determination, -
Re	Reynolds number, -
Re_l	Reynolds number based on the equivalent diameter of the pores, -
u	fluid velocity, m s^{-1}
w, q, r	empirical coefficients, -
x	direction of the one-dimensional flow motion, -
Y	inertial factor, -
Greek letters	
Δp	pressure drop, Pa
ε	porosity, -
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}

1. INTRODUCTION

Plastic nets are widely used in various agricultural applications to protect crops from hail, wind, snow, or strong rainfall in fruit-farming and ornamentals, to shade greenhouses or to moderately modify their microenvironment. Nets are also used for protection against insect virus-vectors and birds, as well as for harvesting and post-harvesting operations (Castellano et al., 2008).

In some cases, nets are placed on the vents of the structure; in others they cover the entire structure (e.g. the so called net-house or screen-house). In both cases, the air flowrate through the net determines both the structural design, the wind loads on supporting elements (Robertson et al., 2002; Mistriotis & Castellano, 2012), and the ventilation performance, together with buoyancy and convective phenomena (Teitel, 2007).

Net types are characterised by different structural features, such as the form of threads, fabrics, shape and dimensions of fibres and their meshing which affects the physical properties of nets such as weight, shading factor, radiometric properties, porosity, air permeability, mechanical characteristics and durability. Starting from the performance required to the net, knowledge of the influence of the structural features on the nets physical properties allows for a proper design of the membrane.

Several studies have been done to correlate the pressure drop of the air flow with the geometric characteristics of the net and the fluid velocity. Net characteristics when penetrated by air have been evaluated either in terms of permeability, based on the motion equation of a fluid through a porous medium expressed by the Forchheimer equation (Bartzanas et al., 2002; Fatnassi et al., 2003; Miguel et al., 1997, Miguel et al., 1998; Miguel et al., 2001; Valera et al., 2005), or in terms of the coefficient of discharge or, equivalently, by its reciprocal, the loss coefficient, based on Bernoulli's flow theory (Bailey et al., 2003; Brundrett, 1993; Fatnassi et al., 2002; Ishizuka et al., 2000; Kittas et al., 2002; Kosmos et al., 1993; Montero et al., 1996; Munoz et al., 1999; Pearson and Owen, 1994; Teitel et al., 1999; Wanga et al., 2007). Previous studies have mainly been based on experimental results on flat woven simple orthogonal weaves with weft and warp threads, or round monofilament high density polyethylene (HDPE) nets. Empirical correlations were found between the airflow characteristics and the structural parameters of tested nets, mainly the porosity and the Reynolds number. In most cases, insect proof nets and thermal screens, which are characterised by low porosity generally in the range from 5 to 30%, and by low Reynolds numbers, were investigated because they reduce the natural ventilation, capacity of greenhouses which has negative consequences for greenhouse microclimate, increasing the interior temperature and humidity (Fatnassi et al., 2006; Harmanto et al., 2006).

Ordinarily, porosity is considered as the main geometric parameter when defining the net air flow characteristics through a net even if porosity itself is not able to describe the airflow through the porous media because nets with the same porosity show a different behaviour when subject to airflow. Many studies in the literature have demonstrated that the loss coefficient is a function of the porosity and of Reynolds number. At low Reynolds number, the flow is laminar and the loss coefficient increases as the Reynolds number decrease (Blevin, 1984) but in high-Re turbulent flow, air pressure drop is largely independent of Re. Other geometric parameters such as thread diameter, wet perimeter, mesh size and kind of fabric have been observed to play a fundamental role. For instance, Teitel and Shklyar (1998) emphasised the importance of hole geometry finding out that a distance between two adjacent threads of a woven screen smaller than five times the thread diameter affects both the pressure drop through the net and the downstream flow pattern.

In order to evaluate the influence of the construction parameters of agricultural nets on the airflow through them, a micro wind tunnel was built – basically inspired by UNI EN ISO 9237 recommendations on the Testing and Engineering Laboratory at Sachim srl (*http://www.sachim.it*), an Italian HDPE technical textiles manufacturer. The experimental results in terms of loss coefficient of eleven flat woven and four knitted round monofilament HDPE nets, with different porosities, mesh size and thread diameter are reported in this paper.

2. MODELS FOR FLUID FLOW

The steady-state incompressible flow of a fluid through a highly porous medium in which the volume of the solid matrix exceeds that of the fluid contained within can be expressed by the Forchheimer equation:

$$\frac{\mu}{K}u + \rho\left(\frac{Y}{K^{0.5}}\right)|u|u = \frac{dp}{dx} \tag{1}$$

Where, the permeability parameter K represents the ability of the medium to transmit the fluid through it and, as consequence of the dimensional analysis, it is expressed in m^2, u is the upstream velocity of the fluid in m s^{-1}, ρ is the density of the fluid in kg m^{-3}, the inertial factor Y represents an empirical function which depends primarily on the micro-structure of the porous media (Bailey et al. 2003) . Equation (1) is derived from the general motion equation of one-dimensional mass transfer through a permeable material (Miguel et al., 1997) and expresses the gradient of pressure drop perpendicular to the direction of the flow, ${dp}/{dx}$, as a function of the upstream fluid velocity. The viscous resistance predominates at low velocities of the fluid, when the voids occupied by the fluid are smaller than those occupied by the solid matrix and when the path through the porous medium is comparable with its cross section (Bejan, 2013).

Some authors, considering a net equivalent to a porous medium, used Eq. (1) to describe the airflow thorough a net. In order to analyse the airflow characteristics of greenhouse screening materials, and to determine the permeability parameter K and inertial factor Y, Miguel (1998) and Valera et al. (2005) tested several screens in wind tunnel, and their findings allowed to state a correlation between the screen permeability parameter and inertial factor to the porosity ε. The porosity ε is a geometrical property defined as the ratio of the non-solid volume (voids) to the net total volume.

The motion regime is described by the Reynold number, $Re = \rho ud/\mu$, which can be interpreted as the ratio between inertial and viscous forces; in the general motion equation of one-dimensional mass transfer through a permeable medium, d, expressed in m, is assumed as the diameter of the particles of the solid matrix (Bejan, 2013). In the formulation concerning the airflow passing through a net, d, which is the geometrical parameter to be used to account for the Re value, can represent, depending on the author, either the mesh size (distance between wires, pore equivalent diameter, etc.) or the wires diameter.

For low velocities ($Re < 1$) the quadratic term in Eq. (1) can be neglected and the equation reduces to Darcy's law:

$$\frac{dp}{dx} = \frac{\mu}{K} u \qquad (2)$$

Increasing the air flow velocity, Miguel et al. (1997) assumed empirically that $Re = 150$ was the threshold value above which the convective inertia effects dominate. Consequently the linear term of Eq. (1) can be neglected and the pressure drop remains that described only by the quadratic term. This leads to the following Bernoulli's formulation:

$$\Delta p = 0.5 \frac{\rho}{C_d^2} u^2 \qquad (3)$$

where the characteristics of the porous medium are accounted for by the discharge coefficient C_d.

Bailey et al. (2003) evaluated the airflow resistance of greenhouse vents with insect screens using the relation proposed by Brundrett (1993):

$$\Delta p = F_s \frac{1}{2} \rho u^2 \qquad (4)$$

where the loss coefficient F_S was directly correlated to the discharge coefficient $C_d = 1/\sqrt{F_s}$ (commonly used to quantify the flow resistance of an opening). Brundrett (1993) and Bailey et al. (2003) expressed the loss coefficient as:

$$F_s = g(Re) h(\varepsilon) \qquad (5)$$

with

$$g(Re) = \frac{w}{Re} + \frac{q}{\log(Re+1.25)} + r \log(Re) \qquad (6)$$

and $h(\varepsilon)$ defining the influence of the screen porosity ε, expressed as

$$h(\varepsilon) = \frac{1-\varepsilon^2}{\varepsilon^2} \qquad (7)$$

In Eq. (6) the Reynolds number is based on the diameter of the wires forming the screen. The first term in Eq. (6) dominates when $Re < 1$; the third term provides the nearly constant value at high Reynolds numbers ($Re > 200$); the second term accounts for the transition between the first and third terms. Bailey et al. (2003) used Eq. (6) as the basis for the correlation of the pressure drop coefficients of five insect screens, and, based on their experimental results, suggested coefficients different from those proposed by Brundrett (1993) (Tab.1). Brundrett (1993) showed that Eq. (7), proposed originally by Pinker and Herbert (1967), fitted the data better than other alternative expressions, cited in the literature, such as $1 - \varepsilon/\varepsilon^2$ and $(1 - \varepsilon)^2/\varepsilon^2$. Previously, also Pinker and Herbert (1967), according to Eq. (5), suggested to split F_S into two independent components as well: a screen porosity function $h(\varepsilon)$ and a Reynolds number function $g(Re)$. With reference to the latter, they tested four different expressions and stated that it was difficult to discriminate among them as the particular form of $h(\varepsilon)$ was more important than that of $g(Re)$.

Munoz et al. (1999) showed that the choice of either the Forchheimer or Bernoulli equations makes little difference in the calculated values, such difference decrease when the screen pore dimension increases. Kittas et al. (2002) used both the porous medium method and the Bernoulli equation to calculate the pressure loss coefficient of the tested screen with a porosity of 0.6 and the values obtained were different up to only 3%. Teitel (2001) compared the two methods and concluded that they agreed well in their predictions of the pressure drop through screens. In addition, Teitel (2007) showed that the differences among the various studies were larger for the values of parameters K and Y in Eq. (1) than for those of F_S in Eq. (5). In this research a loss coefficient approach, based on Bernoulli equation, was adopted.

3. MATERIALS AND METHODS

3.1. Laboratory devices

A micro wind tunnel (Fig. 1) was purposely designed and built at Sachim srl testing and engineering laboratory (Castellano et al., 2015). The steel wind tunnel had a circular cross- section with diameter $D = 0.1345$ m and presents a test section upstream and downstream the specimen of 989 mm. The system allows to vary the air flow velocity in the range of 0 ÷ 15 m s^{-1}. The pressure drop upstream and downstream the fabric specimen is measured by means of a manometer (Aerofiltri MM200600, see *http://www.aerofiltri.it*) able to appreciate a pressure difference in the interval of 0 - 200 ± 5 Pa. The pressure measurement sections were remote from the specimen by more than 5 diameters in order to minimise the effects of the net on the upstream and downstream flow. In addition, the test setup allowed the orientation of the plastic net sample to be modified inside the wind tunnel with respect of the airflow (90° when perpendicular, 60°, 45° and 30°). However, in this paper only measurements with nets perpendicular to the airflow are reported.

The air flowrate through the wind tunnel was measured by means of a hot wire anemometer (SMC PF2A712H, see *https://www.smc.eu*) in the flowrate range of 0.01 - 0.20 ± 1.7 10^{-4} m^3 s^{-1} with pressures in the range 0.1 - 1.5 MPa.

The distributed pressure drop due to the roughness of the inner surface of the pipe was calculated by means of three measurements without net samples at different air velocities. For each tested net, the average value of the distribute pressure drop (calculated as a function of the air velocity) was subtracted to experimental data gathered.

The air velocity, to be used for the fluid dynamics calculations, was calculated with respect to the tunnel cross section. Upstream air velocities < 4 m s^{-1} were not consistent with the characteristics of the manometer as a pressure difference < 5 Pa occurred. The ambient temperature was in the range of 20 ± 1 °C, in compliance with the sensor specifications.

The tests were carried out setting up a pressure drop across the specimen (for this purpose the rotational speed of the fan was adjusted); after waiting for the system to reach a steady state and measuring the corresponding air flow rate through the net in the wind tunnel.

3.2. Tested nets

The net samples were divided in two main sets: set A (Fig. 2a) and set B (Fig. 2b). The first set contains the flat woven nets, characterised by a simple orthogonal weave between weft and warp and with the same thread thickness of the warp and of the weft. As a function of the geometry characteristics, the set A is split into three subsets: A1 (d_{warp} = d_{weft} = 0.28 mm) with porosity in the range 34.4 - 71.6%; A2 (d_{warp} = d_{weft} = 0.23 mm) with porosity in the range 42.3 - 71.1%;

A3, with almost the same porosity ($\varepsilon \approx 50\%$) and different thread thickness (Table. 2). In the further analysis, the net A3-N1 will be considered also as an element of the subset A1; the same will happen for the net A3-N2 referring to the subset A2. Knitted nets, also referred to as Raschel membranes, having different porosities in the range 35.5 - 84.0% formed the set B (Table 2).

The porosity of flat woven nets (set A1, A2 and A3) was calculated analytically as $\varepsilon = l_{warp} l_{weft} / [(d_{warp} + l_{warp}) + (d_{weft} + l_{weft})]$. With respect to the knitted nets of set B, the geometry of the mesh was less regular and porosity was estimated by image analysis (Castellano et al., 2008). Net samples were scanned at a resolution of 1200 dpi by a commercially available image analysis tool (Adobe Photoshop CC). Images were converted into black (net) and white (empty). A representative area was selected from each image and the percentage of white pixels of the whole picture was evaluated by means of the same software. Measurements were repeated at least twice for each sample, using areas of different size, and an average value was obtained.

In Raschel membranes all threads are linked each other in order to prevent the unravelling of the textile; the net is formed by longitudinal chains (warp) and transversal knitted elements (weft) formed by one or more filaments (Fig. 2b).

For the purpose of this study, the knitted nets weave was considered equivalent to an orthogonal one formed by mono-wire threads (Tab. 2). The pitch of the filaments was known from the data sheet of the net; the equivalent thickness of the weft was measured based on an image processing software. An equivalent thickness of the warp, made of longitudinal chains, was determined to match the value of the porosity coming from the image processing.

The equivalent diameter of the pores ($l_{eq} = 4 l_{warp} l_{weft} / (2 l_{warp} + 2 l_{weft})$ [mm]), the elongation ratio of the pores ($l_{sf} = \min[l_{warp}, l_{weft}] / \max[l_{warp}, l_{weft}]$ [-]) and the "wetted" perimeter of the orifice per square centimetre ($P_w = [100/(d_{warp} + l_{warp})(d_{weft} + l_{weft})] [((d_{warp} + l_{warp}) + (d_{weft} + l_{weft})) 2]$ [mm cm^{-2}]), are reported in Table 2.

The loss coefficient F_S, was calculated by means of Eq. (4) as a function of the air velocity inside the wind tunnel in the range between 4.0 and 17.7 m s^{-1}. Each net was tested three times and the average value was taken into account for the following calculations.

The significance of the correlation, when two series of data were compared, was evaluated by means of the coefficient of correlation, R. The coefficient of determination, R^2, was used to describe how well the regression line approximates the experimental data points.

4. RESULTS AND DISCUSSION

All the investigated nets clearly showed a second order very high correlation – coefficient of determination $R^2 > 0.99$ – between the measured upstream air velocities u and pressures drop Δp across the net inside the wind tunnel. Consequently, according to the Bernoulli's theory, a parabola, with the vertex coincident with the axes origin, as Eq. (4) – $\Delta p = \frac{\rho}{2} F_S u^2$ – was assumed. The coefficients F_S of all investigated nets, in the upstream air velocity range 4.0 - 17.7 m s^{-1}, were evaluated by means of the ordinary least squares method (Table 2). The coefficient F_S, which describes the slope of the parabola, depends on the geometric characteristics of the net and the porosity plays an important role. Results confirmed that Eq. (7) – $h(\varepsilon) = (1 - \varepsilon^2)/\varepsilon^2$ – proposed by Brundrett (1993) gives the best correlation with F_S ($R = 0.87$) with respect to alternative expressions, such as: $h(\varepsilon) = \varepsilon$ ($R = -0.78$); $h(\varepsilon) = 1 - \varepsilon/\varepsilon$ ($R = 0.85$); $h(\varepsilon) = 1 - \varepsilon/\varepsilon^2$ ($R = 0.86$); $h(\varepsilon) = (1 - \varepsilon/\varepsilon)^2$ ($R = 0.86$). Figure 3a presents, for each tested nets, values of Eq. 7 plotted against the values of the loss coefficient. The correlation between F_S and $h(\varepsilon) = (1 - \varepsilon^2)/\varepsilon^2$, was assumed to be linear (Fig. 2a). Considering the whole set of the nets, the coefficient of determination of the linear regression curve was lower ($R^2 = 0.87$) than each set evaluated separately ($R^2 > 0.98$) (Fig. 3a). This result was probably affected also by the small number of data points for each set, even if the different behaviour of sets A and B was distinctly observable (Fig. 3a). Sets A1 and A2 are described by two very similar regression lines, meaning that the difference in thickness of threads is not so significant to their slope. Set B regression line shows a lower rate of the slope of the regression line from those of sets A1 and A2 (Fig. 2a).

Concerning set A3, composed of nets with almost the same porosity but with different geometrical characteristics, nets A3-N1 and A3- N3 can be observed to show almost the same loss coefficient, $F_{S,A3-N1} = 2.00$ ($d_{warp} = d_{weft} = 0.28$ mm) and $F_{S,A3-N3} = 2.01$ ($d_{warp} = d_{weft} = 0.17$ mm) respectively, while net A3-N2 ($d_{warp} = d_{weft} = 0.23$ mm) a lower value of the loss coefficient ($F_{s,A3-N2} = 1.53$). This result, systematically obtained performing measurements on the three nets, confirmed that, for the investigated range of air velocity, the thickness of the wires did not affect the loss coefficient and that porosity is not the only geometric parameter to be taken into account for the evaluation of the loss coefficient. This is likely due to the hole geometry of net A3-N2, whose elongation ratio is very low: $l_{sf} = 0.09$ (Table 2). The elongated shape of the hole appeared to generate an effect on the air flow equivalent to a porosity increase. The same effect was identified in net A1-N3, where there was a high deviation between the measured ($F_{S,A1-N3} = 2.14$) and fitted correlation (Fig. 3a). Also, correlating an equivalent increase of the porosity to a low value of the elongation shape factor is possible: $l_{sf} = 0.23$ (Table 2).

These results suggest the use of an equivalent value of the porosity ε_{eq}, depending on the hole elongation ratio of pores l_{sf} (Table 2), according to the following Eq. (9):

$$l_{sf} \geq {}^{1}\!/_{3} \quad \rightarrow \quad \varepsilon_{eq} = \varepsilon \qquad (9)$$

$$l_{sf} < {}^{1}\!/_{3} \quad \rightarrow \quad \varepsilon_{eq} = \varepsilon\left(-{}^{1}\!/_{3}\, l_{sf} + 1.11\right)$$

The coefficients of Eq. (9) were defined empirically based on the experimental results. Because commercially nets require mechanical resistance and shape stability, nets with $l_{sf} \geq {}^{1}\!/_{3}$ are not common. In tested nets, the equivalent porosity ε_{eq} was different from the measured ε only for nets A1-N3 and A3-N2, the latter not being normally available off the shelf, but was specifically manufactured to the purpose of the present experiments. Based on the definition of the equivalent porosity in Eq. (9), the formulation of Eq. (7) had to be changed to:

$$h\left(\varepsilon_{eq}\right) = \left(\frac{1-\varepsilon_{eq}{}^{2}}{\varepsilon_{eq}{}^{2}}\right) \qquad (10)$$

The correlation between F_S and $h(\varepsilon)$ improved when using $h\left(\varepsilon_{eq}\right)$ improving from $R^2 = 0.97$ to $R^2 = 0.98$ for set A1 and from $R^2 = 0.93$ to $R^2 = 0.98$ for set A2 (N.B. net A3-N2 is also an element of A2 (Fig. 2)).

The dependence of F_S on a function $h\left(\varepsilon_{eq}\right)$ of the porosity and on a function $g(Re)$ of the Reynolds number has been also investigated. Concerning $g(Re)$, a distribution based on the Eq. (6) using the empirical coefficients proposed by Brundrett (1993) (Table 1) was assumed, but, unlike Brundrett (1993), the Reynolds number was calculated using the equivalent diameter of the pores l_{eq}, ($Re_l = \frac{\rho u l_{eq}}{\mu}$):

$$g(Re_l) = \left[\frac{7.125}{Re_l} + \frac{0.88}{\log(Re_l+1.25)} + 0.055\log(Re_l)\right] \qquad (11)$$

Hence, the loss coefficient of tested nets became:

$$F_s\left(Re_l, \varepsilon_{eq}\right) = \left[\frac{7.125}{Re_l} + \frac{0.88}{\log(Re_l+1.25)} + 0.055\log(Re_l)\right]\left(\frac{1-\varepsilon_{eq}{}^{2}}{\varepsilon_{eq}{}^{2}}\right) \qquad (12)$$

The formulation of Re_l, due to the geometry of tested nets, induces higher values than Re, based on the wire diameters, especially in nets of set A with high porosity. Concerning set A, Re_l is within the range 95 - 1555, while Re is within the range 61 - 235. In set B, knitted nets, the dimensions of the equivalent diameter of the pore were more similar to the wire thickness and consequently the differences between Re_l and Re were slightly less; the calculated Reynolds numbers were in the range 383 - 1705 and 230 - 770 respectively. In both cases, due to the high values of Reynold number the flow motion was turbulent and the loss coefficient was expressed as Eq. (6) or Eq. (11) which presented a very low variation in the range of investigated velocities.

Due to the high coefficient of correlation ($R = 0.87$) between $h\left(\varepsilon_{eq}\right)$ and F_S and to the function of the Reynolds number as described by Eqs. (6) and (11) which is almost constant when $Re > 200$, a simplified expression of the loss coefficient, depending only on the geometrical characteristics of the net was proposed as alternative to Eq. (12):

$$F_s(c_n, \varepsilon) = c_n h(\varepsilon_{eq}) \tag{13}$$

where c_n is a constant parameter which accounts for the geometry of the net by referring to the wetted perimeter of the orifice per square centimetre P_w. With respect to other expression of P_w , the best correlation with the loss coefficient F_s was given by $P_w^{0.5}$ ($R = 0.72$).

$$c_n = 0.0315\, P_w^{0.5} \tag{14}$$

The coefficient 0.0315 was obtained assuming a linear correlation (Fig. 4) between the values of F_s with the equation $P_w^{0.5} h(\varepsilon_{eq})$. As shown in Fig. 4, the simplified expression of the loss coefficient $F_s(c_n, \varepsilon)$ allows to describe all the tested nets, flat woven and knitted, using only one linear correlation curve with a very high coefficient of determination ($R^2 > 0.98$).

Finally, the pressure drop values measured in the micro wind tunnel for the tested nets were compared with those calculated, for the same nets, according to formulations proposed by Brundrett (1993) and Bailey et al. (2003).

Concerning monofilament nets (sets A1 (Fig. 5), A2 (Fig. 6) and A3 (Fig. 7)) the relationship proposed by Brundrett (1993) and Bailey et al. (2003) presents a good correlation with experimental results, with percentage errors with respect to experimental results of 4.6 ± 2.7% for net A1-N3 and of 25.5 ± 1.1% for the net A1-N4 (Table 3). The percentage errors in Table 3 are calculated as the absolute values of the difference between calculated and experimental values normalised with respect to experimental values. At high porosities, calculated values of F_S are very similar, since different coefficients proposed by the authors (Table 1) in Eq. 6 provide lower significant differences in values of $g(Re)$ as the Reynolds number increases.

Slightly different results can be observed for the knitted nets of the set B (Fig. 8). In this case, the relationships proposed by Brundrett (1993) and Bailey et al. (2003) provide higher differences with experimental results with respect to those calculated for set A1, A2 and A3. Such result was probably due to the adjustment of formulations proposed by Brundrett (1993) and Bailey et al. (2003), defined by the authors for monofilament nets at low airflow speed, to knitted nets at high velocities.

With reference to the relations proposed in this paper, the loss coefficient $F_S(Re_l, \varepsilon_{eq})$ introduced with Eq. (12) shows higher values than that calculated with Bailey et al. (2003) and Brundrett (1993), where it was derived from, except for knitted nets for which the percentage error was almost similar with other literature formulations (Tab. 4). Such result was due to the formulation of Reynolds number since the equivalent diameter of pores is higher than the diameter of the wire in nets of set A1, A2, A3 while it is comparable in set B nets. The loss coefficients $F_S(Re_l, \varepsilon_{eq})$ of set A1, A2 and A3 were lower than calculated ones (Figs. 5, 6 and 7) and the difference shows a low change of the net porosity within the interval 19.9 - 35.9 % (Table 4).

The simplified formulation of the loss coefficient $F_S(c_n, \varepsilon_{eq})$ of Eq. (13), shows a very good accordance with the experimental results (Table 3). In most cases, except for higher porosity nets with (A1-N1, A1-N2, A2-N1 and B-N1), $F_S(c_n, \varepsilon_{eq})$ shows the best matching with the experimental data. In addition, the coefficient $F_s(c_n, \varepsilon)$ describes the distribution of measured values with decreasing porosity better than other formulations do. Hence, when airspeed is above 4 m s^{-1}, it seems that the wetted perimeter of the net per square centimetre provides a better description of the airflow variation through the net compared to the function $g(Re)$. Also, when air velocity is higher than 4 m s^{-1}, the Reynolds number is high enough and $g(Re)$ is almost constant.

5. CONCLUSIONS

The air flow through fifteen nets, at airspeeds above 4 m s^{-1}, was experimentally studied using a purposely-built micro wind tunnel.

The air flow motion was described using the Bernoulli equation in terms of loss coefficient. Results confirmed those available in the literature in terms of dependence of the pressure drop on the velocity squared and on the porosity by means of the parameter $(1-\varepsilon^2)/\varepsilon^2$. The investigation dealt with the influence of the orifice geometry which, when in very elongated aperture shapes ($l_{sf} < {}^{1}/_{3}$), cause an effect equivalent to a net porosity increase. The comparison between measured and calculated values showed that the net porosity is not sufficient to properly describe the pressure drop across nets.

As suggested in other research literature, the loss coefficient was assumed to be the product of two different functions: $h(\varepsilon_{eq})$, depending on the equivalent porosity, and $g(Re_l)$ depending on the Reynolds number. However, different from previous studies, the Reynolds number was calculated with reference to the equivalent diameter of the pores, and not to the diameter of the wire. As a result, $F_S(Re_l, \varepsilon_{eq})$ showed deviation from experimental results in the range of 19.9 - 35.9% and values of the pressure drop were found to be lower than those proposed in other formulations such as those proposed by Brundrett (1993) and Bailey et al. (2003).

A simplified expression of the loss coefficient, depending only on the geometric characteristics of the net, was proposed supported by the high correlation factor ($R > 0.87$) between $h(\varepsilon_{eq})$ and F_S, and the graph of $g(Re)$ which shows it was almost constant for $Re > 200$,. The loss coefficient was expressed as a function of the equivalent porosity and the wetted perimeter per square centimetre of the net. This simplified the expression of the loss coefficient, $F_s(c_n, \varepsilon)$, allowed all the tested nets (flat woven and knitted) to be described by only one linear correlation curve with a very high coefficient of determination (R^2 > 0.98), particularly for nets with low porosity. At high wind speeds (above 4 m s^{-1}), the wetted perimeter of the net per square centimetre seems to match the variation of the pressure drop through the net better than the functions $g(Re)$ proposed respectively by Brundrett (1993) and by Bailey et al. (2003). The simplified formulation of the loss coefficient allows the prediction of pressure drop with respect to the air velocity with good accuracy and shows a percentage error with respect to experimental results in the range from 2.9% up to 24.6% for nets of set A1, A2 and A3. In most cases, except for higher porosity nets with, $F_S(c_n, \varepsilon_{eq})$ shows the best correlation with the experimental data. This result seems to be significant especially in knitted nets of set B for which the relationships proposed by Brundrett (1993) and Bailey et al. (2003) provide higher differences with experimental results with respect to those calculated for set A1, A2 and A3. A formulation of the loss coefficient not dependent on the air velocity using Reynolds number could be very appealing to designers using computational fluid dynamics as it allows simulations to be set up involving elements with pressure drop depending only on velocity as a parameter.

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