Wind tunnel modelling of porous elements

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1 INTRODUCTION

The response of structures to wind is often evaluated through wind tunnel tests, being the analytical calculation quite difficult or, in several cases, almost impossible. On the other hand, the proper prediction of the response requires an accurate definition of the model characteristics, because the geometric scale at which the model is manufactured is often one or two orders of magnitude smaller than the prototype.

In order to achieve a reliable response of the model, several similitude criteria have to be fulfilled and in some cases additional analyses have to be performed with the aim of reaching a suitable definition of all the details which could strongly affect the response of the model and then could lead to great discrepancies between the model and the prototype response. Regarding the geometric scaling, it is hard to represent some fundamental elements of real structures due to the reduced dimensions at the common wind tunnel scales. Consequently the elements that are more complicated to study are those which can be schematized like porous media, that have a permeability different from zero, and that cannot be treated as solid surfaces.

2 POROUS STRUCTURES

2.1 *Applications and use*

Nowadays modern design of structures requires an increased application of accessory elements, chosen and studied to guarantee higher and higher standards of performance. Among them the application of porous structural elements had a strong development because this kind of objects presents many functionalities: architectural design, temperature regulating function, shading function and wind-breaking effect. Both the temperature regulating function and the shading one become fundamental for the buildings for which it is necessary to reach high energetic standards. On the other hand, with reference to the windbreak aspect, this is mostly present in the realization of windbreak shields used on many important infrastructures to reduce and control the wind speed and to safeguard the users.

In the present work, the problem of a suitable modelling of such porous elements at the wind tunnel scale is addressed. After a brief introduction of the state of the art, an experimental campaign will be presented and the main results obtained will be discussed.

2.2 *State of the art*

In the literature there are many experimental studies about the flow through porous media (Miguel, 1998; Bejan et al., 2004) and numerical CFD analyses of porous materials (Costa et al., 1999; Fatnassi et al., 2003; Teitel et al., 2009). As an alternative to the analysis of porous media, there are also experimental works with a typical approach of the hydraulic resistance (Brundrett, 1993; Wu et al. 2005).

The majority of studies related to the flow around windbreaks or other porous structures include field measurements that are difficult to validate (Wilson, 1997), simulations in the wind tunnel (Lee et al., 2002; Guan et al., 2003) and numerical simulations (Pattone et al., 1998). A common way to describe the aerodynamic effects on a porous barrier is to consider its resistance to the flow through the dimensionless drag coefficient (Jacobs, 1985). Many publications show that the drag coefficient decreases when the porosity of the screen increases (Guan et al., 2003). Nevertheless, all the researchers have the common idea that the drag coefficient alone is not enough to characterize the behaviour of porous structures.

3 WIND TUNNEL TESTS

3.1 *Similitude criteria and key parameters*

When it is necessary to get a deep comprehension of the behaviour of porous elements by specific tests with scaled model in the wind tunnel, it is required that the similitude criteria and the key parameters regulating the scaling are known. The existing literature is evasive and elusive on this point or at least there is not a single criterion generally agreed in the scientific community. In addition, a geometric scale modelling of the porous element may be difficult to realize. In fact, applying the geometrical scaling, identical for both the model under testing (bridge section) and its devices (windbreaks), the resulting physical behaviour might be totally different in the two cases. This depends on the difficulty in representing at the wind-tunnel scale those entities that are already small at full scale, such as the little openings of the porous screens with respect to the global dimensions of the structure under examination.

The core of this work is the research of a law of modelling or its approximation for porous elements in the wind tunnel. The porous materials that have been chosen are perforated plates, the so-called holed plank fences (Figs. 1, 2).

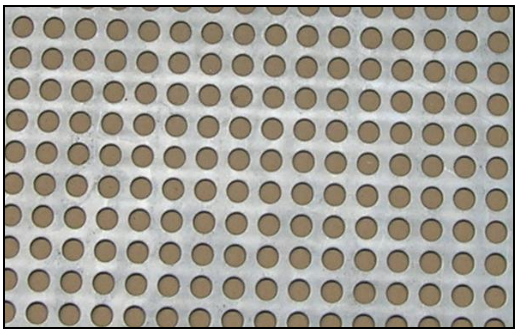

Figure 1. Round holed plank fence.

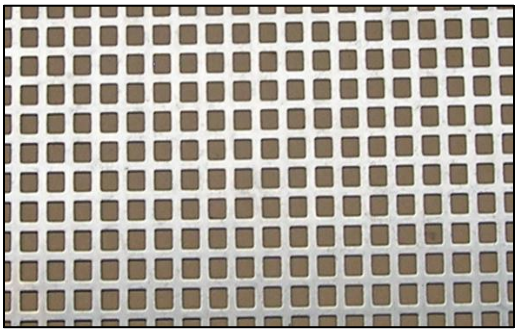

Figure 2. Square holed plank fence.

The fundamental characteristics of porous structures, consisting of holes, are represented by the porosity (ε), i.e., an index expressing the ratio of the area of voids to the total area; by the dimension and the geometric shape of the holes; by the thickness of the screen; and lastly by the height and shape of the structure.

At first the behaviour of porous screens with respect to the air flow in the wind tunnel was analysed. In order to define an equivalence between the full-scale structure and the wind tunnel model, the dimensionless key parameters under examination were: the loss coefficient (K) and the drag coefficient (C_D). These fundamental parameters can be defined for porous samples as follows:

$$K = \frac{\Delta p}{\frac{1}{2}\rho U^2} \qquad C_D = \frac{D}{\frac{1}{2}\rho U^2 A} \qquad (1-2)$$

where ρ = air density; U = wind speed in front of the screen sample; Δp = drop of pressure upstream-downstream of the porous element; D = drag force; and A = total area of the sample.

3.2 *Experimental set-up*

The principal problem is to obtain full-scale measurements on samples of porous materials. For the present work many tests on real screen samples with variable porosity were performed in the CRIACIV Boundary Layer Wind Tunnel.

The experimental equipment consisted in a cylinder positioned in the test section of the wind tunnel, where a porous screen was placed inside. It had the aim to channel the wind stream in order to control the approaching flow on the grid sample. The particular measurement set-up had the purpose of describing the behaviour of the perforated plate by evaluating the wind speed and the pressure pattern upstream and downstream of the obstacle, the corresponding drop of pressure and the drag force on the plate. All these parameters were calculated for 15 different flow speeds. The pressure patterns and the drop of pressure were measured with an appropriate system of pressure taps connected to piezoelectric transducers (Pressure System Unit, PSI 8400). The drag force was obtained with three load cells connected to the screen sample and the flow velocity was measured by means of pitot tubes (Figs. 3, 4).

Figure 3. Experimental set-up.

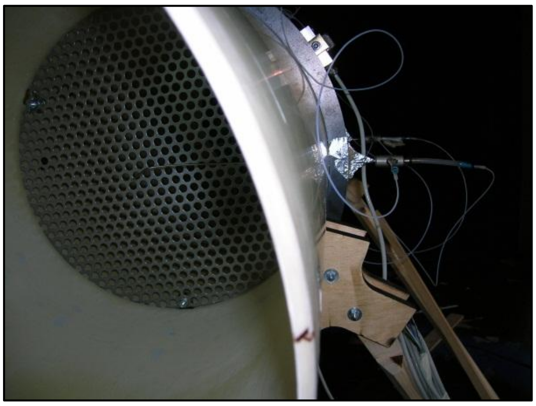

Figure 4. Grid sample in the wind tunnel.

The tests were done both on full-scale and geometrically scaled samples of the screen in order to find a possible scaling criterion. 28 samples of porous media with different characteristics in terms of porosity (22.68% ÷ 69.40%), thickness as well as shape and dimension of the holes were tested. For each type of sample, diagrams were created reporting the patterns of pressure, drag and loss coefficients as functions of the local Reynolds number, defined as:

$$\mathrm{Re}_L = \frac{w_0 \cdot D_h}{\upsilon} \tag{3}$$

where w_0 = wind speed inside the holes ($w_0 = U/\varepsilon$); υ = kinematic viscosity; and $D_h = 4f_0/\Pi_0$ is the equivalent hydraulic diameter, where f_0 = hole area and Π_0 = hole perimeter.

Figure 5 reports the relationship between K and C_D and local Reynolds number for one of the grids tested, with a level of porosity of 46.28%. As for all the other samples tested, the results show that K and C_D present similar values and are independent of the local Reynolds number, at least in the investigated range.

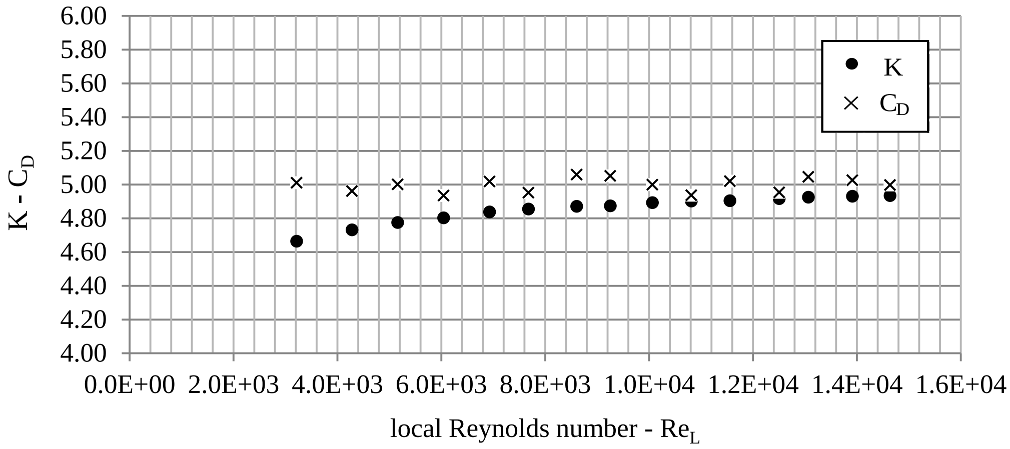

Figure 5. K - C_D vs. Re_L for one of the grids tested (R10T14, round holes, D_h = 10 mm, t = 1 mm, ε = 46.28%).

4 DISCUSSSION OF RESULTS

Since both K and C_D seem to be interchangeable dimensionless parameters used to understand the behaviour of porous plates with respect to the air flow, only the loss coefficient was considered for the elaborations because it resulted more stable than the drag coefficient.

The effect of various parameters that are able to influence the loss coefficient is discussed. More in detail is examined the role played by the level of porosity, by the local Reynolds number, by the thickness of the screen and by the dimension and shape of the holes.

Figure 6 reports for all the samples tested the global effects of all the variables involved with respect to the loss coefficient (K). The loss coefficient takes values in the interval 0.95 ÷ 22.4 and clearly depends on the porosity and increases when the latter decreases (i.e., $K \rightarrow \infty$ as $\varepsilon \rightarrow 0$ and $K \rightarrow 0$ as $\varepsilon \rightarrow 1$).

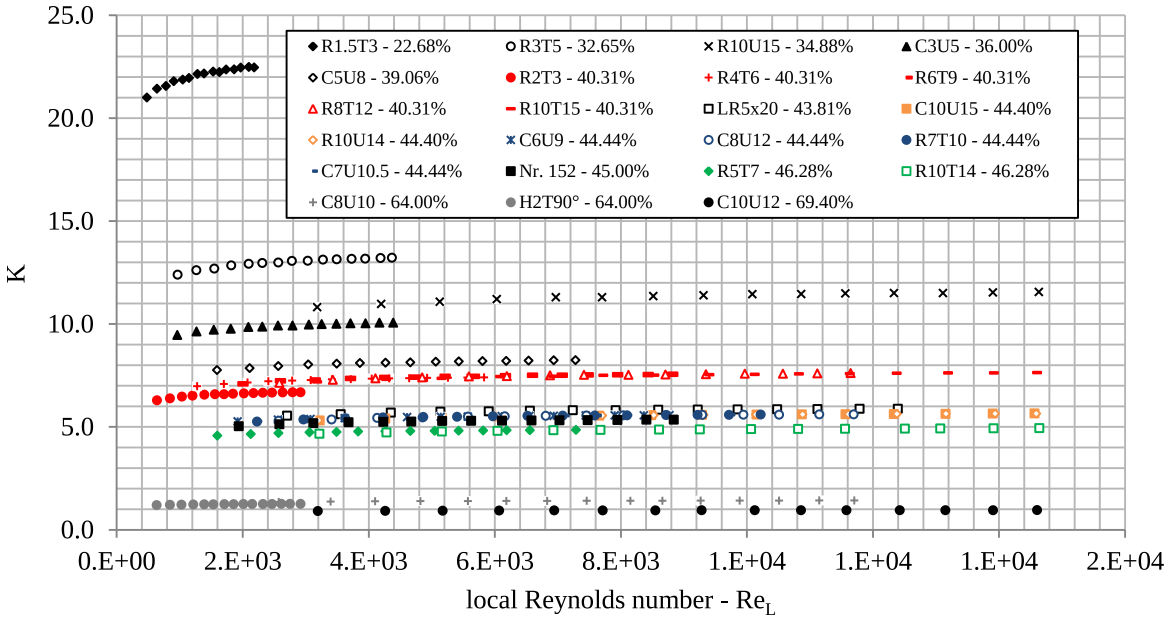

Figure 6. K vs. Re_L for all the grid samples tested. Grid code: A#B@; where A is the shape of the holes (R = Round, C = Square, LR = Oblong, H = Hexagonal, Nr. 152 Cross); # is their dimension expressed in millimetres; B is the arrangement of the holes (T = staggered, U and not specified = in-line); @ is the spacing of the arrangement in millimetres.

4.1 *Effects of porosity and Reynolds number*

The most common practice (Brundrett, 1993; Valli et al., 2009) consists in splitting the loss coefficient (*K*) into two functions, one depending on porosity G(ε) and the other on the local Reynolds number F(Re_L):

$$K(\varepsilon, \mathrm{Re}_L) = G(\varepsilon) \cdot F(\mathrm{Re}_L) \tag{4}$$

For each type of screen, with different levels of porosity, only the mean values of *K* in the range where the loss coefficient is independent of the local Reynolds number (i.e., beyond a certain Re_L value) were considered. By an exponential fitting of the *K* data it was possible to find an analytic expression of the $G(\varepsilon)$ function (Fig. 7).

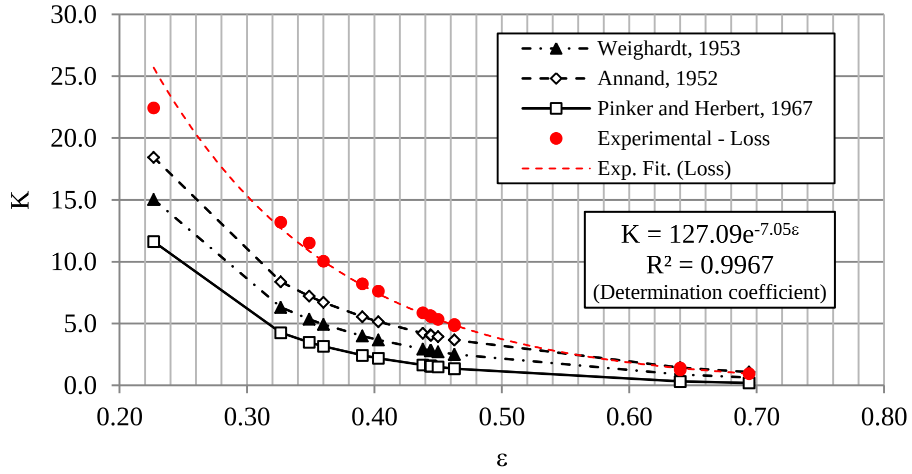

Figure 7. $G(\varepsilon)$ fitting function.

The porosity seems to be the most relevant parameter for the phenomenon, as both the loss coefficient and the drag coefficient are strongly dependent on it. Thus, it is necessary to maintain the same porosity level passing from the model to the prototype. This is the first requisite but it is still necessary to clarify how this level of porosity has to be achieved in terms of shape, dimension, position and thickness of the holes.

In order to isolate the dependency on the local Reynolds number, knowing the $K(\varepsilon, Re_L)$ and $G(\varepsilon)$ functions, the $F(Re_L)$ function can be simply defined as:

$$F(\mathrm{Re}_L) = \frac{K(\varepsilon, \mathrm{Re}_L)}{G(\varepsilon)} \tag{5}$$

This function is able to highlight the viscous and inertial zone and the relative threshold value for all of the samples tested. The boundary between the two regions is identified and it corresponds to a local Reynolds number value of 2000. Therefore, in order to avoid Reynolds number effects it is necessary to operate comparisons at local Reynolds numbers not lower than 2000, for both the model and the prototype.

4.2 *Effects of hole shape*

In order to investigate the role of the shape of the holes, additional experiments were carried out in the wind tunnel on four samples. The screens were compared in pairs which had the same porosity level, the same thickness and hydraulic diameter. They differed only for the shape of the holes (round or square).

Figure 8 confirms that the effects of the shape of the holes are negligible, because the discrepancies between the data for round and square shapes are irrelevant and they are comparable with the errors made by instruments of measure. Therefore, it seems possible to choose arbitrarily the shape of the holes passing from the model to the prototype.

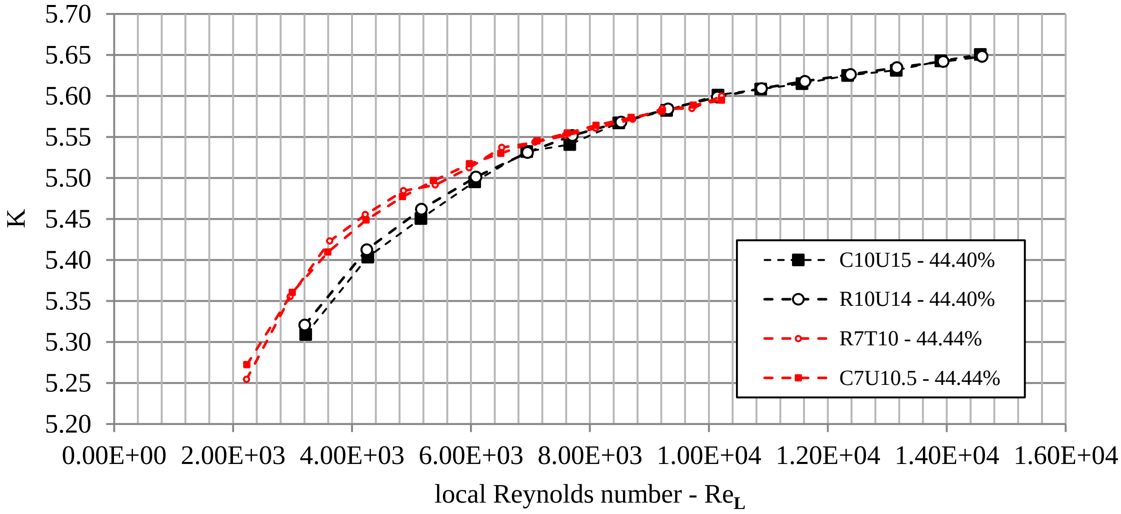

Figure 8. K vs. Re_L for screens with different shapes of the holes.

4.3 *Effects of thickness and diameter*

With the aim of studying the influence and the role played by the thickness of the screen and diameter of the holes, 11 different typologies of screen, with different thicknesses (1 ÷ 6 mm) and hole diameters (2 ÷ 10 mm), but same level of porosity (40.31%) and hole shape (round), were tested. In the tests it was observed that the loss coefficient is higher for the grid samples having smaller values of the thickness. In contrast, higher values of the loss coefficient are found in correspondence of larger hydraulic diameters. Therefore, K tends to increase or decrease as a function of the diameter of the holes and of the screen thickness (Figs. 9, 10).

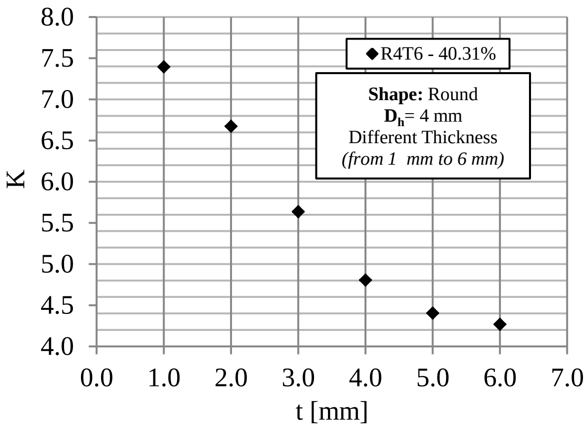

Figure 9. K vs thickness (t).

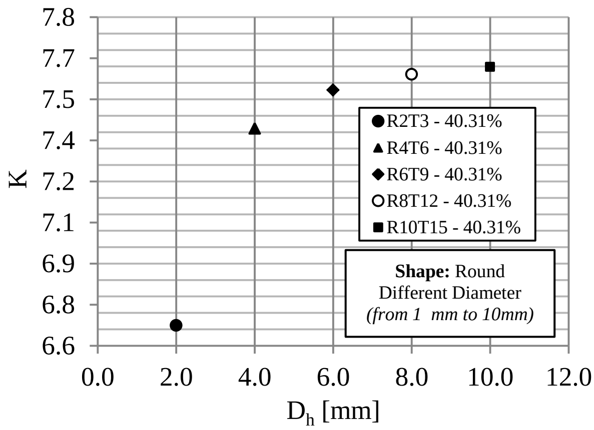

Figure 10. K vs hydraulic diameter (D_h).

The key parameter to describe the influence of thickness (t) and hydraulic diameter (D_h) is the ratio t/D_h. Figure 11 reports the F function mean values (obtained in the zone where Re_L > 2000 and consequently after the dependency of the local Reynolds number is removed) with respect to the ratio t/D_h for all the samples tested.

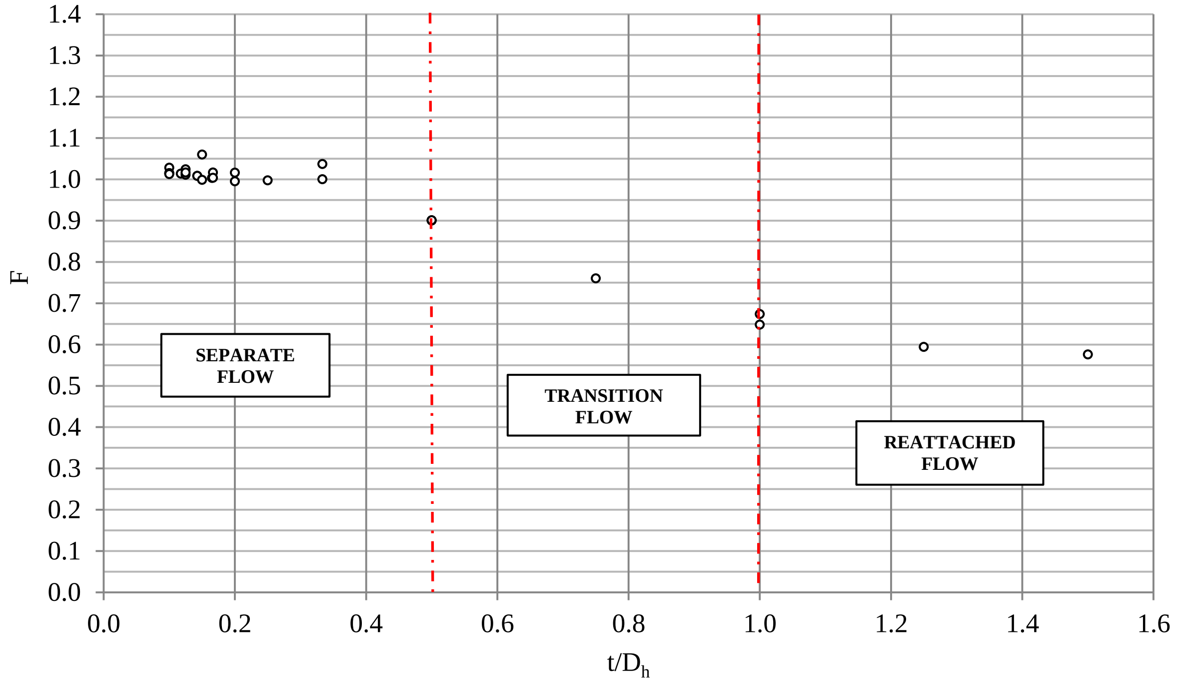

Figure 11. F vs. t/D_h for all the grid samples tested.

The characteristics of the flow through a perforated plate depend on whether the wake formed downstream of the holes remains separated or reattaches to the walls of the openings. Three different regions can be observed: one zone of transition and two stable regions (Idelchik, 1994 and ESDU, 1985). The F function is almost constant and regular for $t/D_h > 1$ and $t/D_h < 0.5$, identifying the zones of reattached flow and separated flow. In fact, in the first zone the behaviour of the holes with respect to the air flow might be similar to the flow inside a long pipe, while in the second zone the flow may be assimilated to a free jet. When flow separation occurs, the drop of pressure is increased and vice versa when the flow reattaches. In the transition zone the flow may exhibit intermittent reattachment and characteristics of the wake intermediate between the separated flow regime and the reattached one. Thus, in order not to change the wake flow regime it is important to conserve the same ratio t/D_h while passing from the prototype to the model scale.

5 PROPOSED SCALING CRITERION

Now it is opportune to define a sort of scaling criterion for the wind tunnel simulation of porous elements. The principal parameters that have to be maintained in this simple scaling criterion are the following:

- Same level of porosity (ε);
- Independence of the local Reynolds number ($Re_L \geq 2000$);
- Same ratio t/D_h.

In contrast, the scaling seems to be independent of the shape and position of the holes.

This kind of scaling rule can be used only to porous elements represented by perforated plates having any shape, arrangement, diameter and thickness of the holes and for porosity level in the investigated range 22.68% ÷ 69.40%. It is also necessary to remember that this rule can be applied only to the portion of an object that can be schematized as a porous medium. Considering the general case of porous façades, windbreak screens, technique surfaces, etc., where it could be necessary to carry out some tests in the wind tunnel, the found scaling criterion can be applied only to the porous part of the fence. On the other hand, regarding the predominant geometrical dimensions of the porous elements (the height in the case of windbreaks or the width times the height for porous surfaces) the classical geometric scaling process can be used. In fact the evaluation and the correct soundness of the geometric scaling process for the predominant geometrical dimensions of the elements will be analysed in future work.

6 CONCLUSIONS

Porous elements are commonly used as accessory devices in many technological sectors of civil engineering. In some cases it is necessary to test their behaviour with respect to the air flow, through appropriate wind tunnel experiments. The scale modelling of porous structures is very complex because their small openings are difficult to be represented at the common scales of the wind tunnels. In this work, the reference porous elements were perforated plates with various levels of porosity, as well as different geometries and thicknesses of the holes.

Using a particular wind tunnel experimental set-up, it was possible to remark that the loss coefficient and the drag coefficient were almost coincident and interchangeable to characterize the aerodynamic behaviour of these porous media.

In addition, the analysis of the wind tunnel data allowed to propose a scaling criterion for porous elements, represented by perforated plates. The criterion found can be used for the porous core of the element, adopting the simple geometric scaling similitude for the overall structure. The correct scaling from the model to the prototype can be achieved by maintaining the same porosity level, obtained with any shape and arrangement of the holes, the same thickness to hydraulic diameter ratio and ensuring that the Reynolds number effects are not present.

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