August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

The CFD modelling of permeable surfaces: a pressure-velocity jump approach

Mao Xu[1], Luca Patruno[2], Stefano de Miranda[3]

[1]*University of Bologna, Bologna, Italy, mao.xu2@unibo.it*
[2]*University of Bologna, Bologna, Italy, luca.patruno@unibo.it*
[3]*University of Bologna, Bologna, Italy, stefano.demiranda@unibo.it*

SUMMARY:
The use of permeable surfaces is very common in modern architecture and in the realization of secondary elements for infrastructures, examples being the outer layer of permeable double skin facades and wind shields. However, the characteristic dimension of the overall structure is usually much larger than that of the pores, so that their study using classical Wind Tunnel Tests, WTT, and Computational Fluid Dynamics, CFD, poses numerous difficulties. In particular, in WTT it is impossible to simply scale down the geometry, as pores become too small and aerodynamic similarity would not be preserved. As regard CFD, the cost of simulations explicitly accounting for the pores geometry is prohibitive. To solve the problem, so-called pressure-jumps can be used to provide a representation of the porous surface aerodynamic behaviour when no significant velocity deflection is expected. Here, a novel Pressure-Velocity Jumps based approach, *PVJ*, is presented. The approach is of general applicability and allows to account for velocity deflections. The approach is validated against detailed CFD models in which the geometry is explicitly modelled for the case of a ground-mounted permeable barrier, showing extremely good agreement. A cyclic boundary condition for OpenFoam implementing the approach is available at `https://site.unibo.it/cwe-lamc/en`.

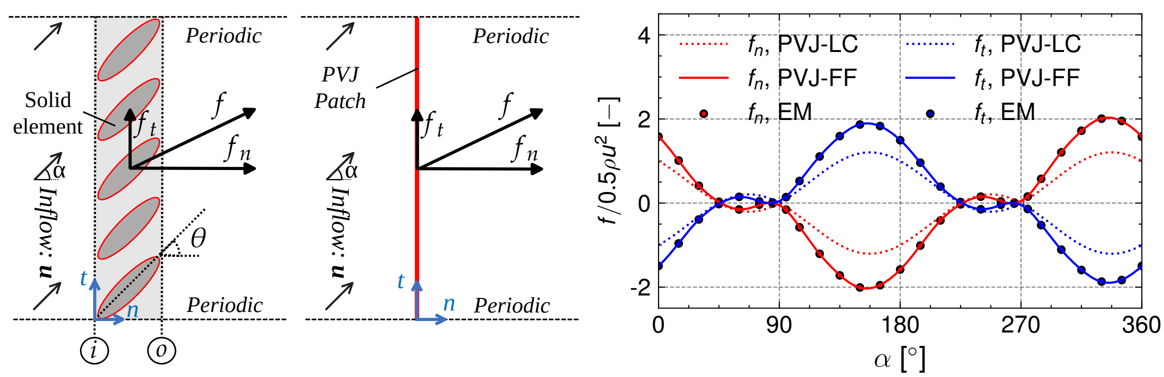
Keywords: Computational Wind Engineering, Permeable surface, Pressure jump, Velocity jump

1. INTRODUCTION

Permeable elements are often used in the construction industry and find numerous applications, especially in modern architecture (Belloli et al., 2014). However, obtaining an accurate representation of their aerodynamic behaviour is extremely challenging when using both, Wind Tunnel Tests, WTT, and Computational Fluid Dynamics, CFD, based simulations. For WTT, the large scale separation existing between the overall structure and the pores does not allow to use reduced-scale models in a straightforward way (Allori et al., 2013). When using CFD similar difficulties are found. Explicitly simulating the pores leads to unsustainable computational costs, so that models obtained reproducing the porous surface geometry are possible only in particularly simple cases. We denote such models as Explicit Modelling, *EM*, in the following. Homogenized models can be used in order to synthetically reproduce the aerodynamic effects induced by the presence of permeable surfaces without explicitly simulating them (Maruyama, 2008; Tominaga and Shirzadi, 2022). In particular, the so-called pressure-jump approach is a well-known technique, which assumes the permeable surface to be of null thickness and disregards the contribution of forces exchanged in its plane (i.e. shearing forces). An alternative approach is to represent the presence of the permeable surface as a thin sheet of a porous medium, relying on the Darcy-Forchheimer model. In this approach, appropriate momentum sinks are defined, accounting for the resistance encountered by the flow in traversing the permeable surface. Usually, for high Reynolds numbers, only inertial contributions are retained and the matrix collecting the Forchheimer coefficients is assumed to be diagonal. The model can be adopted using full matrices and Pomaranzi et al. (2021) used it to represent the aerodynamic behaviour of scratched metal sheets. Inspired by Pomaranzi et al., 2021, we here propose a new approach able to accurately represent the forces exchanged between the fluid and permeable surface. The approach, denoted as *PVJ*, can be substantially seen as a generalization and systematization of the pressure-jump approach, in which we allow for velocity deflections similarly to the use the Darcy-Forchheimer model. Limit cases for which analytical considerations allow to deduce the model coefficients are also detailed, proving that the approach can be used to model a wide range of permeable elements, ranging from porous plates to lamellar screens. The model is validated against *EM* models for the case of a simple ground-mounted barrier, showing extremely encouraging results.

2. THE *PVJ* APPROACH

The first step in the development of the present *PVJ* approach is to relate the forces exchanged by a permeable surface to the corresponding jumps measured when traversing the surface in terms of pressure and tangential velocity. In particular, considering a 2D-case, Figure 1 (a) reports the scheme of an elementary portion of a permeable surface immersed in a flow characterized by velocity $\boldsymbol{u}$ and impinging with incidence angle α with respect to the barrier normal direction, n. The *PVJ* approach aims at eliminating the explicit representation of the pores, leading to a synthetic representation of the porous element effects, as depicted in Figure 1 (b).



(a) *EM* (b) *PVJ* (c) dimensionless forces

Figure 1. Permeable surfaces: (a) *EM* approach, (b) *PVJ* approach, (c) aerodynamic forces as a function of the angle of attack.

In case of incompressible fluid, mass conservation of the control volume bounded by the surface i and o in Fig. 1 (a), requires $u_{ni} = u_{no}$. Subscript i and o are used to identify the location where quantities are measured. Furthermore, assuming to know the aerodynamic forces, $\boldsymbol{f}$, per unit area of the permeable surface, momentum conservation in the n and t directions require

$$\begin{bmatrix} f_n \\ f_t \end{bmatrix} = \begin{bmatrix} p_i - p_o \\ \rho\left(u_{ti}u_{ni} - u_{to}u_{no}\right) \end{bmatrix}, \tag{1}$$

where f_n and f_t are the normal and tangential aerodynamic forces per unit area, p is pressure, u_n and u_t are the normal and tangential components of velocity. It can be easily observed that Eq. (1) allows to calculate the jumps of the pressure and the tangential velocity component based on the exchanged forces and the mass flux across the permeable barrier. The problem thus boils down to the definition of a reasonably simple, yet flexible, approach able to represent the aerodynamic forces for all incidence angles. By defining the velocity versor as $\hat{\boldsymbol{u}} = \boldsymbol{u}/|\boldsymbol{u}|$, the aerodynamic forces are assumed to be expressed as:

$$\boldsymbol{f}(\alpha) = \frac{1}{2}\rho|\boldsymbol{u}|^2|\hat{u}_n|^\gamma \boldsymbol{c}(\alpha), \tag{2}$$

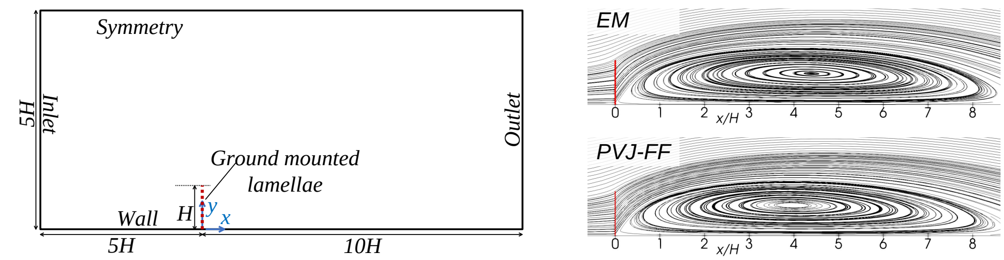
where γ is a coefficient and $\boldsymbol{c}(\alpha)$ can be conveniently expressed in terms of a Fourier series as

$$\boldsymbol{c}(\alpha) = \begin{bmatrix} c_n \\ c_t \end{bmatrix} = \begin{bmatrix} b_{n0} + b_{n1}\cos(\alpha) + b_{n2}\sin(\alpha) + b_{n3}\cos(2\alpha) + b_{n4}\sin(2\alpha)... \\ b_{t0} + b_{t1}\cos(\alpha) + b_{t2}\sin(\alpha) + b_{t3}\cos(2\alpha) + b_{t4}\sin(2\alpha)... \end{bmatrix}, \tag{3}$$

in which b_{n0}, b_{t0}, b_{n1}, b_{t1}, *etc* are model parameters that can be obtained from fitting. For particularly simple cases, the coefficients appearing in Eq. (3), can be obtained analytically. In particular, for lamellar screens, i.e. porous elements made of equally oriented closely-spaced lamellae, the fluid can be assumed to be fully deflected and align with the lamellae direction. This allows to calculate analytically through momentum conservation the coefficients appearing in Eq. (3), also showing that only coefficients b_{n1}, b_{n2}, b_{t1}, b_{t2} are non-null. A comparison of the results obtained from the explicit model *EM*, the analytical solution *PVJ-LC* and the fitting of the coefficients appearing in Eq. (3), indicated as *PVJ-FF*, is reported in Fig. 1 (c). It is observed that only qualitative agrement is found between *EM* and *PVJ-LC*, with closer inspection showing that larger-than-expected flow deflections are produced due to flow separations. The analytical solution nevertheless provides good guidance in the *a priori* estimation of the model coefficients, with the fitting providing very accurate results.

3. RESULTS

The present *PVJ* approach is applied in the case of a ground mounted lamellar barrier, for which strong velocity deflections are expected. In particular, results obtained with *EM* are compared to those obtained with the present approach. An overview of the considered case is reported in Fig. 2 (a), where each solid element of the adopted *EM* lamellae is the same as that shown in Fig. 1 (a).Looking at Fig. 2 (b), it can be seen that the streamlines obtained using the impractical and computationally demanding *EM* model are extremely similar to those obtained by the present calibrated *PVJ* model. The deflection operated by the permeable surface can be clearly observed. Further studies, summarized in Fig. 3 show that the global aerodynamic forces calculated from *EM* models correctly converge to the *PVJ* model as the characteristic dimensions of the pores/lameallae, tend to become small with respect to the overall barrier height (the number following *EM* in the legend is the number of pores/lamellae along the barrier height).



(a) (b)

Figure 2. The application of the *PVJ* approach: (a) the computational domain for the ground mounted lamellar barrier and (b) the streamlines of the time-averaged flow.

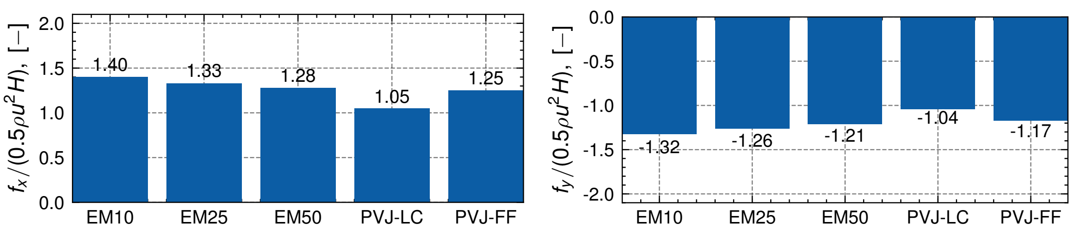


Figure 3. The dimensionless aerodynamic forces of the lamellae modelled with *EM* and *PVJ*.

4. CONCLUSIONS

This study proposes a homogenized approach based on pressure and velocity jumps to model the permeable surfaces in CFD-based simulations. The proposed *PVJ* approach is found to well-reproduce the results obtained by demanding *EM* models, leading to a great simplification of the analysis setup and very large savings in terms of computational costs. The approach is expected to be convenient in all cases for which the scale separation between the pores and the overall structure is large, so allowing to study cases which cannot be simulated using explicit geometrical models. The proposed approach is expected to be extremely convenient also for parametric studies and optimizations.

REFERENCES

Allori, D., Bartoli, G., and Mannini, C., 2013. Wind tunnel tests on macro-porous structural elements: A scaling procedure. Journal of Wind Engineering and Industrial Aerodynamics 123, 291–299.

Belloli, M., Rosa, L, and Zasso, A., 2014. Wind loads and vortex shedding analysis on the effects of the porosity on a high slender tower. Journal of Wind Engineering and Industrial Aerodynamics 126, 75–86.

Maruyama, T, 2008. Large eddy simulation of turbulent flow around a windbreak. Journal of Wind Engineering and Industrial Aerodynamics 96, 1998–2006.

Pomaranzi, G., Bistoni, O., Schito, P., and Zasso, A., 2021. Numerical modelling of three-dimensional screens, treated as porous media. Wind and Structures 33, 409–422.

Tominaga, Y. and Shirzadi, M., 2022. RANS CFD modeling of the flow around a thin windbreak fence with various porosities: Validation using wind tunnel measurements. Journal of Wind Engineering and Industrial Aerodynamics 230, 105176.