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Multi-scale simulations of porous screens for pedestrian level wind analysis

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SUMMARY:
Porous screens are commonly adopted as a pedestrian-level wind (PLW) mitigation measure in urban developments, yet their representation in computational fluid dynamics (CFD) models remains subject to significant uncertainty. This paper presents a multi-scale CFD investigation aimed at assessing the reliability of porous modelling approaches for PLW analysis. The study begins with pore-scale simulations of a representative porous screen geometry, validated against wind tunnel measurements to characterise the downstream flow behaviour. These results are used to parameterise Darcy-Forchheimer porosity models for full-scale simulations of isolated screens under typical atmospheric boundary layer flows, considering a range of wind directions and porous modelling strategies. Finally, the influence of the modelling approaches is examined within a city-scale PLW assessment. By linking pore-scale behaviour to screen and city-scale performance, the work highlights the limitations associated with current CFD practices and provides practical guidance for the application of porous screen models in numerical PLW analysis.

Keywords: Porous Screens, Pedestrian Level Wind, Wind Microclimate, Computational Fluid Dynamics

1. INTRODUCTION

Porous screens are widely used as a mitigation measure in pedestrian level wind (PLW) studies of urban areas. This is based on the principle that porous obstructions can be used to locally improve wind conditions by reducing the velocity and turbulent kinetic energy of the flow in the downstream region. Porous screens are increasingly being relied upon to ensure urban areas meet pedestrian comfort and safety criteria at the design stage, particularly in the planning of tall and/or densely grouped buildings where strong downdraft and funnelling effects are expected.

Pedestrian level wind studies for the design of buildings and urban areas are typically performed using scaled wind tunnel experiments or computational fluid dynamics (CFD) simulations. In both methods, simplifications and uncertainties are inherent in the modelling of porous elements. The most significant limitations of both methods are summarised in Table 1.

A wide variety of porous screen configurations have been used in urban developments to date, some representative examples of which are shown in Figure 1. The screens often feature single or double skin panels, bespoke perforation patterns, and thick solid stands/framing. For design-stage PLW studies, the exact configuration of a porous screen is often unknown at the time of modelling. Therefore, a generalised model is typically used with a specified open area ratio, which is then matched for the installed screen. In practice, however, the pressure drop performance of the installed screen will also be dependent on the specific geometry of the perforations and on the frame geometry.

Table 1. Comparison of limitations and sources of uncertainty in wind tunnel and CFD modelling of porous screens.

CFD Simulations	Wind Tunnel Testing
Idealised screen geometries	Idealised screen geometries
Mesh resolution limitations in porous regions	Scale effects
Turbulence modelling deficiencies	Discrete measurement points
Computational expense	Greater initial setup cost

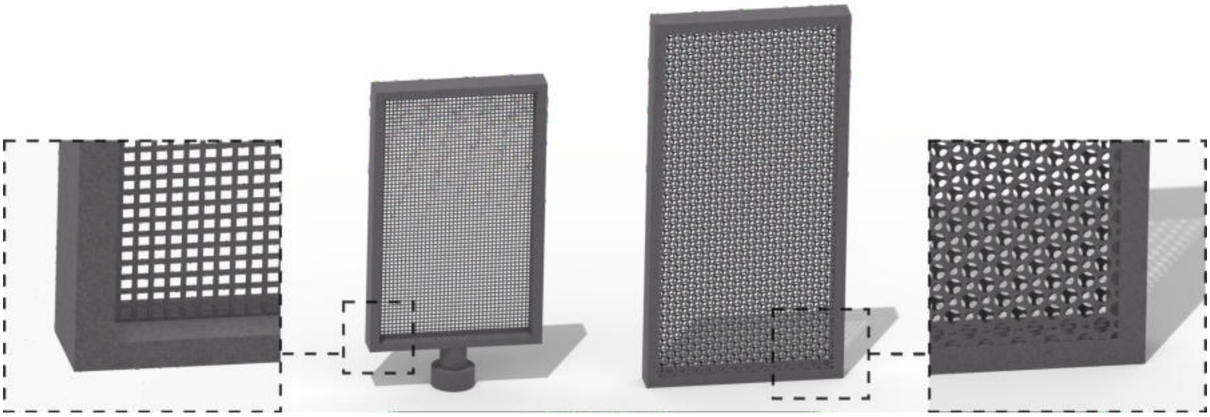

Figure 1. Examples of porous screen types used as pedestrian level wind mitigation measures.

This work aims to evaluate the reliability of CFD modelling methods for porous screens in PLW studies, bridging the gap between the resolution of small-scale wind tunnel models and the full-scale performance of realistic screen geometries. Practical guidelines for CFD modelling will be presented as a conclusion of the simulated results.

1.1. APPROACH AND METHODOLOGY

In this study, a multi-scale approach is taken to validate the computational methods used to evaluate the performance of porous screens in pedestrian level wind analysis. The workflow of the study is summarised in Figure 2. The following three scales of simulation are performed:

1. *Pore-scale:* Detailed analysis of the flow through subsections of a porous screen geometry, which is used to derive pressure drop characteristics. These simulations are validated against benchmark wind tunnel data available in literature.
2. *Screen-scale:* Simulations of isolated full-scale porous screens in typical atmospheric boundary layer (ABL) flows for a range of wind directions. Porous effects are included using Darcy-Forchheimer porosity models based on the pore-scale results, with a focus on comparing the most common porous modelling methods, i.e.:
   - 2D porous baffles
   - 3D isotropic porous zones
   - 3D anisotropic porous zones with custom reference frames
3. *City-scale:* A representative pedestrian level wind study, assessing the influence of the porous modelling methods with the interaction of multiple screens and buildings. Again, the computational results are compared to wind tunnel data for the same PLW case.

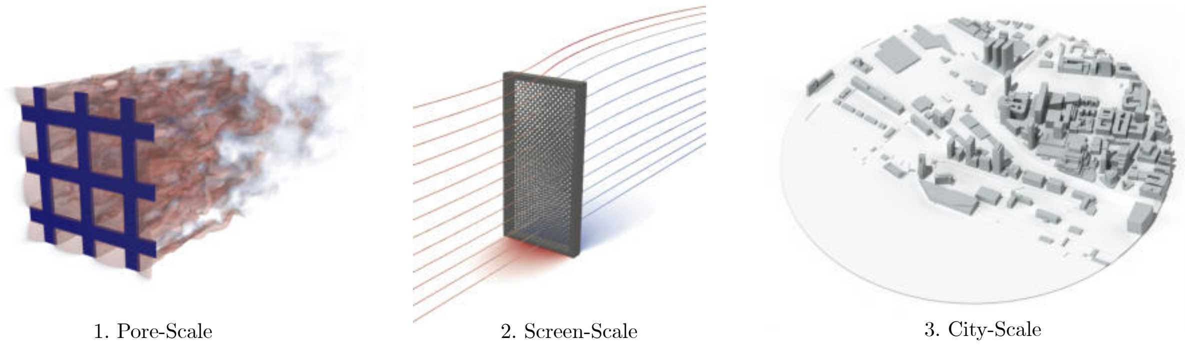

Figure 2. Scales of simulation in the study.

1.2. Pore-Scale Modelling

The first stage of the modelling involves CFD simulations of a representative section of a porous screen that would be used in a wind tunnel PLW study. The experimental setup of Tominaga and Shirzadi, 2022, is used as a validation case to construct the simulations. They performed wind tunnel testing of isolated porous screen samples with a height of $H = 0.2\,\text{m}$ within a representative atmospheric boundary layer flow, created using roughness blocks. Figure 3 shows a schematic view of the simulated domain, constructed to match the wind tunnel parameters.

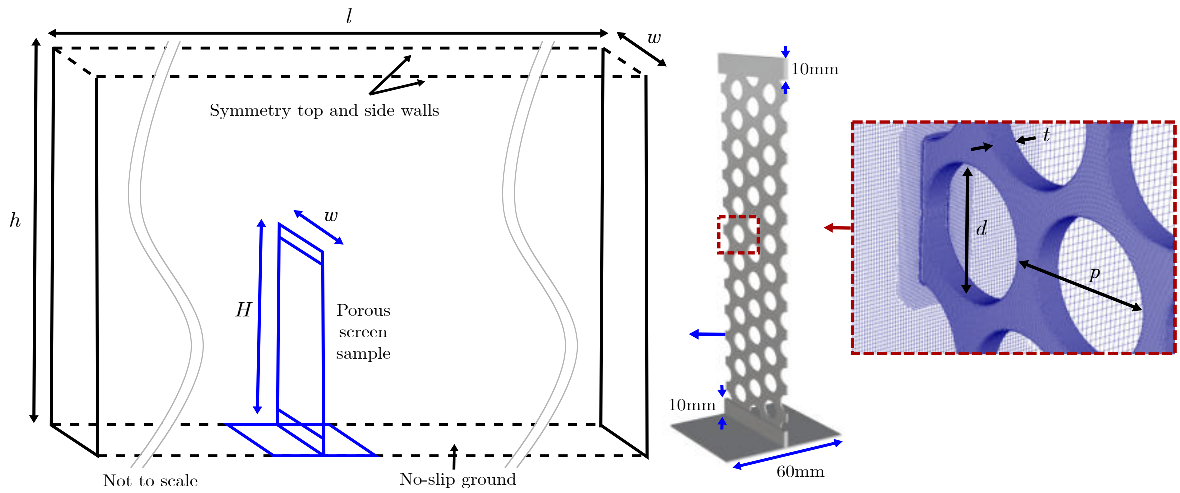

Figure 3. Domain setup and mesh for the detailed sub-model. Perforation diameter $d = 10\,\text{mm}$, pitch $p = 15\,\text{mm}$, thickness $t = 0.8\,\text{mm}$, screen height $H = 0.2\,\text{m}$, domain height $h = 1.8\,\text{m}$, width $w = 52\,\text{mm}$ and domain length $l = 5\,\text{m}$. The open area of the sample screen is 40%.

The simulations are performed using a steady-state finite volume RANS solver and the k-ω SST turbulence model (Menter, 1994). The computational domain consists of a 30 million cell hex-dominant mesh. No-slip wall boundary conditions are applied to the ground plane and the porous screen surface. 5 prism layers are used to resolve the boundary layer on all no-slip walls, with a growth rate of 1.1. Symmetry boundaries are used on the side and top walls of the domain. The wind tunnel results confirm that the flow is uniform across the width of the tunnel, therefore the sidewall symmetry conditions allow simulation of just a small representative width of screen ($w = 52\,\text{mm}$) rather than resolving the full crosswise extent of the tunnel. A velocity inlet condition is set at the entrance of the channel with a height-varying profile matching the measured wind tunnel profile. Empty domain simulations were performed to ensure this profile is adequately maintained up to the screen location. A pressure outlet condition is specified at the far end of the domain.

2. INITIAL FINDINGS

The streamwise velocity contours from the simulations are shown in Figure 4. The velocity profiles at 5 measurement locations ($x/H = -1, 1, 2, 4, 8$) are overlaid, with comparison to the wind tunnel results of Tominaga and Shirzadi, 2022. It is seen that the overall match between the numerical and experimental results is good. The largest discrepancies are observed close to the ground, $z/H < 0.4$, where the simulation predicts a more severe velocity deficit in the recirculation region downstream of the screen. Further downstream, by $x/H = 8$, the velocity profile recovers a similar shape to that of wind tunnel results.

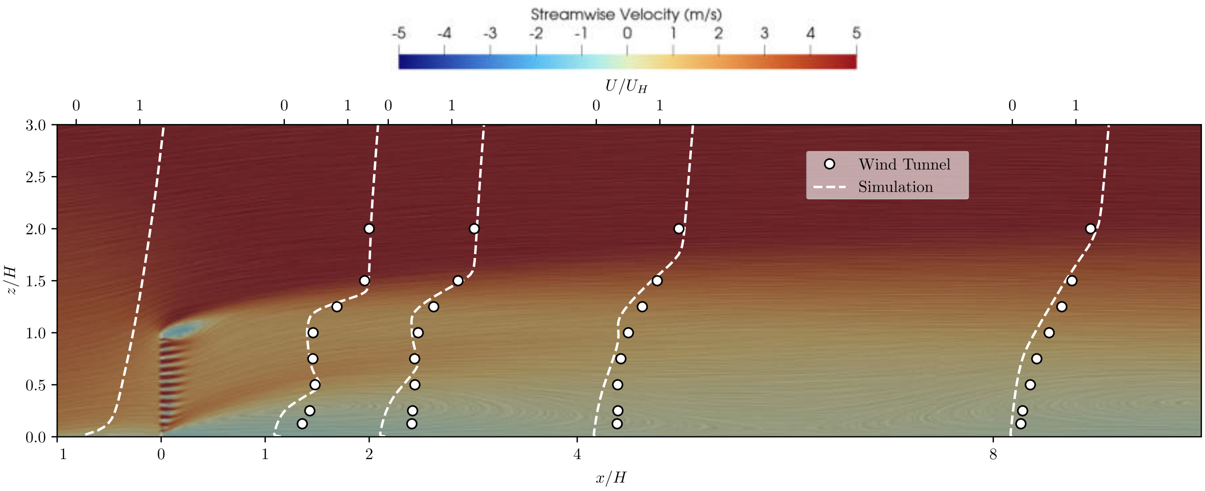

Figure 4. Simulated streamwise velocity results for the screen sample, with comparison to the measured wind tunnel profiles of Tominaga and Shirzadi, 2022.

3. CONCLUSIONS AND FUTURE PROSPECTS

Pore-scale resolved CFD simulations are shown to accurately capture the wake velocity profile downstream of a representative porous screen section when compared with wind tunnel data. This setup can be tested with varying screen orientations relative to the oncoming flow, with the resulting velocity and pressure drop characteristics used as the basis for porosity modelling at the screen-scale and city-scale.

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