

Modeling airflow in an urban landscape

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Abstract: The windbreak effects on pedestrian level wind speed reduction were examined in a series of generic layouts, both in wind tunnel and by CFD modeling. The effects on the horizontal wind-speed reduction curves were examined as well as the horizontal velocity contours. The 2D and 3D windbreak were both applied in the CFD simulations, with different positions and limited range of incidence angles to the wind.

Keywords: windbreak; wind tunnel; urban; open space; landscape; CFD.

1. Introduction

It has been a long history that natural trees and hedges are regarded as a crucial element of urban landscape design, either for their aesthetic value, which contributes to the concept of "Green City" or for their functional aspect, which is mainly adapted to provide better design for comfort indoor and outdoor environment. There are numerous studies in the past have contributed greatly to the understanding of the effects of tree-belts or windbreaks on the airflow structure, particularly on the wind speed reduction. Caborn [1] gave a general review of windbreak, including the classification of the windbreaks, the microclimatic factors affected by windbreaks, and the research procedures. Plate [9] reviewed several quantitative investigations on windbreaks, providing rather comprehensive knowledge on aerodynamics of shelterbelts. Kaine and Stevenson [2] presented the measurements of the wind speed and the energy spectra in the leeward of model fences together with a brief review of the windbreak aerodynamics. Wilson [3] carried out the study of mean wind speed and turbulence behind artificial porous fence with various vertical distribution of porosity. Heisler and Dewalle [4] gave another valuable review on the effects of windbreak structure on wind flow, as well as some secondary effects related to the wind speed reduction.

Most of these studies were carried out in attempt to figure out the sheltering effect of a windbreak on large rural open space or farmstead that only windbreak itself was considered in the simulated flow domain. Although the findings of these studies have also been used by urban planners and landscape architects in their designs for years, it appears that these windbreaks are

considered as an isolated object in an open plane and the presence of buildings in the leeward of the windbreak has been omitted. Consequently the effects of the solid obstruction are ignored. As many buildings behind the windbreaks are close enough so that their existence would affect airflow and then sheltering effects, these designs assuming no presence of buildings would have much less practical values. The interactions between the porous vegetation and the solid objects, like buildings, have been found significant in a previous study, where wind blows right onto a straight windbreak and over to a solid cube right behind the windbreak [10]. The interaction affects the horizontal wind speed profile along the central line of this symmetric layout.

The research reported in this paper is a continuation of a previous study. The flow domain in this study contains more than one windbreak and more than one building. Based on a previous literature review, a set of generic layouts of buildings and vegetation rows were designed as representative configurations in a normal urban context. Two parameters, the wind ratio and turbulence intensity, were examined in these layouts, which were tested in a boundary layer wind tunnel as well as modelled by a CFD code. This exercise was also expected to validate a set of CFD modelling techniques developed to numerically simulate wind flow in built environment where both porous media and bluff bodies are in presence.

2. Methodology

2.1 The Basic Layouts

There were four generic layouts tested in this research, including a I-shape windbreak and a single

cubic building, a L-shape windbreak and a single building, an enclosed windbreak with the single building at its centre, and an enclosed windbreak with a group of four buildings in its center (Figs. 1 and 2). In the wind tunnel tests, the model windbreaks were made of branches of Christmas trees, trimmed and arranged to represent different porosity and geometry shape. The buildings were made of wooden cubes.

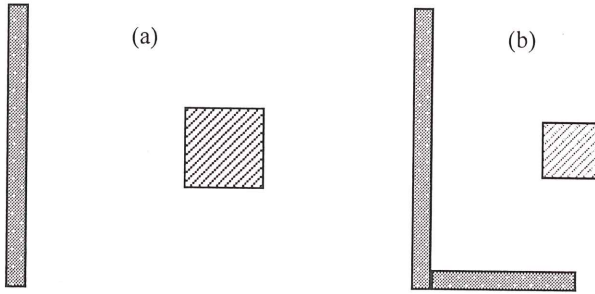


Fig. 1 Windbreak & building: (a) I-shape; and (b) L-shape

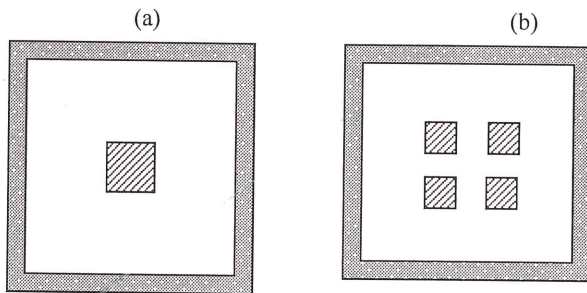


Fig. 2 (a) A enclosed windbreak & Building; (b) Enclosed windbreak & buildings

2.2 Wind tunnel experiments

2.2.1 The Boundary Layer Wind Tunnel

The wind tunnel tests were conducted in the newly refurbished Boundary Layer Wind Tunnel in Heriot-Watt University. Its total length is 30.2 m with a testing section of $3.2 \times 1.52 \times 10.8 \text{ m}^3$ and two axial fans that produce airflow with maximum speed at about 20 ms^{-1} . The long testing section ensures that the roughness on its floor is capable to reproduce the natural wind with the right vertical profiles of speed and turbulence for scaled building model tests.

2.2.2 The profile of the wind speed and turbulence

The roughness elements were made of cubic blocks arrayed on the floor of the working section, right after the grid of turbulence-generator at the entrance. These two devices generate boundary layer profiles of the velocity and turbulence (Fig. 3). The simulated atmospheric boundary layer in this wind tunnel was validated against the full-scale wind data published by ESDU International Ltd [6], regarding to the following

equation

$$\frac{u(z)}{u(z_{\text{ref}})} = \frac{\ln z - \ln z_0}{\ln z_{\text{ref}} - \ln z_0} \quad (1)$$

where $u(z)$ is the wind speed at any height z/cm , $u(z_{\text{ref}})$ is a reference speed at a chosen reference height z_{ref} , z_0 is the ground roughness length.

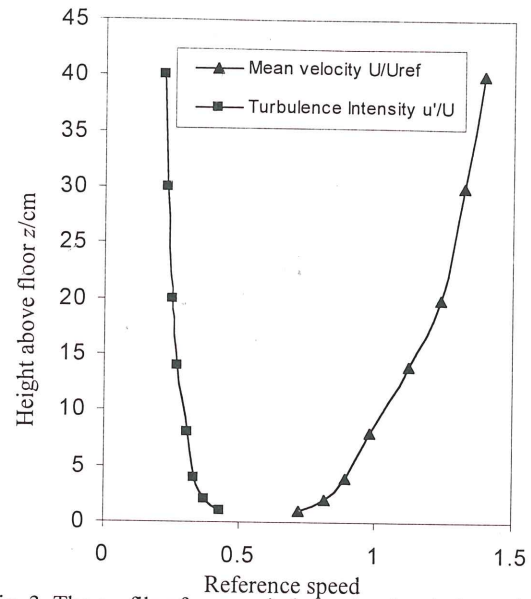


Fig. 3. The profile of mean wind speed and turbulence intensity

2.2.3 Instrumentation

The data acquire system consists a newly installed 2D traversing system and a multi-channel Dantec constant temperature hot-wire anemometer. The traverse is driven by step-motors and control by a PC, and test signals collected at the hot-wire probes is digitised by an A/D & D/A converter for computer logging.

2.3 CFD Simulations

2.3.1 Mathematical description

The formulation used in the numerical study is based on the spatially averaged adiabatic mean momentum and mass conservation equations, which are expressed in tensor notations:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} \right) - \frac{1}{2} K_r |u| u \quad (2)$$

where u_i denotes the velocity, P pressure, and ρ density. The last term on the right side is the drag force term, in which K_r is defined as a function of the porosity (Eq. 3). For the narrow vegetative or artificial windbreak, the porosity or penetrability is equivalent to the optical porosity, which can be acquired by taking black-white pictures behind windbreak and counting the percentage

of the white area.

The drag force term included in the mean momentum equations is formulated as a pressure drop to take the resistance exerted by windbreaks into account:

$$\Delta P = \frac{1}{2} K_r |u| u \quad (3)$$

where K_r is the resistance coefficient, which can be related to the porosity by an empirical relationship given by Hoerner (1965):

$$K_r = \frac{1}{2} \left[\frac{3}{2\beta} - 1 \right]^2 \quad (4)$$

where β is the porosity.

2.3.2 CFD model development

The numerical models of airflow in urban landscape were developed with a commercial CFD package, PHOENICS. The dimension of the domain was set to 300 m × 300 m × 50 m and the horizontal grid resolution at the concerned areas was set to be 1 m. There are two ways to simulate airflow through windbreak, the 2D model, which applied in large-scale urban simulation, and 3D model, which is suitable for micro-scale or courtyard simulation. The 2D windbreak is simulated as a zero-thickness object with certain porosity and relative resistance coefficient. In the same way, 3D presentation of a windbreak can be made plus defining the thickness in horizontal direction. In this CFD modeling, the windbreaks were modeled in 3D presentation. As it has been proved in the previous study, the KE-2L turbulence model and SMART differential scheme give better simulation for wind modeling in a built-up environment. Therefore this turbulence model and the differencing scheme were applied in this CFD modeling.

3. Results and discussions

As the main objective of this study was to validate the set of measures used to develop a CFD model for wind simulation in built-up area, the study was carried out in three stages, namely the preliminary study, the basic generic study and the meso-scale/real urban site study. The first study has been reported elsewhere [10]. This paper presents the results of the second study, in forms of speed curves and velocity contours. The effect of oblique wind direction was also examined.

3.1 I-shape windbreak and single building

The first wind tunnel test was to repeat the test

conducted earlier in BRE. The measured data were compared with the BRE wind tunnel test data and CFD modelling prediction. (Fig. 4). The velocity drop right behind the windbreak ($x=0$) in both experiment is not distinct, because the probe was set away from the windbreak for preventing damage to the fragile hot-wire.

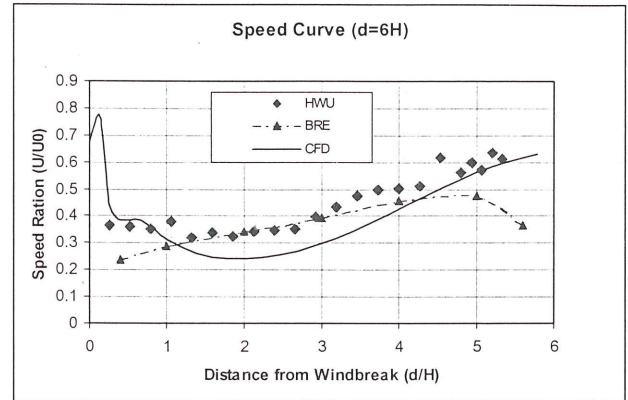


Fig. 4. Wind speed curve behind the windbreak

The second test was made for the simple layout when the wind came from oblique direction to the windbreak. The incidence angle in this test varied only from 0° to 30°. Fig. 5 shows the horizontal velocity contour of the cases with 30° incidence angle, both experiments and CFD.

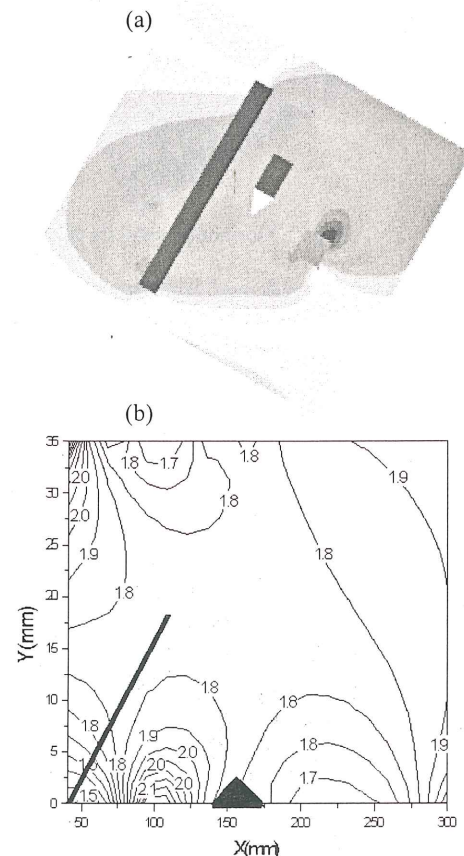


Fig. 5. Horizontal velocity contour (30° incidence angle): (a) CFD; and (b) Experiment.

3.2 L-shape windbreak and single building

The L-shape windbreak is believed to be more efficient and offering more protecting area. Fig. 6 shows that the low speed area increased dramatically,

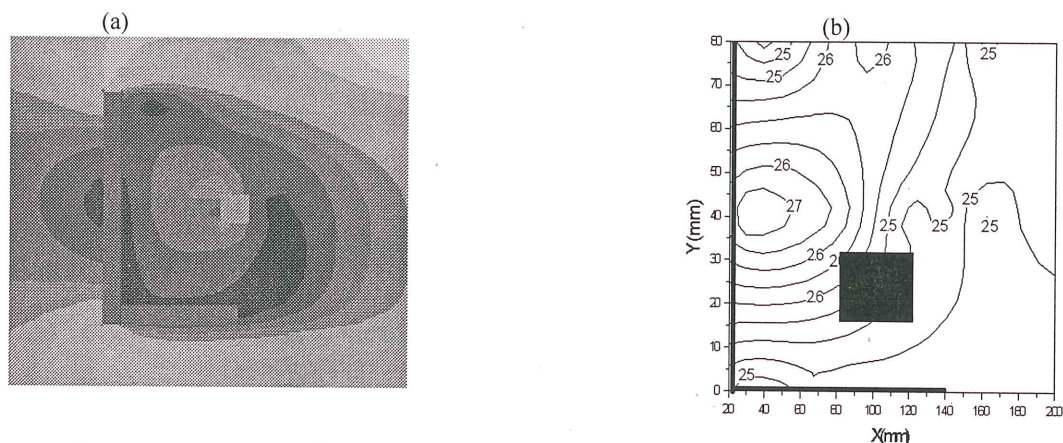


Fig. 6. Horizontal velocity contour (L-shape, 0° incidence angle): (a) experiment; and (b) CFD

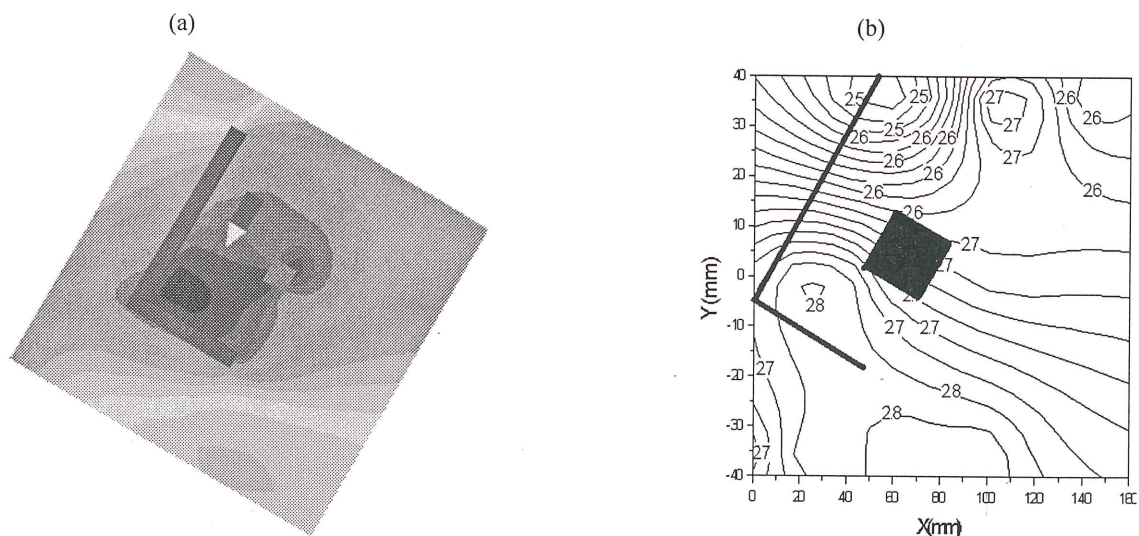
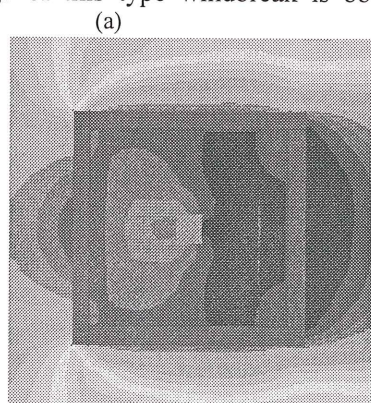


Fig. 7. Horizontal velocity contour (L-shape, 30° incidence angle): (a) experiment; and (b) CFD

3.3 Enclosed windbreak and building(s)

In a windy place, either a city or a countryside, the enclosed windbreaks are quite popular, even though they need more ground area and higher maintain cost. The advantage of this type windbreak is obvious. It



especially in the area behind the building. Such windbreaks becomes more effective in sheltering leeward area when the wind comes from an oblique direction (Fig. 7).

should bear in mind, however, that over-reduced air movement would cause other problems, such as inefficient building ventilation and dust/aerosol contaminant accumulation.

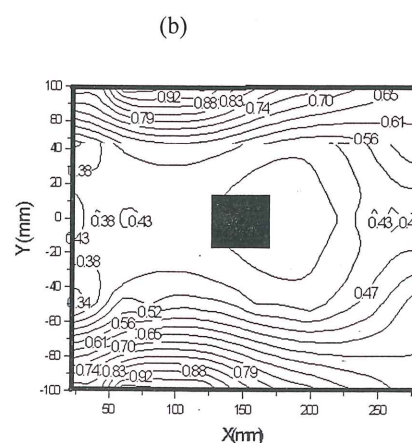


Fig. 8. Horizontal velocity contour (Enclosed, single building, 0° incidence angle): (a) experiment; and (b) CFD

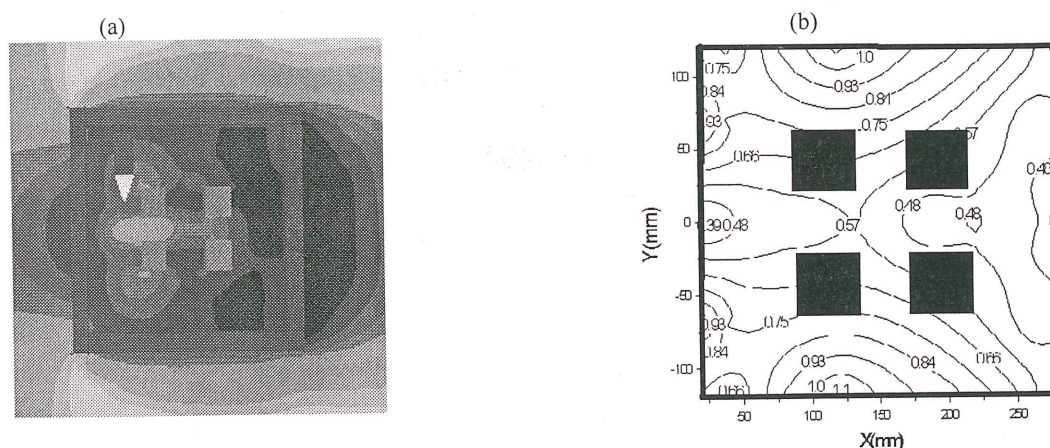


Fig.9. Horizontal velocity contour (Enclosed, grouped buildings, 0° incidence angle) : (a) experiment; and (b) CFD

4. Conclusions

By introducing an extra drag term into the governing equation, airflow through porous trees can be simulated efficiently using either in two dimensional windbreak presentation or 3D presentation. The oblique wind blow onto a windbreak can also be modeled, but how to specify the effective porosity of the windbreak needs to be examined in future research.

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