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WINDBREAK SHELTERING EFFECTS ON OUTDOOR OPEN SPACE

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ABSTRACT

This paper presents a study of windbreak sheltering effect on the outdoor open space using Computational Fluid Dynamics (CFD) techniques and the wind tunnel experiments carried out for validating the CFD models. Although the influence of a windbreak on the reduction of wind speed is fairly well known, it is still uncertain how this influence will be affected by the buildings in an urban area where the windbreaks are placed for providing better wind comfort to the people in outdoor open space. The objective of this study was, firstly to seek a suitable numerical model for simulating urban wind environment with windbreak's existence, and secondly to identify the effectiveness of a windbreak in a built-up area regarding to its physical parameters.

The principal results drawn from this study are as follows. (1) The KE-Two-Layer model would be the better turbulence model for simulating a domain with both windbreaks and buildings inside. (2) The SMART discretization scheme would be a good choice for the convection discretization in this kind of simulation. (3) The effect of buildings on the flow regime behind windbreak is significant, due to the presence of the standing vortex in front of the building. (4) The distance between the windbreak and the building is a key factor to the reduction of wind speed, instead of the porosity of the windbreak, if the outdoor space is comparatively small.

INTRODUCTION

There has been a long history for the windbreaks, including natural trees and artificial fences being used for preventing wind damage, increasing productivity, and improving the quality of the living environment. Different structures of windbreaks, in terms of length, height, composition by species and penetrability to the wind, have been proved to have distinct effects on the character of the microclimate in its vicinity. In the past fifty years, investigations of the sheltering effects of the windbreaks have been carried out by many researchers in the ways of laboratory experiment, full-scale field test and computer simulation.

Caborn (1957) has provided a general review of windbreak characteristics, including the classification of windbreak, the microclimatic factors affected by windbreak, and the research procedures. Since that time there have been many contributions and attempts to predict sheltered airflow by either experimental or numerical methods. Plate (1971) reviewed several quantitative studies of windbreak, providing intensive understanding of shelterbelt aerodynamics. Heisler and Dewalle (1988) have given a historical and thorough review on the effects of windbreak structure on wind flow, in which the direct effects of a windbreak on air movement and the indirect effects on air temperature and humidity are discussed in details. In the regime of numerical studies of windbreak, Wilson (1985) investigated the applications of several turbulence models on the simulation of an isolated windbreak. He has pointed out that the Reynolds-Stress model is proved to be more accurate. Wang and Tackle (1995 and 1996) conducted a series of numerical studies about the wind flow pattern around windbreaks, both in 2D and 3D dimensions.

Most of these studies have contributed greatly to the understanding of the mechanism of the airflow around windbreak and their results have also been accepted as the guidelines for the design of windbreak systems, based on the assumption that the effectiveness of a windbreak is determined by the properties of the windbreak itself and the status of approaching wind. A common feature of these studies is the windbreaks are assumed existing in a fully open space, like countryside, with no obstruction in its vicinity or such objects are so small that their influence is negligible. In a built-up area or an urban environment, however, the presence of buildings can no longer be ignored due to their sizes comparable to those of windbreaks and the short distances between them, where the interaction from the building will definitely affect the effectiveness of the windbreak, particularly when a building is right behind the windbreak in the leeward. Therefore understanding the interactions would be important to correctly apply the tree-belts or windbreaks in the urban area when their sheltering effect is concerned.

To evaluate the effects of a windbreak on reducing pedestrian level wind speeds in outdoor open space for providing wind comfort, a CFD investigation was carried out in this study and a relevant wind tunnel experiment as well. This paper reports the numerical strategy on the simulation of windbreak sheltering effect and some unique phenomena associated with windbreaks in built-up areas.

METHODOLOGY

This study was designed to investigate the efficiency of windbreaks on the reduction of wind speed at pedestrian level. In a built-up area, the outdoor spaces are confined by the surrounding buildings, which work as barriers to airflow influencing the objects nearby. The windbreaks used in this area, under the impacts of those buildings, can no longer be studied as isolated porous sheets as those used in the studies of windbreaks for agricultural purposes. Therefore the windbreaks in this study simulated by porous objects in CFD (perforated metal sheets in wind tunnel experiments) were tested with a building, the cube, at various distances in the downstream. Several other parameters defining the geometry of the windbreak were also considered, such as the height, length, and porosity. A commercial CFD package, PHOENICS and a boundary layer wind tunnel in the Building Research Establishment (BRE), were used in this study.

Models of the building and the windbreak

In the CFD simulations, the windbreaks were simulated by the porous objects with certain geometrical sizes and different porosity. The building was simplified as a cubic blockage (Figure 1). The domain size was determined by the strategy that its boundaries should be kept away from the objects inside at least 5 times of the height of the windbreak to minimise the boundary interference.

In the wind tunnel experiments, a total of twelve porous metal sheets were fixed on the floor of the testing section to simulate scaled windbreak, together with a wooden cube representing a simplified building at the scale of 1:200 (Figure 2). The material of these sheets is perforated metal with various hole-sizes to give different porosity. Both the sheets and cube were set perpendicular to the wind direction.

Wind flow profile

In the wind engineering applications, the characteristics of the wind are presented as functions of a single ground roughness length z_0. This length is the free constant in the logarithmic function relating the wind speed $u(z)$ at any height z to a reference speed $u(z_{ref})$ at a chosen reference height, z_{ref}.

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

The constant z_0 is correlated with the intensity and frequency spectrum of turbulence and is shown to be strongly related to the category of terrain (Table 1).

In our study, the airflow was assumed to be in the built-up area, which can be treated as equivalent to the city centre, where the applicable roughness length is represented as $z_0 = 0.7$.

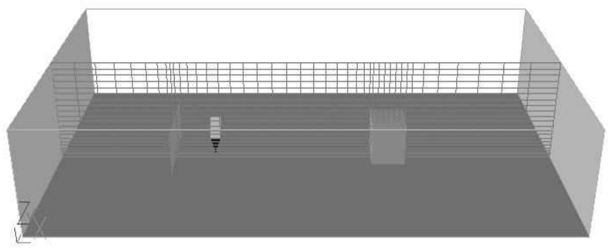

Figure 1. The layout of computational domain

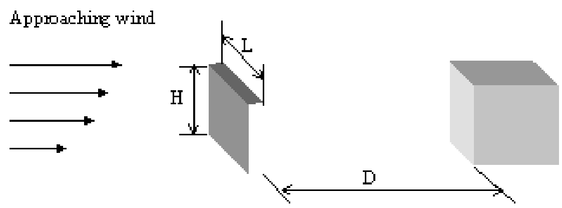

Figure 2. The layout of the building and windbreak (L—Length, H—Height, D—Distance)

Table 1. Typical values of terrain roughness parameter (ESDU 84011,1984)

TERRAIN DESCRIPTION	APPROX. VALUE OF Z_0
City centre; forest	0.7
Small town; suburbs; wooded country	0.3
Outskirts of small towns; villages Countryside with many hedges, some trees and some buildings	0.1

NUMERICAL SIMULATION

Modelling windbreak

In an urban area, many of the windbreaks, either vegetative or artificial, may be regarded as fences with limited thickness. Most of the investigations in the past have been carried out on the simulation of the fences, of which the geometrical parameters, such as porosity and its distribution can be easily controlled. Wilson (1987) has given a full description of a windbreak-flow model, which is applicable to simulating two-dimensional neutrally stratified mean flow over a porous fence with infinite length.

In the numerical simulations of this study, a drag force term was included into the mean momentum equations as a pressure drop to take the resistance exerted by windbreaks into account:

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

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

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

Where β is the porosity.

Governing equations

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

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{...............................(4)}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right) - \frac{1}{2} K_r |u| u \quad \text{......................................(5)}$$

Where u_i denotes the velocity, P pressure, and ρ density. The last term on the right side is the drag force term mentioned above, in which K_r is defined as a function of the porosity (Equation 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.

Turbulence models

To close the system of mean flow equations (4) & (5), the turbulence models must be introduced and so that the set of equations can be solved for a variety of flow problems. To figure out the effect of different models on the quality of the simulations, three turbulence models, namely KE (Launder and Spalding, 1972), KE-RNG (Yakhot and Orszag, 1986) and KE-Two-Layer (Rodi, 1991), were used separately in this study.

The KE model is by far the most widely used two-equation turbulence model. Its applications in most calculations are carried out by using wall functions in the near wall layers. The KE-Two-Layer (KE-2L) model is the revised KE model, which uses the high-Reynolds-number KE model only in the fully-turbulent region, away from the wall, and the near wall viscosity-affected layer is resolved with a one-equation model. The KE-RNG model has the general same form as the standard KE model except the model constants are calculated by Re-Normalization Group (RNG) methods giving somewhat different values.

Discretization Schemes

The Finite Volume Method (FVM) was used to discretize the governing equations, about which there are several kinds of differencing schemes that can be used for the discretization of the convection and diffusion terms, such as the central and upwind schemes, the high-order linear schemes and the high-order non-linear schemes (Versteeg and Malalasekera, 1995). To identify the performances of these schemes, three of them selected from each category were tested in this study.

- The HYBRID differencing scheme is based on a combination of central and upwind differncing schemes. It produces physically realistic solutions and is highly stable when compared with the high-order schemes. But its accuracy on the basis of Taylor series truncation error is only first order.
- The QUICK differencing scheme uses a three-point upstream-weighted quadratic interpolation for cell face values and falls into a category that can be classified as linear. It has greater formal accuracy than the central, upwind or HYBRID scheme. But in terms of complex flow calculation, the use of this scheme can lead to subtle unbounded problems, such as the undershoots or the overshoots of the solutions.
- The SMART difference scheme, as one of the non-linear schemes attempts to adapt the discritization to avoid the unwanted behaviour

of the linear schemes QUICK, such as the unboundness.

WIND TUNNEL EXPERIMENT

The boundary layer wind tunnel in BRE has an open-working section with a cross-section area of 1.75 meters in width and 1.0 meter in height, capable of simulating the atmospheric boundary layer at approximately 1:150 to 1:400 scales. A traversing system in this tunnel controls the positions of the hot-wire probes that measure the velocity.

The measurements of wind speed were carried out using a Dantec constant temperature hot-wire anemometer with single normal probes, which were mounted on the traversing mechanism with manual controls.

The origin of a Cartesian co-ordinate system was located on the floor, at the middle of the windbreak with the x-axis in the horizontal streamwise direction and upward oriented vertical z-axis. The instantaneous velocity component *u* and *w* were in the x and z directions respectively.

RESULTS AND ANALYSES

In the graphs of this section, the wind velocities are normalised by two dimensionless parameters, the reference speed or the open-field speed U_0 at a certain height and the windbreak height H. Wind flows from the left, where the windbreak stands, to the right, where the building exists. The speed reduction rates at different positions or so-called wind curves represented by these two parameters will be discussed accordingly to the following topics.

On the turbulence models

The performances of the turbulence models, KE, KE-RNG and KE-2L, have been tested in this study, and the KE-2L model was proved being able to give better agreement to the results of wind tunnel experiments (Figure 3 and Figure 4). It was well known the Reynolds Number of the airflow within windbreaks is very low that only the Low-Re turbulence models can work fairly well. But the Low-Re KE models require high resolution in the near wall regions and the KE model itself works very poor when there is adverse pressure gradient within the boundary layer, therefore, the KE-2L model which use one equation models for simulating low-Re near wall flow has shown great advantage on the simulation of the airflow through windbreaks.

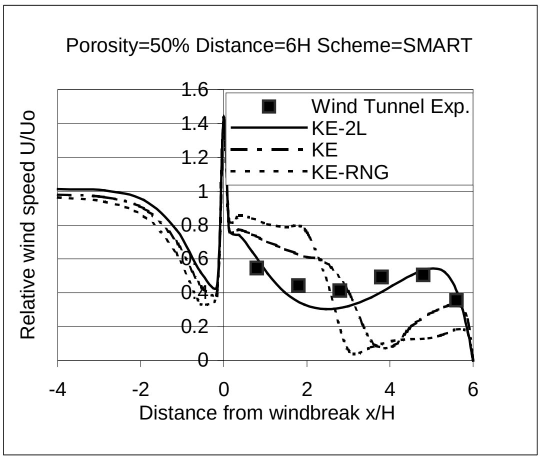

Figure 3. Mean horizontal wind speed ratio at the ground level (Comparison about different turbulence models application; d= 6H).

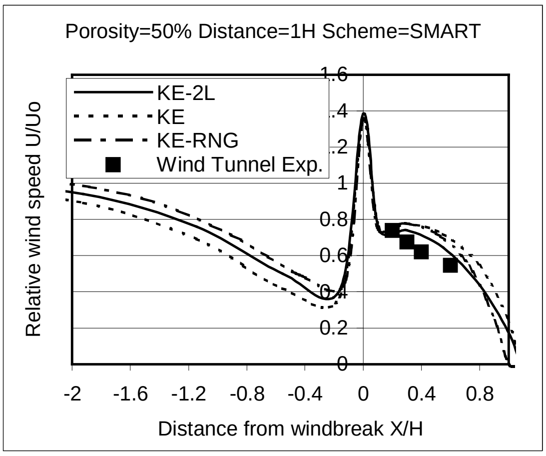

Figure 4. Mean horizontal wind speed ratio at the ground level (Comparison about different turbulence models application; d= 1H).

On the discretization schemes

For the simulation of windbreak, which gives the momentum sink to the main flow as a kind of source to the governing equations, the choice of using QUICK or other linear schemes would be unwise, because under this circumstance, they tend to produce out-of-bound values which often lack of physical means. Although the HYBRID scheme is more stable and can reduce the running time of the simulations, the shortcoming of unable to deal with the flow from the diagonal direction to the grid makes it uncompetitive to the high-order non-linear schemes, like SMART, especially when the computers are powerful enough. It was also confirmed by this study that SMART scheme gave the best agreement to the results of the wind tunnel experiments and the QUICK the worst (Figure 5).

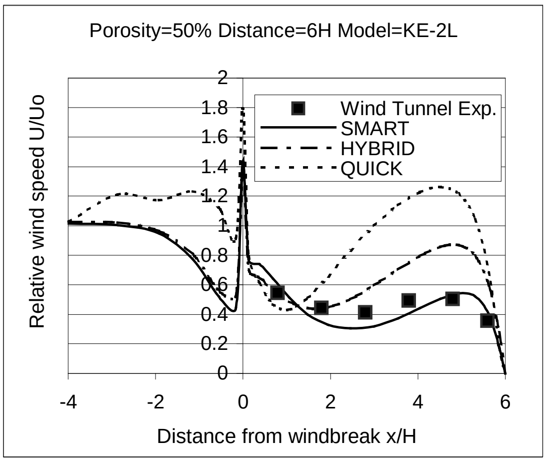

Figure 5. Mean horizontal wind speed ratio at the ground level (Comparison about different discretization schemes application; d=6H).

On the speed regimes

Before discussing the wind speed reduction, it would be better to consider the difference on speed regimes between flow fields of windbreak-only and windbreak–plus-building. Bean (1975) described the flow regimes behind a windbreak as three parts in case of windbreak-only (Figure 6). In the first regime, the air jets penetrating the porous barrier play an important role. Within a short distance downward, the jets begin to merge with the flow crossing over the top of barrier and create the second flow regimes. The third regime develops when the crossing flow dominates the flow field behind the barrier.

In our experiments, the similar divisions of flow field were also observed, but with slight differences due to the presence of the building. The flow field in the leeward of windbreak was broken down into four regimes, of which the first three were the same as that just mentioned. The fourth regime was created by the standing vortex in front of the building, which decreased the speed in the vicinity of the building. The standing vortex affected not only the flow near the building, but also the entire flow field between the building and windbreak, especially the regime III and IV (Figure 7). When the building existed, the wind curve was changed dramatically as well as the position where the minimum mean speed occurs.

On the difference of distances

For the windbreak was placed at various distances to the building, the speed reduction curves shows different effects exerted by the building and windbreak (Figure 8). When the distance was less than 4H, the standing vortex in front of the building dominated the lower part of the flow field, and the effect of the porous windbreak showed no difference to that of nearly solid one. But, if the distance exceeded 4H, the penetrability of the fence became very important, or equivalent to the effect of the building.

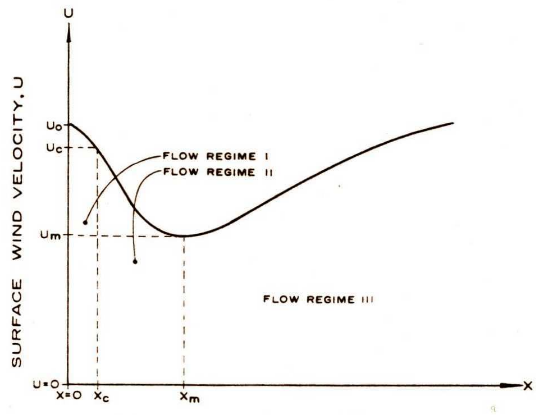

Figure 6. The flow regimes behind the windbreak (Bean 1975) (U_m-- The minimum mean wind speed. x_m-- the x position of the minimum wind speed).

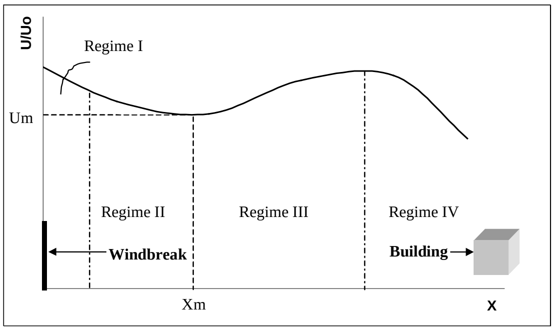

Figure 7. The flow regimes behind the windbreak with building in certain distance (this study).

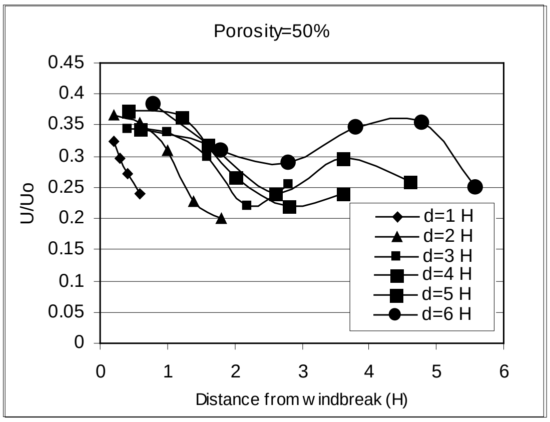

Figure 8. The wind curves of speed with different distance (d) between windbreak and building (wind tunnel experiment; the windbreaks stand at x=0.0, the buildings stand at the x position of the end of each curve respectively).

CONCLUSION AND FUTURE WORK

From the results of the numerical simulations and the wind tunnel experiments described in the previous sections, the following main conclusions can be drawn:

- For simulating airflow through windbreaks, which associated with Low-Re phenomena, The KE-2L model would be the better turbulence model.
- The SMART scheme or some other high-order non-linear schemes could be the good choices for the convection discretization in the simulations of source-related flow.
- The effect of the downstream building on the flow regime behind windbreak is significant, especially on the positions where minimum speed occurring.
- If the windbreaks are not far away from buildings, the distance between them is the governing factor on the reduction of wind speed, in stead of the porosity of the windbreak.

The study reported in this paper is the results of the first stage of our research project, modelling airflow in urban open space, of which the major concern is the outdoor wind comfort and will be extended to the energy saving of buildings. Some further studies on the sheltering effect of windbreak to be carried out in the near future include:

- The generic studies of windbreak sheltering effect on groups of buildings.
- The studies of windbreak sheltering effect in urban area with different scales, such as the micro-scale, meso-scale and the macro-scale.
- The studies of the effect of urban wind environment on the efficiency of windbreak. For example, the wind approaches the windbreak with different turbulence intensity and at different angles.

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NOMENCLATURE

β	Porosity of windbreak
ρ	Density of air
ΔP	Pressure drop
D	Distance between windbreak and building
H	Height of windbreak
K_r	Resistance coefficient
L	Length of windbreak
P	Pressure of air
d	Distance between windbreak and building
u,w	Velocity components
$u(z)$	Wind speed at certain height
$u(z_{ref})$	Wind speed at reference height
U_0	Reference wind speed
U_m	Minimum wind speed
x_m	X position of minimum wind speed
z	Height above ground
z_0	Ground roughness length
z_{ref}	Reference height above ground

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