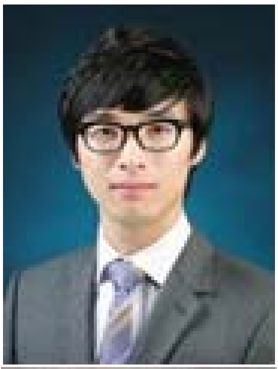
Assessment of pedestrian wind environment of high-rise complex using CFD simulation



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Summary

The outdoor wind environment plays an important role for pedestrian comfort. In general high-rise complexes, wind gust frequently occur due to the building form which has a complex airflow Therefore, when designing high-rise buildings, it is important to plan mitigation strategies for wind gusts which lead to pedestrian discomfort.
Pedestrian comfort is quantified by the outdoor wind velocity and the probability of an excess threshold velocity. The case study is carried out to generate the findings of pedestrian wind comfort in high-rise complexes. Firstly, the wind comfort of the high-rise complex was analysed by a CFD simulation, then mitigation strategies were established by a climate response design for the landscape plan. The results show that the mitigation works affect the climate response design plan, which could help Architects during the design phase.

Keywords: CFD simulation, Pedestrian wind environment around buildings, High-rise building, Climate response design

1. Introduction

Recently, many high-rise buildings have been constructed around the world with the development of building technology. This development changes not only the outlook of a city, but also creates local wind environmental conditions which are unpleasant and sometimes dangerous for pedestrians walking around the buildings. The discomfort of pedestrians is caused by strong winds which increase significantly during the winter.[1] The wind flow at pedestrians level around buildings is the result of the complex interaction between the wind(incidence, mean vertical speed gradient, turbulence) and the buildings themselves(shapes, sizes, setting etc.).[2, 3] Narrow gaps between buildings especially create a wind valley which leads to an increase of wind velocity and hence the discomfort of pedestrians. Designers should therefore consider these problems during the design phase in order to find solutions and apply them.[4]

In the last decades, Computational Fluid Dynamics(CFD) has been studied intensively as a tool for evaluating the indoor and outdoor environment of buildings.[5] Indoor Airflow Analysis has been studied and well established yet there are not many studies done on outdoor applications. Usually a wind tunnel test is used to analyse the outdoor wind environment. However, wind tunnel testing has some disadvantages for practical applications. They are expensive and difficult to model with errors built up as a result of the simulation undertaken on reduced scale models. Furthermore, only point measurements are obtained by wind tunnel experiments.

For these reasons, CFD simulations could be an effective alternative because it can avoid some of the stated problems with other procedures. In addition, CFD can modify the reduced scale model results to full scale effects and calculations. The possibility of full-scale modelling and the variety of results from single demonstrations are a significant benefit of CFD. However, to get accurate analytic results, many different factors such as boundary conditions, mesh properties and governing equations need to be covered precisely and carefully.

This study will show the winter outdoor airflow of three high-rise complexes by using CFD simulation analysis. The results of this analysis can be used to improve problems with outdoor airflows by proper planning followed by analysing the data. It is carried out with the following process : (1) Establish the building analytic plan by using the Wind data of the targeted area(base model); (2) Analysis of the air environment around the building using a CFD simulation at pedestrian level; (3) Finding an alternative solution model(alternative model) after determining possible problems from the simulation; (4) The consideration of improvements through the analysed alternative model.

2. Analysis of wind data

2.1 Wind criteria for wind comfort

Pedestrian discomfort occurs when wind effects become so strong and occur so frequently (say on time scales up to 1 h), that people experiencing those wind effects will start to feel uncomfortable, and will eventually act in order to avoid these effects.[6] The biggest influence on the wind comfort of pedestrians is the outside wind speed. The comfort criterion consists of the discomfort limit and the pedestrians' acceptance of its probability. The comfort criterion has been demonstrated in numerous other pieces of research.[2, 6-9] Some have used the hourly mean wind speed as the relevant parameter to assess the human wind comfort whilst others use the gust wind speeds or effective wind speeds (integrating the wind-speed standard deviation).

In The Netherlands, the method used to evaluate the wind climate is prescribed in an official standard, the NEN 8100:2006 "wind comfort and wind danger in the built environment".[10] This standard allows the possibility of using both wind tunnel experiments and CFD to evaluate the wind climate. In the NEN 8100 code, the threshold for the mean wind speed is 5 m/s for all grades of

Table 1 Criteria for wind nuisance and danger according to NEN 8100

Probability of Exceedance $P(V_{loc} > V_{threshold;wind\ nuisance})$ in percentages of the number of hours per year	Quality-level	Activity-level		
		I. Walking, normal pace	II. Walking Leisurely-strolling	III. Sitting longer time
1< 2.5	A	Good	Good	Good
2.5 – 5	B	Good	Good	Moderate
5 – 10	C	Good	Moderate	Poor
10 – 20	D	Moderate	Poor	Poor
≥ 20	E	Poor	Poor	Poor
Probability of Exceedance $P(V_{loc} > V_{threshold;wind\ danger})$ in percentages of the number of hours per year		Qualification		
$0.05 < p < 0.30$		limited risk		
$p \geq 0.30$		dangerous		

wind comfort and 15 m/s for danger to pedestrians from wind forces (Table 1). The choice of the probability P(VIS45 m/s) in NEN 8100 is based on the feedback by clients, especially by developers of shopping centres. The code defines five grades of wind comfort from A to E.[11]
This study is completed on the outdoor wind environment around high-rise complexes at a 5 m/s threshold velocity.

2.2 Wind environment around the building

The analysis of the wind environment of the surroundings is the precedent to determine the CFD of a high-rise building complex.
The object building is located in downtown Beijing, China. Actual measurement data is being used to determine the wind environment of the actual plot. Fig.1 shows the wind rose which has been determined by the weather data of the winter wind environment (from Dec to Feb) mentioned earlier.
So the main wind direction for the winter season is North-West. This direction constitutes 15.66% of the winter wind. Fig.2 is the wind direction categorized by the wind velocity between 0~10 m/s. Up to 6m/s, the wind velocity contains 93.9% of the winter wind. If the wind environment is satisfied above this reference velocity, the probability of excess wind in winter V_{thr} is below 6.1%. In this study the wind environment of the building surrounding is analysed through the CFD simulation. The data is calculated in every 1m/s up to 7m/s of its wind velocity.

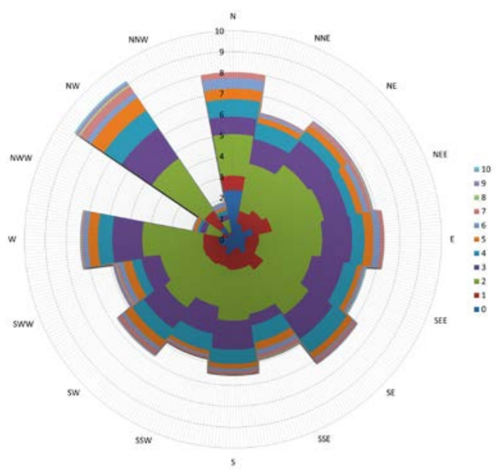


Fig. 1 Wind rose around building

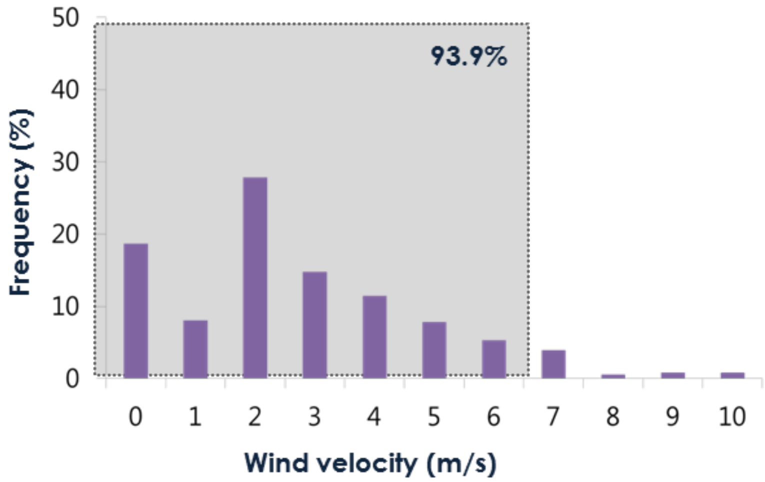


Fig. 2 Distribution of wind velocity

3. CFD simulation for outdoor built environment

3.1 CFD simulation method

The methods of analysing the wind environment of the external built environment are divided into two parts, Reynolds-Averaged Navier Stokes(RANS) simulations and Large Eddy Simulation(LES). RANS equations are appropriate when calculating a steady state solution due to their effects on the mean flow.
Steady RANS modelling with the k-ε model and other turbulence models has become quite popular for pedestrian-level wind studies. Several CFD studies of pedestrian wind conditions in complex urban environments have been performed.[5, 12-16] Almost all studies were conducted with the steady RANS approach and a version of the k-ε turbulent model. In this study steady state RANS equations with standard k-ε turbulent models are selected for calculating pedestrian wind comfort with the outdoor built environment.

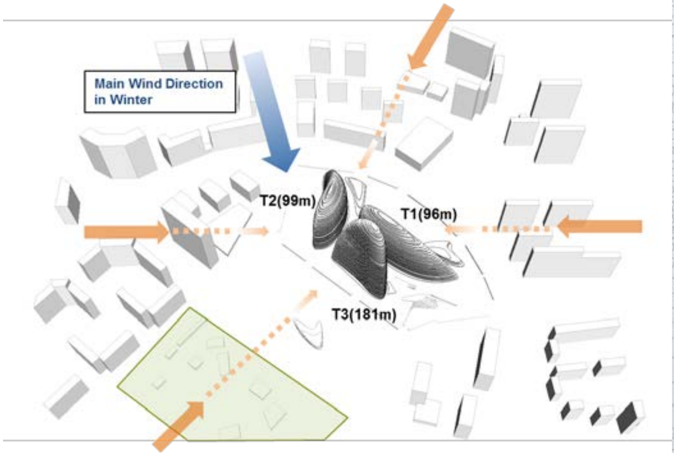


Fig. 3 Wind direction around building

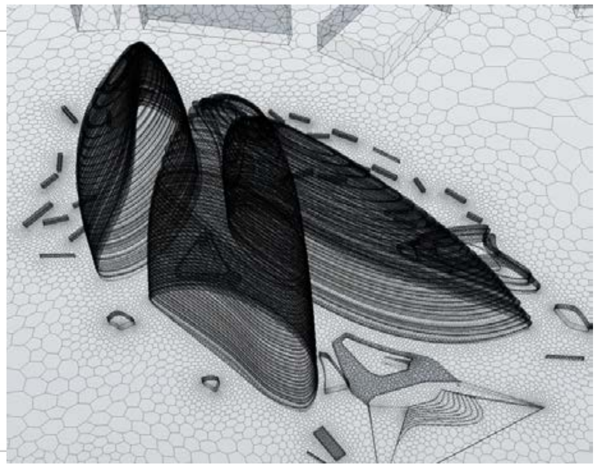


Fig. 4 CFD grid description

3.2 Simulation model

The simulation modelling of this study is based on actual high- rise buildings in Beijing which has office and retail use. There are three buildings on the total site area of 115,393m^2, two of them have 25 floors (96m, 99m high) and the other one has 45 (181m high) floors. The buildings are closely placed with narrow spaces between them it could lead to a very fast air flow speed. Furthermore, it can be expected that the sunken areas of the complex which is used for retail shops, also gives an impact of overall air flow in the basement.
Therefore, this study includes the conditions as stated above for the accurate simulation modelling. Based on these analyses, the object buildings were modelled as shown in Fig 3, Fig 4. Additionally, the form of the object building uses a very complex geometry (atypical shape) and every floor has horizontal louvers as well. Apart from this, an ellipse type floor plan can affect the air flow speed too. It is therefore necessary to consider all details for the simulation modelling.

3.3 Boundary condition for CFD simulation

The computational domain size is 2,000m*2,000m*500m. Using the automatic mesh generation system of the commercial CFD simulation program star ccm+, polyhedral mesh was selected for the complex shape of buildings. The mesh contained about 2,000,000 cells. The density of the grid was concentrated at pedestrian level and the space around the low level (1st~3rd floor) of the 3 main tower buildings. The size of the grid was the minimum 0.5m to the maximum 50m (surface growth rate was 1.3).

Table 2 Detailed boundary condition

Item	Condition
Turbulence model	Standard k-ε model
Scheme	1st order upward differential scheme
Inlet	Turbulence intensity : 0.01(Constant) Turbulent length scale : 0.1m
Outlet	Flow-split outlet Split ratio (0.5, 0.5) (South, East)
Wall	Log law(offset 9.0) Von Karman constant : 0.42
Number of mesh	About 2,000,000 polyhedral cells

To solve the RANS equations for the simulations, a standard k-epsilon turbulence model was chosen. The CFD calculation needs to be finished after sufficient convergence of the solution. COST suggests that scaled residuals should be dropped by 4 orders of magnitude.[17] However, the convergence criterion of each simulation was 3 times the normalized residuals over all the control volumes for all variables (energy, momentum, turbulent kinetic energy, turbulent dissipation rate) for the efficiency calculation.

The CFD simulation of wind flow was carried out for a North-West wind direction only for the winter, due to the climate analysis result in Fig 1 and Fig 2. The results are analysed for a wind velocity from 1~7 m/s.

The boundary condition of every wall is no-slip except the top wall of the domain. The detailed calculation conditions are shown in Table 2.

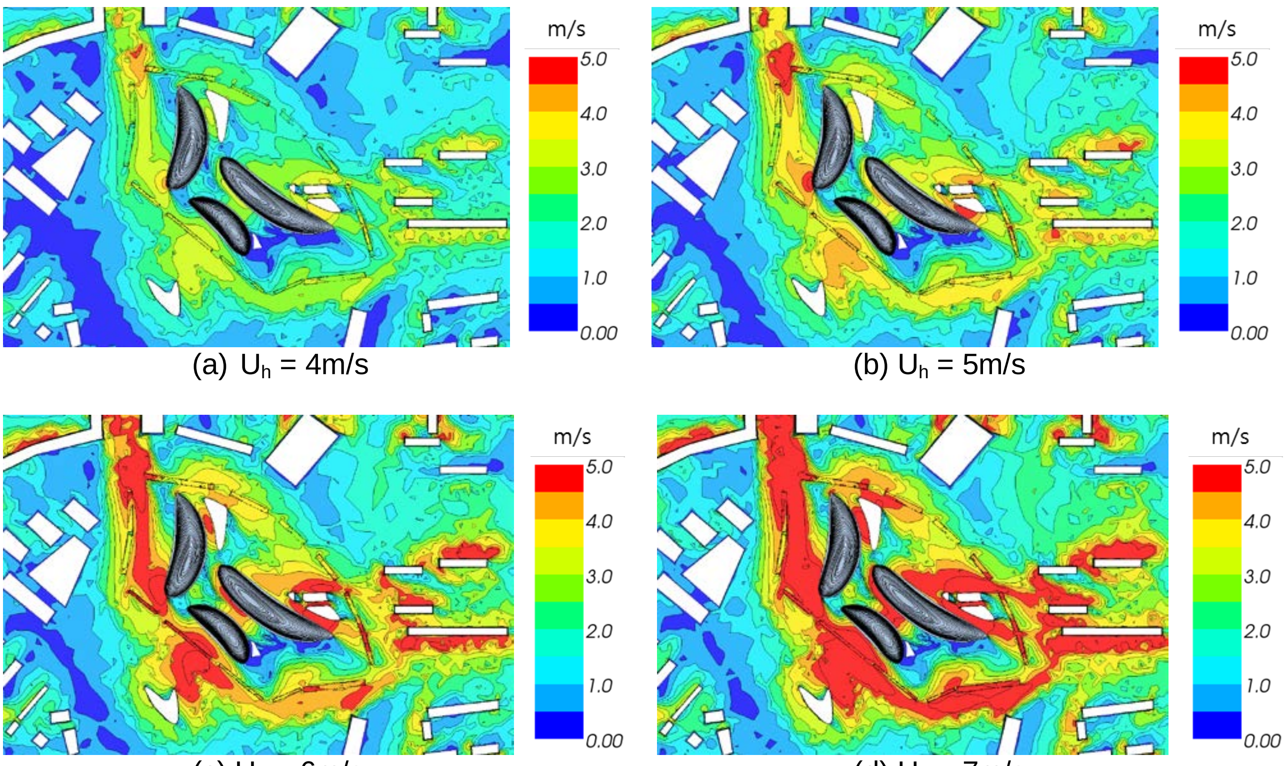
4. CFD simulation results

4.1 CFD simulation of base model

Fig. 5 shows the distributions of wind velocity at pedestrian level (1.75m) for each case under the CFD simulation. Fig 5 shows only 4 simulation results because when Uh is under 3 m/s, almost every part of the site remains in the comfort condition (velocity magnitude < 5m/s). High wind speed began to appear at the north-west side of the site when U_h is 5m/s.

Areas vulnerable to reduced pedestrian comfort (velocity magnitude ≥ 5m/s) were observed at U_h=5m/s. The red zone on the NW direction experienced high wind gusts at the site entrance because of the wide road. High wind velocity distribution could be easily observed at the narrow spaces, such as the space between the tower and the pavilion etc. It was thought that the pressure level drops because of the narrow wind way, and therefore the wind velocity was increased at this space.

The vulnerable area at Uh=5m/s was 0.3% (220m^2). However its vulnerable area ratio increased sharply in accordance with the increase of U_h. When U_h is 6 m/s, the vulnerable area ratio is 3.5% (4,330m²) and 15.5% (10,920m²) with the U_h=7m/s. Therefore, design modification or special action is required when Uh > 5m/s.



(a) U_h = 4m/s (b) U_h = 5m/s

(c) U_h = 6m/s (d) U_h = 7m/s

Fig. 5 Velocity distribution of wind speed 4~7m/s at the pedestrian level (1.75m)

4.2 CFD simulation of alternative model

For pedestrians comfort, low wind speeds are required for the outdoor wind environment. To decrease wind speed on site, special measures are required, such as planting trees and installing barriers at the middle of the wind ways.

In this project, two main measures were selected as mitigation strategies for strong wind. Fig. 6 shows mitigation strategies for strong winds by landscape design. Based on the wind way analysis, 61 evergreen trees and 19 wind barriers are installed at the critical wind way position. The wind barrier is a flat plate structure for defending pedestrians from strong winds.

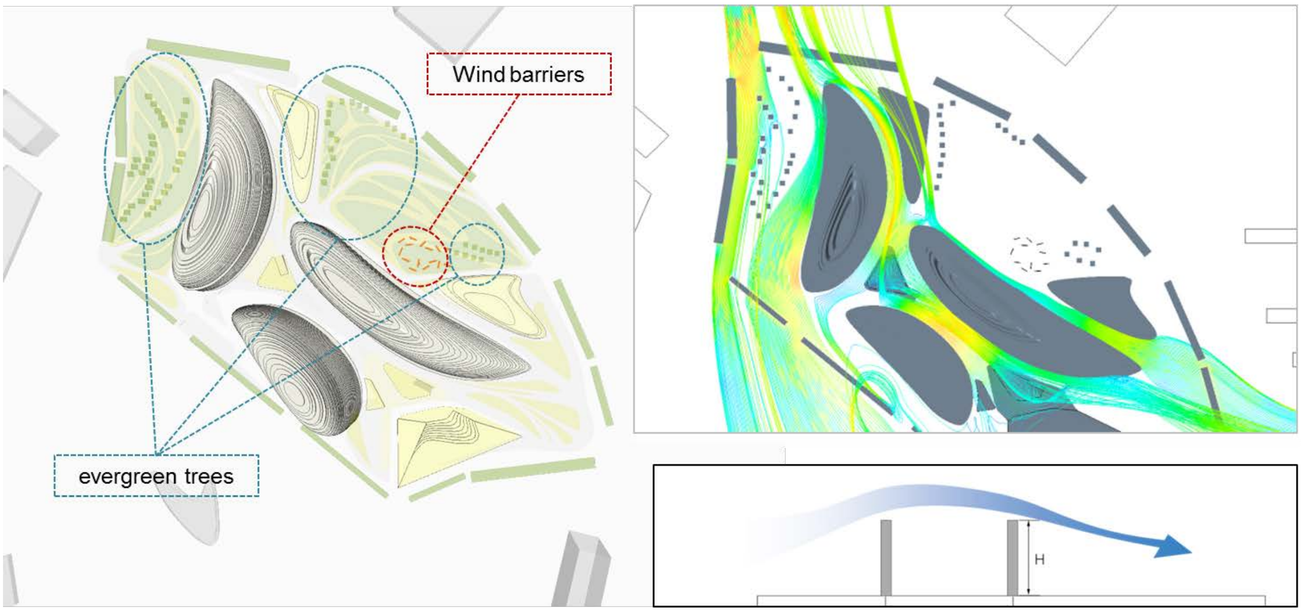


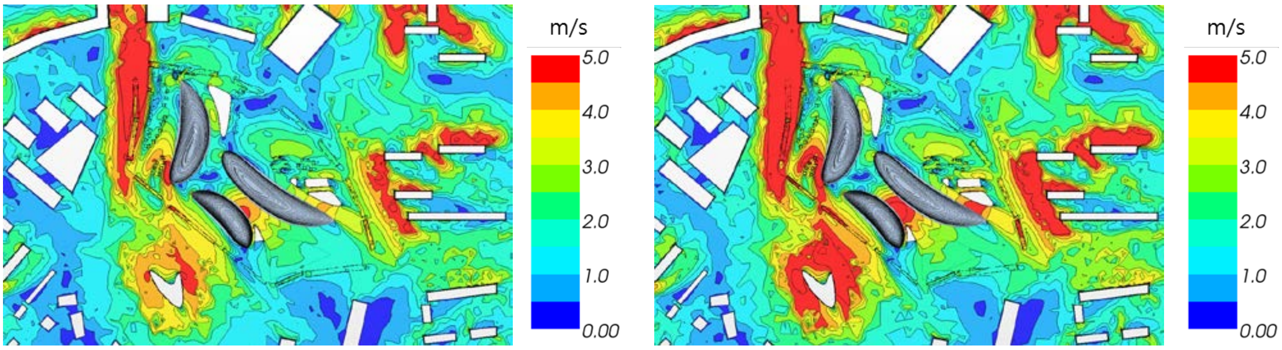
Fig. 6 Land scape design plan for mitigation of strong wind at pedestrian level

Additional CFD simulations are performed with the alternative model. Fig. 7 shows the wind velocity distribution of the alternative model with U_h=6,7m/s.

The overall wind distribution of the alternative model is improved over that of the base model. The most problematic locations were the main entrance (NW side) and the narrow space between the towers and the pavilions. Airflow from the main entrance is not fully mitigated. However, the wind distribution of the open space around tower 2 is considerably lower than the base model. It was thought that the wind stream is diverted from the SE direction (around the main street) to the SW direction (around the sub entrance) by the trees around the tower 2.

There are 6 wind barriers at the upper side of tower 2. These wind barriers defend strong wind from the main entrance. Wind distribution at the upper side of tower 2 improved in the alternative model, while there are much more vulnerable areas in the base model.

Although the wind distribution of the objective site was improved remarkably in the alternative model, the wind environment at the main-street (the narrow space between tower 1, 3) partially remains. Because of its use of space, it was hard to install any kind of structures or plants. Therefore, additional wind converting strategies could be helpful around the main street.



(c) U_h = 6m/s (d) U_h = 7m/s

Fig. 7 Velocity distribution of alternative model at the pedestrian level (U_h=6, 7m/s)

5. Conclusions

Pedestrian wind comfort depends on wind velocity and the probability of wind excess. Therefore, it is important that there needs to be not only wind distribution of site but also the probability of strong wind based on the weather data.

The objective of this study was to analyse the pedestrian wind environment of a high-rise building complex and provide useful mitigation strategies for strong wind. The outdoor wind environment around the buildings were calculated by a CFD simulation. A group of high-rise buildings was analysed for pedestrian comfort. The outdoor wind environment was analysed to satisfy comfort conditions above 90%. Then mitigation strategies were applied for improving pedestrian wind comfort. As a result of this study, optimized landscape plans for objective buildings were established.

The wind environment could change in accordance with the reference velocity. Therefore, the outdoor wind environment should be planned based on the probability analysis of weather data.

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7. References

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