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Outdoor Wind Environment Study of High-rise Residential Buildings in Urban Areas

A Literature Review

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Abstract: As wind environment is one of the key elements in the sustainable and environmental design, there is a need to study local wind environments of modern cities. In urban areas, especially when the density of city is increasing, the influence from buildings to wind environment is becoming higher and higher. This paper presents a literature review for outdoor wind environment study of high-rise residential buildings in urban areas. First, the previous wind environment research is reviewed. It not only helps to understand the fundamentals of interaction of how wind flows around objects such as buildings on the earth's surface, but also present the gap between the formal study and the nowadays contemporary residential buildings in urban areas. Second, as there are two methods of wind tunnel and computational fluid dynamics (CFD) for simulating the wind environment, this paper focuses in summarizing the existing CFD tools and setting up the fundamentals for developing future workflow. Third, the evaluation criteria of wind environment from different standards is compared. In the end, a possible framework to evaluate wind environment is discussed. The literature review is intended to highlight the limitations of previous research of novel high-rise residential buildings and current adaptation analysis methods. In particular, for the hot-summer and cold-winter climate, and with the development of architecture, novel forms and arrangements of residential buildings have been developed, wind environment design strategy response to this kind of climate and forms is insufficient. The review helps to set up the fundamentals for our following research to explore the optimization of outdoor wind environment of residential buildings in urban areas by establishing early-stage design principles.

Keywords: Wind environment; high-rise residential building; CFD; design principles

1. Introduction

As sustainable design has received more and more attention in recent years, environmental analysis is sometime needed in the early stage in design process. To be one of the key elements in the sustainable and environmental design, local wind environment of modern cities is needed to evaluate.

This paper reviews the wind environment studies, CFD simulation tools. It is finished on the focus to the discussion of the research gaps. The literature review responses to the seeking for good early design principles that generate favourable outdoor wind conditions for residential buildings, especially in hot-summer and cold-winter urban areas.

2. The Development of Wind Environment Study

The definition of natural ventilation can be described as using the natural forces of wind and buoyancy to introduce fresh air and distribute it effectively surround or inside buildings. For natural ventilation to be effective, there has to be a close relationship between the wind and the built forms, the site environment in a particular location, and the layout within the buildings (Loftness and Haase, 2013). In this section, a literature review on wind environment studies is provided. First, the development of wind environment study is introduced. Second, it presents the interaction of wind flow and buildings based on the building aerodynamics. Third, it reviews the studies around the world.

In 1960s, with the rapid development in the field of materials science building and construction technology, the height of the building is also on the rise. However, due to lack of awareness and preventive measures at the time, high-rise buildings have negative effects, leading to a deterioration in the wind environment and other related issues. As the frequency of wind environmental problems was growing, with some even directly affect the safety of users, making it getting attention by engineers and researchers.

At first, people started to study wind because it can generate loads on high-rise buildings. Starting from the 1960's, building aerodynamics has secured its place in scientific literature thanks to the construction and use of improved boundary layer wind tunnel facilities, which made it possible to accurately simulate the flow around buildings (Blocken and Carmeliet, 2004). At that time, a vague standard says if the distance between two buildings is more than about six to eight times the average of the horizontal size of the building, their mutual influence can be ignored (Simiu, 1985). But the reality is not the case, because the city's land area is restricted very limited land resources. As building density is becoming higher, large space in urban areas is basically impossible. Recognizing the importance of the outdoor wind climate, many urban authorities nowadays require studies of the pedestrian wind environment for large construction projects.

The majority of studies in the past have been conducted with wind tunnel modelling. In the last three decades, CFD (Computational Fluid Dynamics) has become available as an additional tool (Blocken and Carmeliet, 2004). Study in building wind environment using CFD method began in the middle of 1980s last century. To study the air flow, the Reynolds Equation (Dowson, 1962) and the Smagorinsky Model (Scotti, 1997) are usually used. Using Cartesian grid and simulation method are generally based on the standard k-ε turbulence model. But the lack of standards and defects of k-ε model in the early nineties made the simulation difficult to implement.

In 1990s, researchers began establishing relevant research model to make the studies closer to the actual situation, including the modification of turbulence models. A large part of the research work is a combination of wind tunnel tests, aimed at solving practical engineering applications are issues involved. The CFD simulation analysis of rectangular-shaped buildings was made at that time. In 1996, scholar Mingde Su and his colleagues did the research about wind velocity field and wind pressure in cuboid-shaped high-rise building under different wind directions. Simulation studies and the data obtained were calculated with the experimental achievements and then compared (Su, 1996). To study the results of the peak factor of the wind pressure on building surfaces, wind tunnel experiments for high-rise buildings were operated by Wu Taicheng and other researchers. They used a dynamic pressure model for analysis (Wu and Chen, 2007). The researchers of Launder and Kato proposed an improved turbulence model (Launder and Kato Model) on the turbulent energy equation (Launder and Kato, 1993; Selvam, 1996). The model was further amended on the basis. Murakami and other researchers set up the CFD simulation using the LES method (Kondo, Murakami and Mochida, 1997). It was found that the results from using LES Method is closer to the wind tunnel test data than using the Reynolds Equation Method (Murakami, 1998). A solution of similar model is suggested (Kawamoto, 2000).

3. The Interaction of Wind Flow and Building

Wind environment study requires fundamental knowledge of wind engineering principles (Stathopoulos, 2007). The construction of a building inevitably changes the outdoor climate at the building site (microclimate). Wind speed, wind direction, air pollution, driving rain, radiation and daylight are all examples of physical aspects that constitute the outdoor climate and that are changed by the presence of the building. The change of these quantities depends on the shape, size and orientation of the building and on the interaction of the building with the surrounding buildings and other obstacles (Blocken and Carmeliet, 2004).

3.1. Pressure and Force

Wind pressures on building surfaces are expressed as coefficients relative to the dynamic pressure of the approaching wind. By convention, positive pressure coefficients indicate pressure acting toward a surface while negative pressure coefficients indicate suctions or pressures acting away from a surface (Aynsley, 1999).

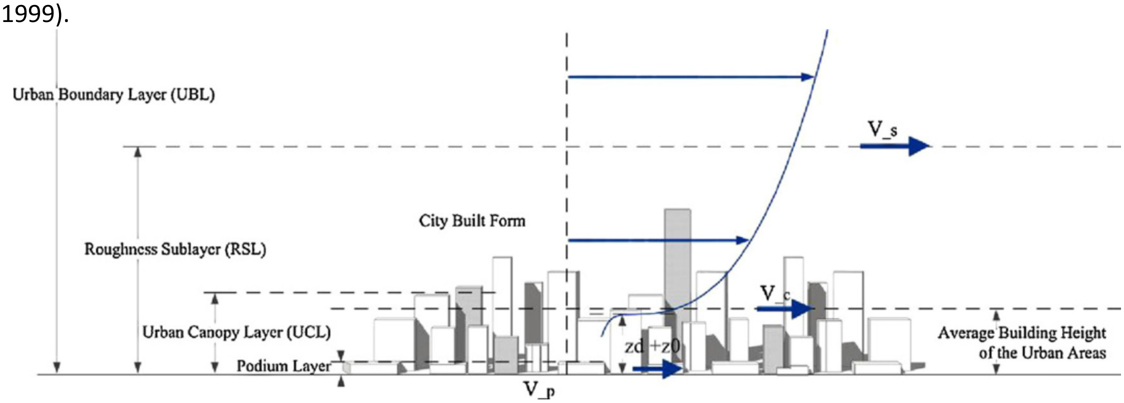

Figure 1. The figure shows the wind speed profile of podium layer, urban canopy layer (UCL), roughness sublayer (RSL) and urban boundary layer (UBL). Vp, Vc, Vs are the wind speeds of these layers (Oke, 2006; Ng et al., 2011).

Force on buildings generated by wind is somehow closely related to pressures. There are lift force and drag force. As air flows around a solid body, it exerts varying degrees of air pressure around the surfaces of the object. If the total effect of surface pressures normal to the direction of the flow on either side of the object are not equal and opposite in direction, then the resulting force, normal to the direction of the airflow, is referred to as the lift force. Drag forces act in the direction of flow on a body in a steady air flow. Drag force is the sum of viscous skin friction force and pressure drag which results from net differences in surface pressures on the windward and leeward sides of the body (Aynsley, 1999).

3.2. The Influence of Roughness Properties of Urban Areas

For modern cities as shown in the figure (Figure 1.), the velocities and flow paths of wind, the scales and intensity of turbulence are influenced by the roughness properties of the urban areas (Landsberg, 1981). The total drag on a roughness surface includes both a pressure drag on the roughness elements and a skin drag on the underlying surface, and a skin-drag on the ground surface (Raupach, 1992; Shao and Yang, 2005). Because the skin drag is relatively small and is not a factor controlled at the urban scale, only the pressure drag is usually considered in most studies (Ng, 2011). A logarithmic function is developed to set up a semi-empirical relationship by taking two aerodynamic characteristics of roughness length and the zero-plane displacement height into consideration (Oke, 1987). It is reliable for evaluating such aerodynamic characteristics of urban areas for depicting and predicting urban wind behaviours (Grimmond and Oke, 1999). Currently, there are three classes of methods for estimating the surface roughness: Davenport roughness classification (Davenport et al., 2000), morphometric and micrometeorological methods (Grimmond and Oke, 1999).

3.3. The Influenced Air Flows

Most buildings with flat surfaces and sharp corners are referred to as "bluff" bodies. The air flow separates from their surface at the sharp corners when its momentum overcomes the weaker cohesive forces of attached objects such buildings. Shear layer is generated along the lines of separation of turbulent wake beside and behind the bluff body. The predictable separation of flow at sharp edges and corners of bluff bodies results in constant flow pattern characteristics and pressure distributions for a given wind direction over a wide range of wind speeds (Aynsley, 1999) (Figure 2.).

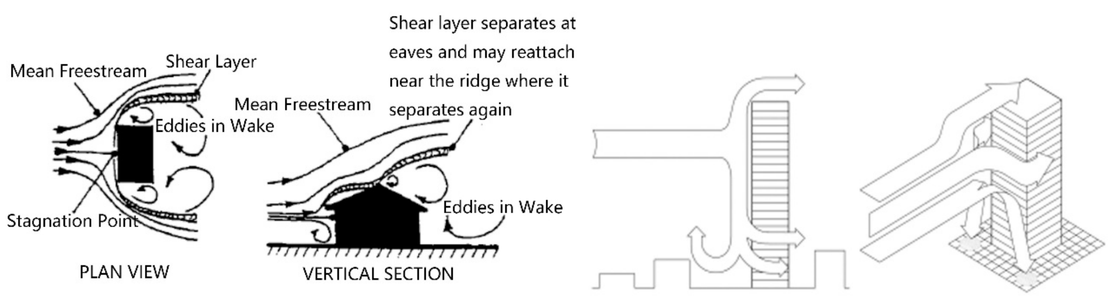

Figure 2. Left - Typical air flow features around a building (Aynsley, 1999). Right - Iinteraction of air flow and a normal rectilinear floor plan building. It explains the mechanism of downwash and high-speed wind areas may be expected at the pedestrian- level corners (Cochran, 2004).

Generally, buildings will induce high wind speeds at lower levels if a significant part of them is exposed to direct wind flows. Building is often designed in a rectilinear floor plan with curtainwall to ground level. High-rise buildings may aggravate pedestrian-level winds by allowing the high-elevation, faster winds to flow down the face of itself, which is called downwash mechanism (Figures 2.). As the air flow reaches the ground it is then accelerated around the pedestrian-level corners.

4. Wind Environment Studies around World

In this section, the wind environment study around world is introduced briefly. In recent years, lots of scientific studies dealing with the wind environment and modelling have been established quickly (Oke, 1987; Cermak, 2003). Though many countries have relevant codes and design guidelines for gust and strong wind problems, few has touched on the issue of urban air stagnation and city air ventilation problems (Ng, 2009). The research about outdoor climate has received relatively little attention in the building physics community (Blocken and Carmeliet, 2004), except some dealing with air pollution and dispersion.

4.1. Studies in America and Europe

In America and Europe, study in this field started early. Researchers studied a statistical procedure for a performing air quality simulation model (Cox et al., 1989). In relative research, researchers did the evaluation of CFD data with experimental data (Gromke et al., 2008). Influence of avenue-trees on air quality at the urban neighbourhood scale was studied (Gromke and Blocken, 2015). Researchers have done a lot of study for indoor environment. In the indoor environment quality (IEQ) section of many standards in different European countries, the establishment of relative rules aims to improve indoor air quality (Dimitroulopoulou, 2012). Researchers studied in the validation and optimization for the turbulence model (Yu, 2016). A comparison was made between ENVI-met and Autal2000 to study their modelling performance (Paas and Schneider, 2016). In Germany, developments are required not worsen the climatic conditions of the site. Urban climatic maps have been produced to guide planning and development decisions. Take the city of Kassel as an example, a planning evaluation map has been translated from the climatic map to factor the dynamic characteristics of the wind environment in the urban area for planners to decide future development (Katzschner, 2000).

4.2. Studies in Asia

As it has been discussed in the above section of development of wind environment study, relevant research started early in Japan. Some calculation models have been set up since 1980s. Researchers used wind tunnel tests to study the pedestrian wind environment in residential neighbourhoods in major cities in Japan (Kubota, 2008). A CFD study was conducted to study the climate in the Greater Tokyo area (Murakami et al., 1999). The CFD method was also used to study air pollution issue in cities in Japan (Kondo, 2006).

In Singapore, a parametric study is done to understand the gross building coverage ratio variation on outdoor ventilation in high-rise residential estates. In the study of building geometry on outdoor ventilation for high-rise residential estate, guidelines and algorithm have been reviewed (Lee, Jusuf and Wong, 2015). Researchers have done the study of outdoor ventilation of high-rise residential housing estates for a deeper understanding of wind flow with respect to different levels of height variation (Lee, Jusuf and Wong, 2015).

In Hong Kong, high-rise residential buildings are found blocking the sea breeze “fresh air” which is important for air ventilation and pollutant dispersion in the street canyon (Ng, 2009). The air ventilation impacts of the “wall effect” caused by the alignment of high-rise buildings in complex building clusters is investigated (Yim et al., 2009). The researchers try to improve the wind environment in high-density cities by understanding urban morphology and surface roughness (Ng et al., 2011). Then they have done a practical application of CFD on environmentally sensitive architectural design in Hong Kong (Yuan and Ng, 2014).

In China, Tang Yi, Meng Qinglin and other researchers did the study of the summer monsoon CFD simulation in Guangzhou Jiangnan Garden residential district in 2001. The ventilation openings of different situations and different simulated wind speed were set. Various modifications of the program were made to be compared. The distribution of wind velocity of residential areas was illustrated as a qualitative basis for planning and design for the construction of residential district (Tang and Meng, 2001). In 2002, Prof. W. K. Chow and other scholars used CFD simulation and a wind tunnel to study a financial high-rise building in Beijing. The CFD software they used is the Phoenic. The results from the CFD simulation and the wind tunnel tests were analysed to obtain the specific distribution of dynamic analysis diagram of the high-rise building (Chow and Gao, 2002). In 2003, Chen Jianguo and other researchers from Tsinghua set up the 2D and 3D models to analyse the Lanqi Ying residential building groups in Beijing. Understanding of stroke case load and environmental impact were deepened through CFD numerical simulation of wind environment for users and residential high-rise building designers (Chen, 2007). Zhang Aishe and other researchers did the CFD simulation of wind environment of two adjacent buildings, taking into account of the spacing ratio and building height and other conditions. The CFD simulation results reveal the areas of renewable wind load of high-rise buildings. The mechanism was formed to provide a theoretical basis for high-rise residential buildings and urban planning which has a certain reference value (Zhang, 2008). The researchers from Tongji University explore climatic adaptability of high-rise buildings from the wind environment (Chen, 2008). For the hot-summers and cold-winters area, a study was done on grand urban windway planning (Hong, Yu and Li, 2011). The strategy of climate adapt design of the existing building was studied in a practical project in Wuhan (Gan et al., 2013). Researchers have begun using surface roughness evaluation to study urban wind environment, as in the research of GIS-based surface roughness evaluation in the urban planning system to improve the wind environment for Wuhan (Yuan, Ren and Ng, 2014).

5. Discussion of Research Gaps

Wind environment is an important topic for sustainable design. Though researchers from different countries have done lots of studies in this field, gaps can still be found which leads to our future research.

Compare to American and European countries, the local climates, urban forms and residential building types are largely different from the Asian cities in hot-summer and cold-winter areas. As types of high-rise residential building are similar to mainland China, researches in Hong Kong and Singapore can be very good references. However, those researches in Hong Kong and Singapore response to the hot and humid climate in the tropical cities instead of the hot-summer and cold-winter climate in the temperate zone. The outdoor wind environment of residential buildings in the hot-summer and cold-winter climate is rarely considered. In addition, previous researches are focusing on urban scale or indoor ventilation. The influence from the forms and arrangements of architecture, especially novel residential buildings, is not clear yet.

According to their different forms, the buildings can be categorized into regular forms such as cuboid shapes, or irregular forms such as arc-shapes. Analogously, the arrangement of building groups can be categorized into regular types such as linear arrangements, or irregular types such as curvilinear types (Zhang, 2012). The increase in the number of tall residential buildings and the more or less arbitrary, with respect to wind, installation of large structures have frequently demonstrated the lack of adaptation of the structural environment to wind phenomena. Manifestations at ground level, such as zone of high speeds or eddies, make the approach to buildings uncomfortable, sometimes even dangerous for the pedestrian (Gandemer, 1978).

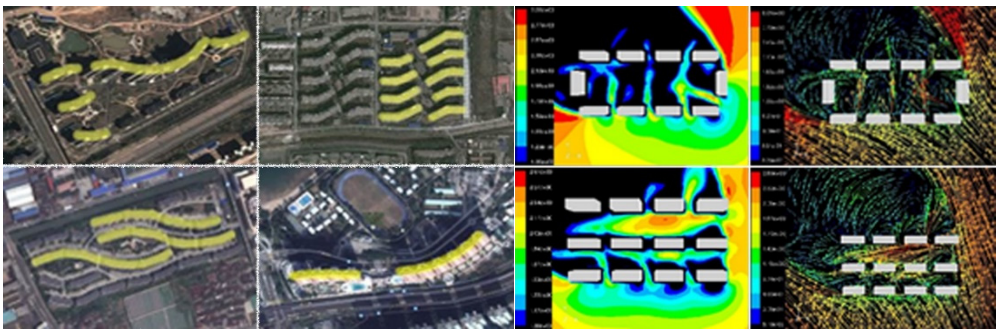

Figure 3. Left - Samples of residential building groups with curved layouts in Wuhan, Beijing, Shanghai and Hong Kong respectively (Google Map, 2016). Right - Previous studies which are generally regular-shaped layout buildings (Du, 2009).

The non-standard curvilinear residential buildings that don't follow conventional rectilinear block structures are becoming increasingly more popular recently. Curved layouts are becoming increasingly popular because of their elegant expressions (Figure 3.). Compared to conventional, rectangular layouts, curved-layout ones have superiority in their innate aesthetic functions and their flexibility of arrangements (He and Schnabel, 2016). Also, circular shapes typically do not cause flows of the type that generated by the ones with rectilinear floor plan (Cochran, 2004). It has been stated that, curved buildings generally promote lateral flow, so they behave better as far as effects of pedestrian-level winds are concerned (Stathopoulos and Baniotopoulos, 2011). However, though various studies of ventilation conditions of conventionally design buildings have been made, research of the novel irregular buildings with curved-layout is still limited. It is said that: 'Most people, and includes architects, without a sound grounding in the science of fluid dynamics, frequently reach wrong conclusions regarding the relationship between the shape of an object and its interaction with the surrounding airflow (Aynsley, 1999).'

6. Conclusion

The review has identified ad-hoc studies in urban areas dealing with the wind environment from different countries. But for the hot-summer and cold-winter climate zone and novel forms of high-rise residential buildings, wind environment studies are still rare. In sum, the conclusion can be summarized as follows.

1. Future Research: There is a need to study the mechanism behind for developing early design principles that generate favourable outdoor wind conditions for residential buildings in urban areas response to hot-summer and cold winter climate.
2. Theoretical Framework: There are several green building evaluation criteria around the world. In these evaluation criteria, the standards from various manuals are different. Some are indistinct or even primitive for outdoor wind environment among buildings. According to the themes of evaluation criteria of wind speed probability and statistics, the balance of wind velocity is proportional to human sense of comfort. Combined with the research methodology, the theoretical framework for our future research can be founded considering the rate of aeration which depends on wind flow velocity, distribution of the flow velocity and wind velocity transition of different areas, on the basis of the requirements from the 'Green Building Evaluation Standard'.
3. The Methodology: For our future research, to do the research, as the conventional in-depth simulation is time-consuming, a practical integrated workflow to immediately evaluate the performance for each design alternative is needed.

In the future, by bridging the parametric modelling and CFD simulation, we intend to develop an advanced work flow that is capable to optimize design through iteration analysis. Accordingly, our future study will contribute to this field in both expanding the study of categorized subjects of novel forms response to certain climate and analysing methodology creatively, which would help practical architecture projects.

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