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Study on Natural Ventilation Design Optimization Based on CFD Simulation for Green Buildings

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Abstract

Natural ventilation is crucial for conserving the energy, reducing carbon emission, and improving the comfort level of the built environment and the indoor air quality. The Computational Fluid Dynamics (CFD for short) represents the combination of the modern fluid dynamics, numerical mathematics and computer science. By employing CFD wind environment simulation technology, the architects are able to accurately project and intuitively describe the building wind environment of a design proposal, conduct analysis in combination with knowledge in building technology science and the simulation results, and analyze the strength and weakness of various design options and accordingly revise the architectural design. The paper shows the methodology and case study of optimizing the building's natural ventilation through CFD wind environment simulation from three aspects, i.e. site planning, building shape and building envelope, in a bid to offer some ideas to address the mismatch and poor synergy between architectural design and technological analysis.

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Keywords: natural ventilation; CFD simulation, green building; wind environment; architectural design optimization

1. Introduction

China is now witnessing a rapid development in green building which requires energy conservation and quality built/exterior environment in its design. Natural ventilation not only plays a crucial role in energy conservation and

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emission reduction, but also greatly enhances the comfort level and air quality of the built environment [1, 2, 3]. A good natural ventilation system can reduce the use of air-conditioning equipment in transitional season, thus has naturally become the most effective passive design strategies for Lingnan area where has a hot and humid climate [4, 5]. Therefore, the architects should give more consideration to the natural ventilation technologies nowadays when air conditioning technology and mechanical ventilation are being widely used [6, 7, 8, 9].

The conventional natural ventilation approach is actually a rough solution based on the analysis and utilization of wind–rose diagram, the interpretation of climate zoning requirements, and the architect's experience, failing to accurately reflect the micro-environment of the building and properly tackle the natural ventilation problems. The Computational Fluid Dynamics (CFD), though offers a more scientific and refined simulation and analysis method and establishes a more accurate and intuitive scientific basis for the building wind environment design [10], there are still problems noted in the current architectural design process, such as isolation and poor coordination between the architectural design and technical analysis. And all of these require the architects to make good use of CFD simulation analysis to realize the integrated use of natural ventilation strategy.

2. Comparisons between CFD simulation and the conventional design approach for building natural ventilation

In early architectural design practices, empirical evidence was mainly used in designs of building wind environment based on analysis and utilization of wind-rose diagrams and interpretation of climatic zoning requirements [11]. Also, the experiences of architects were drawn on in empirical research as well.

In recent years, with the development of computer technology, computational fluid dynamics (CFD) has also made rapid progress. The technology of CFD involves fluid mechanics, computing methods, computer graphics and many other disciplines [10, 12]. Table 1 shows the comparison of building natural ventilation optimization approaches. In CFD simulations, computer models are set up based on an architectural design scheme, where CFD software such as FLUENT and PHOENICS is employed to simulate the site when it is under the influence of its surroundings and wind environments inside and outside of the building and develop simulated diagrams for wind speed and wind pressure under natural ventilation as well, providing scientific basis for evaluating the effects of building wind environment design [13, 14, 15, 16]. With the technology of CFD wind environment simulation, architects are able to better forecast and more intuitively describe the building wind environment in a design scheme, and conduct an analysis based on relevant building technologies and simulation results, with which they can make comparisons among various options and improve the design scheme.

Table 1.Comparison of building natural ventilation optimization approaches.

Method	Empirical evidences	CFD simulations
Design basis	Analysis and utilization of wind-rose diagrams and theoretical experience of architect	Intuitive data resulting from simulated conditions
Strengths	It is based on rough research results, simple and viable with certain degree of accuracy.	CFD sets up models quickly, has a strong computing power and produces powerful data reports and visual analysis result, all of which make the design more scientific.
Weaknesses	It is unable to precisely describe the micro-environment of the building. An architect can only briefly predict if the building meets ventilation requirements based his/her personal experience. No scientific approaches are available to forecast the wind environment.	The reliability of numerical simulation method needs to be constantly reviewed and revised. Also, an architect needs time to be versed with CFD.

3. Building natural ventilation optimization based on CFD simulations

An architect needs to understand site landform and impact of site surroundings on wind environment through CFD simulations of wind environment. After thoroughly studying the respective relations between building natural ventilation and the three aspects of site plan, building shape and building envelope interface, the architect conducts a qualitative analysis and integrates natural ventilation design integrated into the design scheme, on which CFD wind environment evaluation will be carried out for improvements. The purpose is to detect undesirable wind environment at the earliest possible time, work out corresponding improvement measures and find the optimal architectural scheme through comparisons among various schemes.

3.1. Site planning based on CFD simulations

The wind environment design of a building is based on its external environment. CFD technologies can be used to optimize the relations between a building and the other aspects such as the project site, surrounding buildings, prevailing wind direction and building clusters, so as to maximize natural resources and create better conditions for natural ventilation while at the same time, mitigate the impact of adverse wind environment on some areas. The purpose is to eventually create an outdoor wind environment that is comfortable and safe.

First, CFD simulations are developed to analyze the wind environment of a project site, including prevailing wind directions and strengths in winter and summer, wind field changes resulting from surrounding buildings or structures, orographic lifts generated in certain terrains, so as to find out if unmoving air mass or excessively high wind speed will occur in a certain terrain or surrounding.

In site planning, buildings can then be reasonably positioned based on the analysis result of the wind environment, while other factors such as daylighting, noise, building coverage, height, orientation, spacing and configuration are addressed as well. On the other hand, open spaces like roads, green areas, waters and squares are used to form air flues to bring in the prevailing wind in summer [17].

Airflow circulation, wind direction and wind speed vary with the site planning strategy. Two aspects potentially brought by an inappropriate site plan should draw the attention of an architect. The first one is excessively high wind speed in the outdoor, meaning that the wind speed is too fast for human activity and pedestrian comfort. The excessively high wind speed is usually a result of narrow wind tunnels created in a compact building layout or a result of strong air current that cannot be effectively blocked out by buildings or outdoor plantation. The second one is poor air circulation in outdoor spaces and among singular buildings that negatively affect the ventilation and cooling both indoors and outdoors. Unsmooth air circulation is caused by a wind shadow zone which in turn is a result of blockage by upwind buildings. Due to the slow wind and changeable wind direction in the wind shadow zone, it is not easy for downwind buildings to have cross ventilation, which is unfavorable to ventilation both inside and outside of a building [11].

Therefore, CFD simulations are employed on a site plan to study various indicators of the outdoor wind environment, such as average wind speed, scope of wind shadow zone, size of calm zone (in which the wind speed is lower than 1m/s), size of strong wind zone (in which the wind speed is higher than 5m/s) and wind pressure on building surface, so as to provide more basis for design scheme optimization and comparisons.

In the design of Shenzhen Archive Center, models of buildings surrounding the project site were produced to have simulation analysis of the wind environment. As indicated in Fig. 1, an obvious ventilation corridor starting from the southeast corner towards the northwest corner of the site is formed under the prevailing wind in summer.

The building layout responded to the characteristics of the wind environment in summer. Specifically, traffic passages and open-up floors were created along the main path in consideration of the functional requirements. The simulation result as indicated in Fig. 2 shows that such layout facilitates natural ventilation in summer and offer comfortable open-air relaxation and activity places for people. Moreover, the wind that flows along the traffic passages accelerates dissipation of pollutants emitted from vehicle exhaust.

In the design practices of He Jingtang Architectural Creation Studio of South China University of Technology (SCUT), as indicated in Fig. 3,the building layout is closely integrated with the courtyard space so that the perimeter structures form the basic enclosure of the courtyard. Building clusters are linked up via connecting corridors which also contribute to the spatial transition.

During the simulation process, comparisons among the three levels of enclosure (respectively full enclosure, enclosure on 2/F and open-up on G/F, fully open-up) of the connecting corridor were made. As indicated in Fig. 4, when the corridor is fully enclosed, a large calm zone will appear in the west courtyard. As indicated in Fig. 5, when the 2/F is enclosed, the wind speed will accelerate compared to the situation when it is fully enclosed. However, there is still a rather large calm zone in the west courtyard. As indicated in Fig. 6, when the corridor is fully open, the prevailing wind in summer can effortlessly pass through the courtyard. The wind speed at the pedestrian height of 1.5m is about 1 to 1.5m/s, which is within a comfortable range. Moreover, it creates the smallest calm zone and the best outdoor wind environment.

Fig. 1. vector of wind speed distribution at pedestrian height on the site.

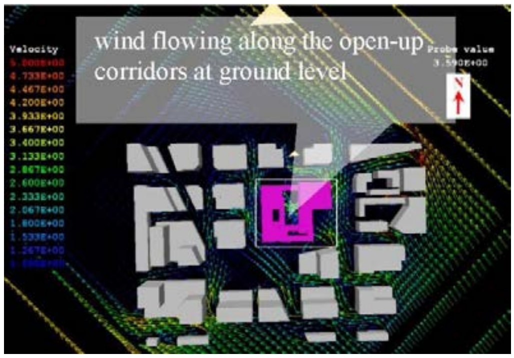

Fig. 2. vector of wind speed distribution at pedestrian height around the building.

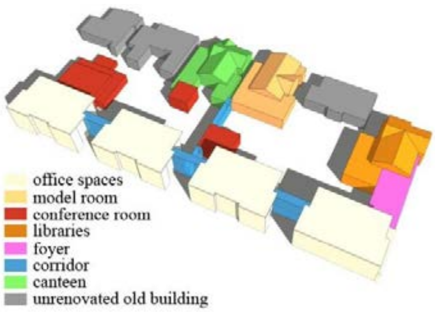

Fig. 3. analysis of master layout.

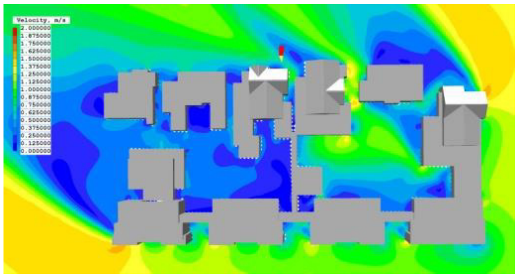

Fig. 4. wind speed levels – all corridors enclosed.

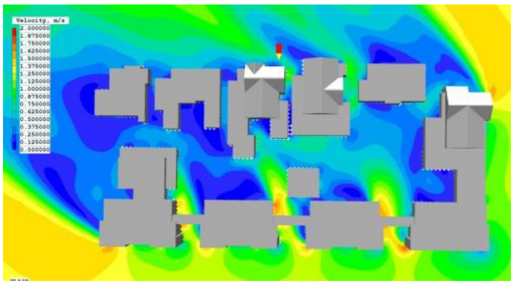

Fig. 5. wind speed levels – corridor on F2 enclosed.

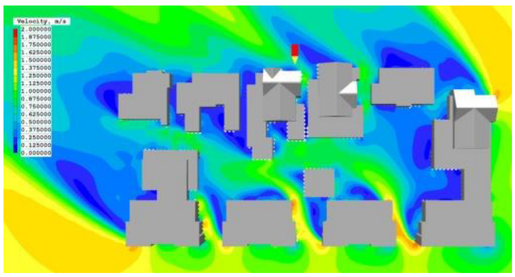

Fig. 6. wind speed levels – all corridors transparent.

3.2. Building shape design based on CFD simulations

With CFD technologies, an architect is able to select a reasonable building shape and design suitable interior spaces, so as to make it possible to create comfortable outdoor/indoor wind environments and thermal environments. The two most important modes of building ventilation are wind pressure ventilation and thermal pressure ventilation [18], while building shapes and internal spaces are responses to the corresponding modes. Under most circumstances, natural ventilation within a building is realized in both modes rather than just one [1]. When it is calm outdoors or when there is a large indoor space, thermal pressure ventilation plays a key role in facilitating building ventilation.

In refining and detailing the building shape and floor plan, an architect needs to look at the following three aspects. First, after the functional requirements are met, make sure room depths are reasonable. Second, with comprehensive consideration given to elevation aesthetics and plane functions, create certain forms at suitable positions of a building to deflect wind and form through wind tunnels by distributing building volumes and creating open-up spaces and openings, so as to facilitate natural ventilation. Third, create spatial forms that help thermal pressure ventilation when necessary, such as atrium, patio and alleyway. With basic ventilation theories and knowledge, an architect can get a clear picture of the factors that influence natural ventilation in a project, thus improving building natural ventilation in designs of plane, elevation and section.

Pressure difference on building surface is the fundamental force that enables wind pressure ventilation, though it varies by building shape. Wind pressure values on building surface are acquired through CFD simulations to calculate the surface wind pressure difference of rooms and assess the potential of wind pressure ventilation. For places like wind-deflecting building shapes, open-up spaces and openings, CFD simulations are conducted to compare and optimize the airflow paths, so as to effectively improve ventilation with airflow. For the surrounding places of wind-deflecting building shapes and openings, CFD simulations are conducted to monitor if the wind speed is too high, which might be less comfortable and safe to users.

The result of thermal pressure ventilation depends on temperature difference, height difference and planar position of ventilation space. Some CFD software can have coupling calculation on the radiation and temperature of a model. With readings of wind speed and temperature, the result of thermal pressure ventilation can be estimated, and then used as the basis to compare and improve the building thermal pressure ventilation.

As result of the staggered layout of the Teaching Buildings 31-34 on SCUT campus, a large calm zone is formed between Teaching Building 33 and 34 under the influence of summer prevailing wind and adversely affects the natural ventilation. To address this unfavorable wind environment noted in CFD simulation, the open-up spaces are incorporated into the building forms. Specifically, the entire ground level of Teaching Building 32 is opened up and that of Teaching Building 33 is partially opened up. Comparisons between Fig. 7 and Fig. 8 show that the wind speed between Teaching Building 32 and 33 goes up to 2~2.5m/s from 1~2m/s. Moreover, the size of the calm zone between Teaching Building 33 and 34 becomes much smaller and the wind speed in some areas rises to 2~2.5m/s from below 0.5m/s, effectively improving the wind environment of the teaching buildings and creating favorable conditions for natural ventilation in classrooms.

Openings are created on the windward side of Teaching Building 31 as well. Comparisons between Fig. 9 and Fig. 10 show that the wind environment of the atrium is much better and natural ventilation in the north classrooms is also improved to a degree.

3.3. Envelope design based on CFD simulations

With CFD technologies, an architect is able to have optimized designs of envelope openings and wind deflection structures, reasonably organize indoor airflow paths, avoid blockage and make sure that air flows smoothly through the use areas [12]. At the same time, wind deflection measures will be reasonably taken to improve the indoor wind environment in some places, reduce the size of indoor calm zone, shorten the age of air and speed up the supply of fresh air.

To refine the details of an indoor wind environment is to find a balance between indoor wind speed and airflow distribution density, provided that the indoor wind speed is suitable. To achieve this, an architect needs to look at the following three aspects. First, position, size and opening way of an opening (door, window, ventilation structure and so on) should be appropriate. Second, install wind deflection boards at poorly ventilated positions to improve airflow distribution. Third, potential negative impact of sun-shading components on indoor ventilation should be taken care of.

Thanks to CFD simulation technologies, an architect is able to analyze the distribution of wind speeds, temperatures and ages of air on planes and sections, then conduct coordinated design of door/window opening and ventilation structure with a clear picture of the whole space in mind without sacrificing the functions of such components. Positions of wind deflection boards can be adjusted as needed to suit the wind field of the indoor space. CFD simulations help find out indoor wind speeds and airflow distribution evenness when different forms of sun-shading components are selected, which, together with other performance indicators relating to sun-shading and daylighting, can be used in design scheme evaluation and finalization.

In the design of Taizhou Folk Custom Exhibition Center, suitable openings on the envelope structure were created to organize indoor airflow paths in view of the distribution of outdoor wind pressure and wind speed. Simulation results as indicated in Fig. 11 show that there is a rather large calm zone in the glazed corridor where ventilation is poor. In view of the preliminary simulation results, adjustments are made to operable windows and doors. Side windows on the east and the west in the patio are all opened to increase the ventilation volume in the glazed corridor. Fig. 12 shows that the ventilation is obviously improved with the adjustments; however, there are still large calm zones in some areas. Again, adjustments are made to the positions and sizes of operable windows and doors in areas indicated in Fig. 13. Eventually, indoor ventilation of the center is greatly improved as indicated in Fig. 14.

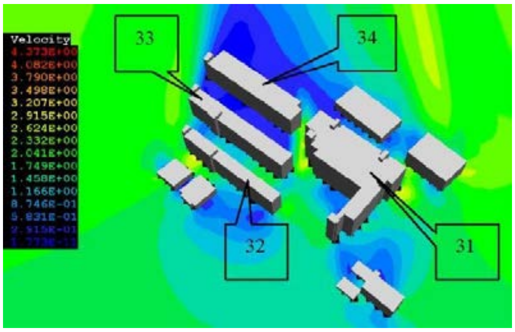

Fig. 7. summertime wind speed levels – no open-up design.

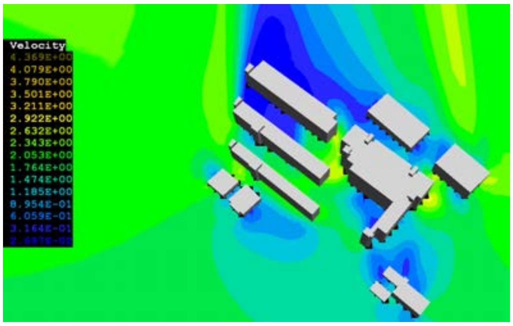

Fig. 8. summertime wind speed levels –teaching building 31-34 with partial open-up design.

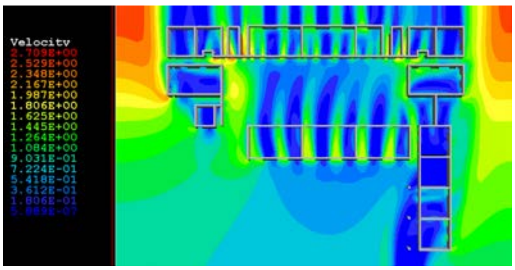

Fig. 9. summertime wind speed levels –teaching building 31 with no opening in building shape.

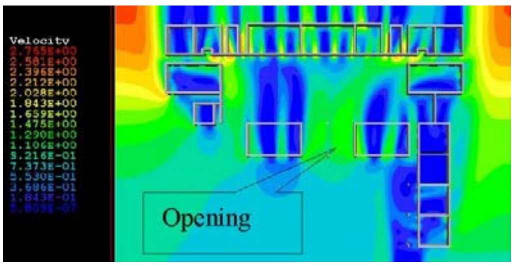

Fig. 10. summertime wind speed levels –teaching building 31 with opening in building shape.

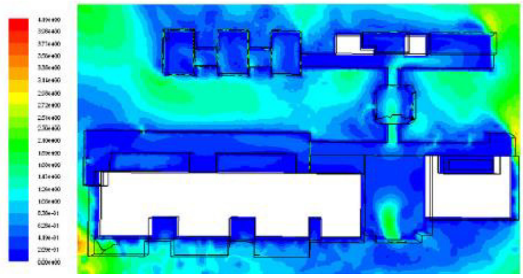

Fig. 11. wind speed levels at level 1.5m in rooms on F1 in preliminary simulation.

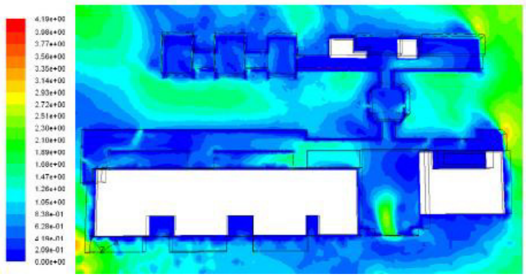

Fig. 12. wind speed levels at level 1.5m in rooms on F1 after preliminary adjustment.

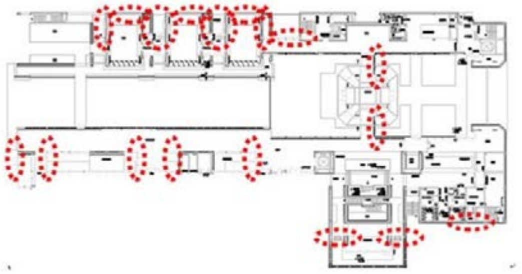

Fig. 13. schematic diagram of adjustments.

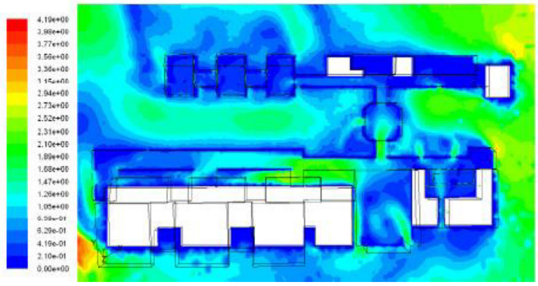

Fig. 14. wind speed levels at level 1.5m in rooms on F1 after final optimization.

4. Conclusion

CFD simulation technologies play a key role in optimization of green building designs as they can help architects complete qualitative analysis and evaluation of building natural ventilation. This paper, as indicated in Fig. 15, from the three aspects of site plan, building shape and envelope, studies methods and cases relating to building natural ventilation improvement with the assistance of CFD wind environment simulations, so as to give some ideas to building wind environment optimization. Hopefully, it will help architects adjust and re-shape their work modes, adhere to the original purpose of architectural design and develop green buildings that are energy efficient and environmentally friendly.

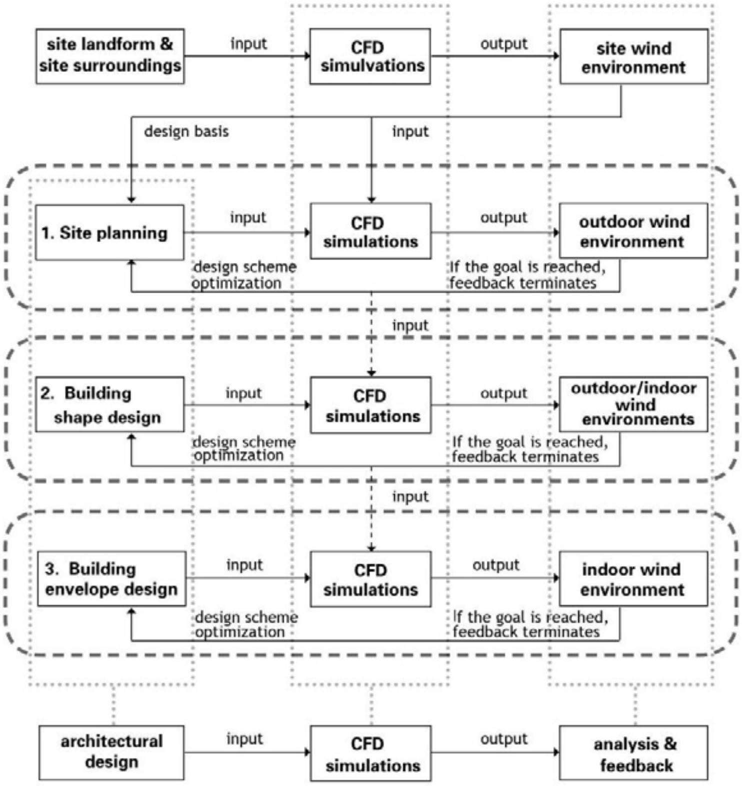

Fig. 15. flow diagram for optimized design of green building natural ventilation based on CFD simulation.

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References

[1] X.Y. Chen, B. Zheng, K.M. Hou , et al. Building Design and Natural Ventilation. China Power Press, Beijing, 2012.
[2] Sue R., Adapting Buildings and Cities for Climate Change, in: A 21 st Century Survival Guide, Burlington: Architectural Press, 2005.
[3] O. Victor, Design with Climate: Bioclimatic Approach to Architectural Regionalism, Princeton University Press, New Jersey, 1967.
[4] L. Yang, J.C. Lam, J.P. Liu, Bioclimatic building designs for different climates in China, Architectural Science Review. 48 (2005) 187–194.
[5] J.C. Lam, L. Yang, J.P. Liu, Development of passive design zones in China using bioclimatic approach, Energy Conversion and Management. 47 (2006) 746–762.
[6] G. Baruch, Climate Considerations in Building and Urban Design, Van Nostrand Reinhold Company, New York, 1998.
[7] G. Baruch, Passive and Low Energy Cooling of Buildings, Van Nostrand Reinhold Company, New York, 1994.
[8] G. John, D. Clements–Croome, G. Jeronimidis, Sustainable building solutions: A review of lessons from the natural world, Building and Environment. 40(2005) 319–328.
[9] H. Richard, Climate Responsible Design: A Study of Buildings in Moderate and Hot Humid Climates, St Edmundsbury Press, London and New York, 2001.
[10] M. Shuzo, CFD and Building Environment Design, Beijing: China Architecture & Building Press, 2007.
[11] F. Chen, Z.Y. Cai, F. Wang, Generation and significance of building form under wind environment concept. Architectural Journal, 07(2007)29–33.

[12] Yang, L., Ye, M. and He, B.J. (2014) CFD simulation research on residential indoor air quality. Science of the Total Environment, 472:1137-1144.
[13] Tominaga, Y., Mochida, A., Yoshie, R., et al. (2008) AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. Journal of Wind Engineering and Industrial Aerodynamics, 96(10-11):1749-1761.
[14] Mochida, A., Lun, I.Y.F. (2008) Prediction of wind environment and thermal comfort at pedestrian level in urban area. Journal of Wind Engineering and Industrial Aerodynamics, 96(10-11):1498-1527.
[15] Kubota, T., Miura, M., Tominaga, Y., et al. (2008) Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. Building and Environment, 43(10): 1699-1708.
[16] Okada, H., Ha, Y.C. (1992) Comparison of wind tunnel and full-scale pressure measurement tests on the Texas Tech Building. Journal of Wind Engineering and Industrial Aerodynamics, 43(pt 3): 1601-1612.
[17] Yang,L., 2014. Green Building Design: Wind Environment of Building. Shanghai: Tongji University Press.
[18] Peter F. S. (2005). Architecture in a Climate of Change: A Guide to Sustainable Design. Burlington: Architectural Press.