A CFD Analysis of Wall-Effect Building Groups in a Curved Layout: A Study in Sha Tin, Hong Kong

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Abstract

Hong Kong's building density is one of the highest in the world. Since ventilation is a key element in sustainable and environmental design, there is a need to evaluate local wind environments of high dense cities such as Hong Kong. In recent years non-standard curvilinear residential buildings that don't follow conventional rectilinear block structures are becoming increasingly more popular. Though various studies of ventilation conditions of conventionally design buildings have been made, research of non-standard curvilinear building layouts is still limited. Previous research mainly explored rectilinear block-shaped layouts that typically cause a so called 'Wall-Effect' by blocking adequate ventilation on street- and mid-levels around buildings. Our paper presents and summarizes the analysis of airflow and ventilation of non-standard curvilinear buildings based on Computational Fluid Dynamics (CFD) simulations. The Flow Simulation of Solidworks has been used as our analysis software tools. Its technology is based upon the use of Cartesian-based meshes and solving the Navier-Stokes equations. Nonstandard and curvilinear shaped building arrangements are categorized into various groups and analyzed in respect to their performance of ventilation on street and mid-levels using a case study of high rise buildings in Sha Tin, Hong Kong. Hong Kong's climate is subtropical warm and humid in summer, subsequently a higher ventilation is needed and building design has to accommodate good airflow around the buildings. Our findings show that curvilinear buildings lead to a more favourable ventilation environment since they have a smaller wind resistance. Non-standard curvilinear designs perform better in terms of general ventilation since the airflow around the buildings is faster and less turbulent. Our simulations present that convex-shaped buildings have a better overall wind environment than concave-shaped ones. We conclude our paper with a classification of various nonstandard curvilinear buildings that offer a general better airflow and ventilation due to their shape. This classification allows designer to understand quickly wind resistance, airflow, and turbulences that a non-standard curvilinear design has on the immediate environment.

Keywords: CFD; ventilation; nonstandard curvilinear building; airflow; Wall Effect.

1. Introduction, Problems & Motivation

1.1. Introduction

Nowadays, with both rapid development of technology and great improvement in life quality, people have much higher requirements in the planning and building of living quarters. In recent years non-standard curvilinear residential buildings that don't follow conventional rectilinear block structures are becoming increasingly more popular. Arc-shaped building layouts are becoming increasingly popular because of their elegant expressions (Figure 1). Compared to conventional, rectangular layouts, arc-shaped ones have superiority in their innate aesthetic functions and their flexibility of arrangements. The area between two arc-shaped buildings can be developed easily into various styles matching the overall design expression. The arc-shaped arrangements can work either in concert or exist independently.

1.2. Problems and Background

The lack of research in arc-shaped building arrangements is the driver of this study. The so called 'Wall Effect' is often produced by wall-like buildings in high-density urban areas such as the city of Hong Kong. These dense groups of buildings may block the sunshine and reduce the wind velocity. These negative effects are usually called Wall Effect or Urban Heat Island Effect.

There has been increasing concern over the Wall Effect caused by uniform high-rise developments

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which adversely impact air circulation. At the expense of the free-flow of air ventilation, developers of estates are financially motivated to maximize the view from the buildings. Especially, huge wall-like estates along the waterfront are often constructed.

An environmental group in Hong Kong called 'Green Sense' expresses concern that their survey on 155 housing estates found 104 of them have a 'wall-like' design (Yung, Chester (21 December 2006). "'Asia's walled city' leaves-residents longing for air". The Standard. Retrieved 21 March 2007). It cited many estates as examples. Some legislators called for a law to prevent developers from constructing tall buildings which adversely affect air flow in densely populated areas, but the bid failed. Since 2007, residents of Tai Kok Tsui (a neighbourhood in Hong Kong), increasingly aware of the problem, have been lobbying against further proliferation of such high-rises in their area which threaten the last air corridor.

Fig.1. Samples of residential building groups with curved layouts in Wuhan, Beijing, Shanghai and Hong (Google Map, 2013).

1.3. Research Motivation

Usually, classification study for building wind environment is not included in most research. Researchers usually concentrate on specific designs instead of comparing different architecture forms and layouts, studies of ventilation rules are still limited. Previous studies generally analyze square and other regular shaped layout constructions (Figure 2).

However, layouts of architecture tend to be diversified, in spite of the pressures to build wall-like estates. Thus, of course, analysis for specific programs under specific conditions is needed, but a classification of different lay-layouts is also important. By establishing basic laws of ventilation, designers can use them within their design processes avoiding some of the problems.

In this research, nonstandard and curvilinear shaped building arrangements are categorized into various groups. Especially for the arc-shaped building arrangement, it is categorized into several forms, among which some widely-used ones are analyzed. Then they are studied in respect to their performance of ventilation on street and mid-levels using a case study of high rise buildings in Sha Tin, Hong Kong.

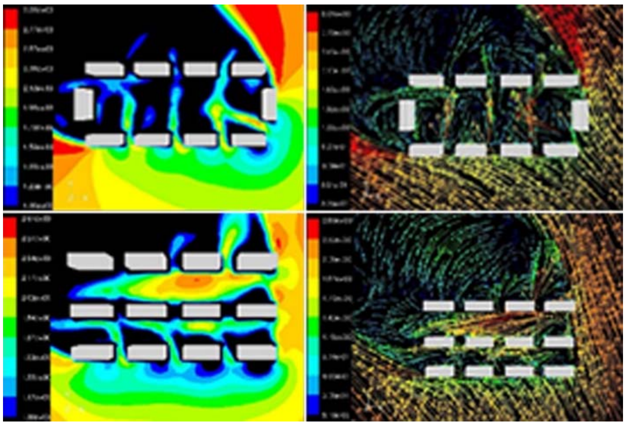

Fig.2. Images above show the previous studies which are generally square or other regular-shaped layout constructions. (Graphs from essays: DU Guimei, Numerical Simulation of Wind Environment in some typical layout Residential Districts, B. E. (Hunan University) 2002. A thesis submitted in partial satisfaction of requirements for the degree of Master of Engineering in HVAC in the Graduate School of Hunan University. Apr, 2009)

2. Evaluation Criteria & CFD Application

2.1. Evaluation Criteria of Outdoor Wind Environment

There are several green building evaluation criteria such as LEED (US), BREEM (UK), BEAM (HK) and the national 'Green Building Evaluation Standard' (China, GB/ T50378-2014). In these evaluation criteria, the standards from various manuals are different. Some are indistinct or even primitive for outdoor wind environment among buildings. In the section of 4.2.6 in the 'Green Building Evaluation Standard', there are clear requirements for wind environment by defining the suitable velocity and pressure. For the condition of typical wind velocity and direction in winter, the speed of air flow surrounds buildings is suggested to be less than 5m/s (scoring 2 points in the evaluation); the pressure difference between the windward and leeward sides is suggested to be less than 5 Pa (scoring 1points in the evaluation). For the conditions of summer and transition seasons, vortex and no-wind area are suggested to be prevented (scoring 2 points in the evaluation); the wind pressure difference between indoor and outdoor of more than 50% window area is suggested to be more than 0.5 Pa (scoring 1 points in the evaluation). According to some general evaluation standards researchers and engineers usually adopt, the outdoor wind environment is closely related to the distribution of velocity of wind; this effect can be determined. According to the above references, our evaluation criteria for outdoor wind environment can be concluded on the basis of related requirements from 'Green Building Evaluation Standard' (China) and BEAM (Hong Kong). The evaluation standards are based on the rate of aeration; e.g. wind flow velocity, distribution of the flow velocity and wind velocity transition of different areas. 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.

2.2. The Application of CFD Software Tools

In recent years, CFD software tools are often applied in the study of ventilation by simulating the air flow. Some are accurate, suitable for scientific analysis; some are suitable for application of architecture and urban planning; some have multiple functions. However, there are also disadvantages for some tools such as hard to set the simulation of mathematical model, lack in types of grid or lack in calculation models. As this closely relate to the accuracy and efficiency of analysis, using a proper software tools for simulation is crucial for the study.

In our research, the software tool of Flow Simulation of Solidworks is used for CFD simulation. One of its advantages is its convenience in model set-up. Architectural models can be either easily modified or imported to the program. Therefore, it is suitable for both research and engineering application. Its technology is based upon the use of Cartesian-based meshes. Because of this, it has the advantages include: speed and simplicity of the mesh generation algorithm, minimization of local truncation errors and robustness of the differential scheme.

As a result of using Cartesian-based meshes we have cells which are located fully in solid cells, fluid cells and cells intersected the immerse boundary. This allows conjugate multi-physics calculations, using one computation mesh having fluid cells, solid cells and partial cells. According to this, it is able to do fluid flow analysis for fluid regions, heat transfer and electrical current calculation in solid regions.

For fluid regions, Flow Simulation of Solidworks solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws. It is supplemented by fluid state equations defining the nature of the fluid and empirical dependencies of fluid density, viscosity and thermal conductivity on temperature. To close the system of equations, Flow Simulation employs transport equations for the turbulent kinetic energy and its dissipation rate, using the k-ε model. The modified k-ε turbulence model (Lam and Bremhorst, 1981) with damping functions can describe laminar, turbulent, and transitional flows of homogeneous fluids.

3. Theoretical Basis Establishment

In this section, arc-shaped building arrangement can be categorized into several forms: (1) the curved layouts of convex-type and concave-type without an opening in the middle; (2) the curved layouts of convex-type and concave-type with a gap between buildings; (3) the curved layouts of convex-type and concave-type without an opening in the middle protruded windward type and protrude leeside type of gap between the buildings. These widely-used forms are analyzed as follows.

3.1. The Curved Layouts of Convex-Type & Concave-Type without an Opening in the Middle

These two types of building groups shown in Fig.3 are typical. The layout of the front building and the one behind it have a close symmetrical relationship. The space between them is usually designed as public garden, landscape or green area etc.

As shown in the figures, the uniformity of wind velocity distribution in the two types is significantly different. Convex-type velocity distribution is more uniform than in the concave-type, as the flow rate of the concave-type has much greater variation, especially in the region of the edge of the buildings. In addition, the rear region of the concave-type has a negative ventilation effect (you can see that the flow area in the figure is in darker blue, and extends longer. In contrast, the convex-type layout on the left not only has better ventilation in the space between the building groups, its rear area also has better ventilation. Thus, groups of buildings or public spaces in the rear region of the building group will benefit from the convex shaped arrangement.

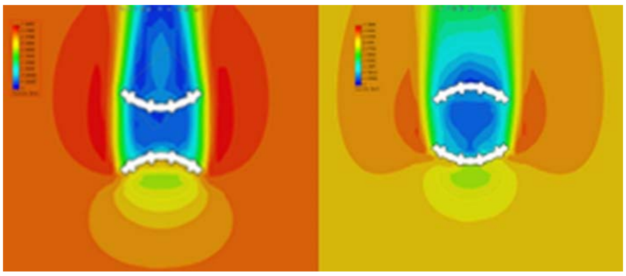

Fig.3. Plan of distribution of velocity of wind environment of convex & concave curved layouts without opening in the middle of the building groups

3.2. The Curved Layouts of Convex-Type & Concave-Type with a Gap between the Buildings

To improve ventilation, sunlight and landscape, channels are often set between residential building groups. As it is shown in Figure 3 (1) and (2), the simulation of wind flow around the buildings is similar in convex and concave curved layouts that don't have a gap in the middle between them. Once there is a gap between the buildings, the convex-type has better performance of ventilation; this gap causes the improved wind environment.

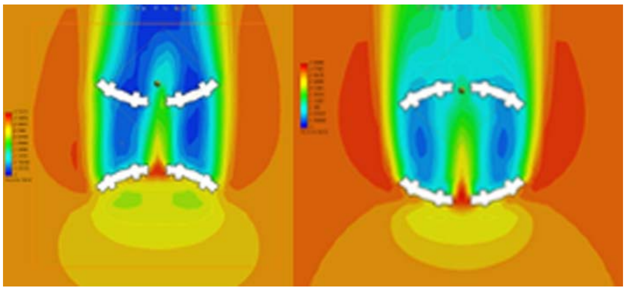

Fig.4. Plan of distribution of velocity of wind environment of convex & concave curved layouts with a large gap the building groups

Through the analysis of the air flow movement, the main problem is that a concave-type layout can easily cause turbulences that are uncomfortable or even harmful for users when the wind speed is too high. The velocity distribution of convex-type is more uniform than the concave-type one as it is shown in the figures 3(1-3). In the situation of the concave-type, the air flow is stumbled between the two units of buildings and can only escape from the space after several rounds of whirl, which has a negative influence on the process of updating air.

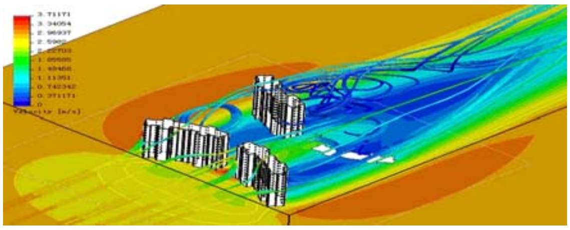

Fig.5. 3D view flow analysis & simulation of concave curved layout with a large gap between the building groups.

3.3. The Curved Layouts of Convex-Type & Concave-Type without an Opening in the Middle Protruded Windward Type & Protrude Leeside Type of Gap between the Buildings

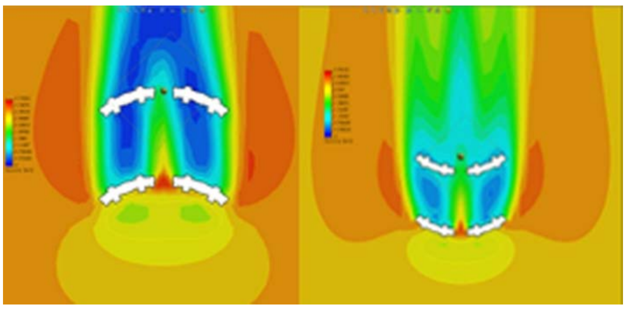

Fig.6. The Distribution of Velocity of Wind Environment of Protruded windward type and Protruded leeside type with a tunnel in the middle. (The windward faces to the south)

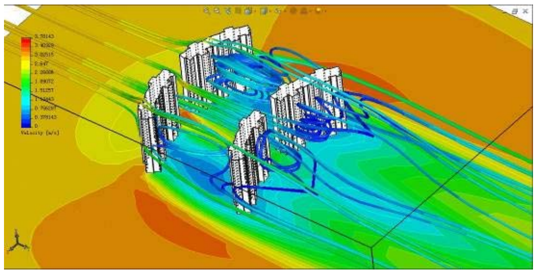

Fig.7. The Flow Analysis and Simulation of the Protruded windward type curved layout with a tunnel in the middle of the building groups. (The windward faces to the south)

By analyzing the simulations of the protruded windward type layouts as shown in Fig. 6 and Fig. 7, we can see they have a better performance of the distribution of velocity of wind environments than the convex-type, which is more uniform. Another advantage of the protruded windward type layout is that it can become the protruded leeside type and could block seasonal winds from entering the building groups that come from other sides.

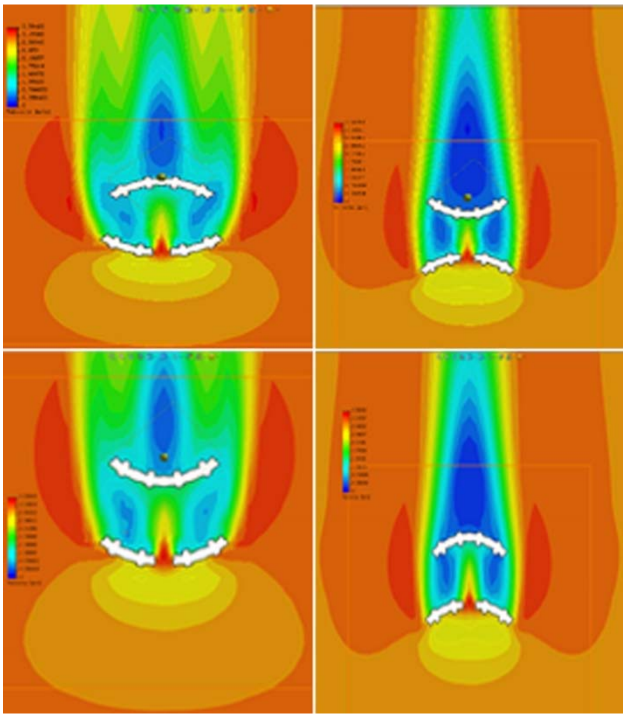

Fig.8. The Distribution of Velocity of Wind Environment of Other types of building groups. (Several types are modified from the basic situation discussed above.)

Several different types can be obtained from the modification of the basic situation as presented above. Figure 4 shows the analysis of the Distribution of Velocity of wind environment of the modification. Because the flow speed in the situation of the protruded windward type with a gap between the buildings is very slow, it has a similar performance to the protruded windward type layout that has a gap between the buildings groups.

4. Typical Case Study

The case study focuses on the Wind Environment Analysis of Residential Building Groups, Ma On Shan, Hong Kong. In this part, a typical case study is applied to verify the classification simulation analysis.

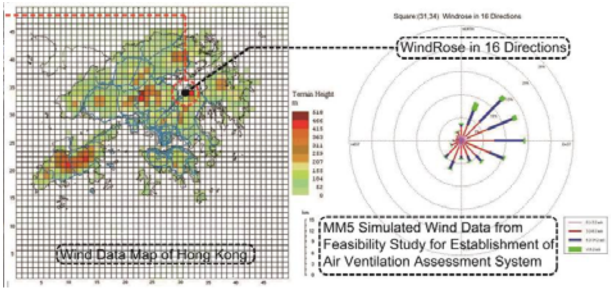

Fig.9. MM5 Simulated Wind Data from Feasibility Study for establishment of Air Ventilation Assessment System is applied in the case study.

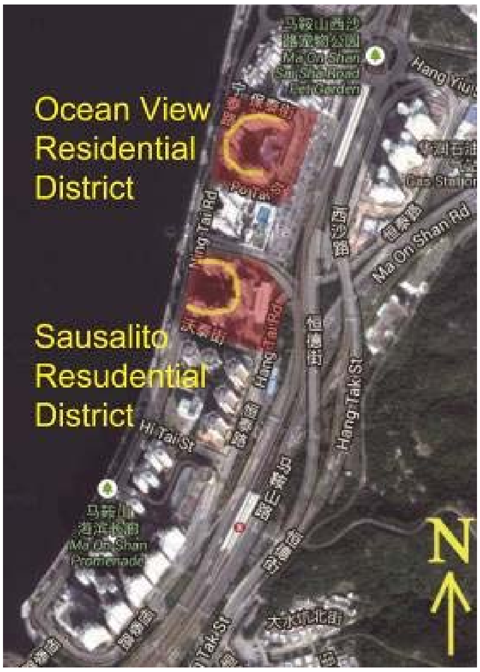

Fig.10. The figure shows the location of the residential districts

The density of Hong Kong is one of the highest among the mega-cities in the world. Since land is limited, residential buildings are often built high and close to each other to increase usage space among architectures. However, this may cause the wall-effect and obstruct ventilation. The Ma On Shan area is a typical example of the situation, where a large number of residential buildings are located along the coast line.

Two residential districts, called 'Ocean View' and 'Sausalito', are selected to represent convex-type and concave-type situations. The building group layouts comparison of these two residential districts have been marked in Fig. 10 and Fig. 11. Because the locations of these two residential districts are close to each other, the two study objects can share the pre-conditional simulation data. The wind data of this area can be achieved by using the MM5 tools (Fig. 9). It is from feasibility study for establishment of Air Ventilation Assessment System. According to this, we can set up the air flow parameters in the CFD software tools for simulation.

Both building clusters are located beside the sea shore. There are several other residential buildings located to the north east and south west of Ocean View and Sausalito. There are freeways and railway to the south east. Ocean View, located in 77 Po Tai Street, is a private residential estate. The project, including a total of five buildings, was completed in 2003. Sausalito is also a private residential project similar to Ocean View (No.487, Sha Tin, Hong Kong). The building was completed in 2008.

As Fig. 12-14 show, in the situation of Sausalito, only a little turbulent air flow is generated at the rear region; a lot of turbulent air flow is generated which could be harmful to the surrounding public environment. So, compared with Ocean View, the convex-type layout like Sausalito is more favorable in regards to ventilation and wind environment.

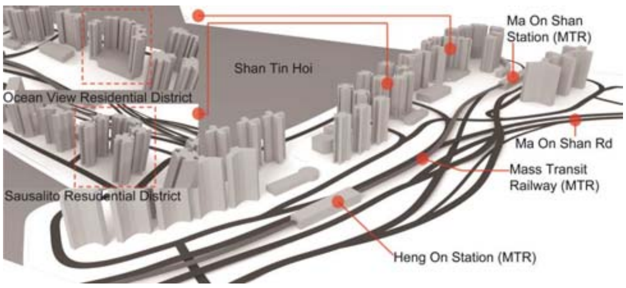

Fig.11. The study area (Ma On Shan, Sha Tin, New Territories, Hong Kong). There are a series of residential building groups along the sea shore

However, the CFD analysis figure shows that the west region of both residential districts is blue and extends a long way. According to the analysis, the convex-type velocity distribution is similar to the concave-type one in this case. Differences within these two types are rare. There are several reasons for this situation: (1) there are buildings (a car park, etc.) about 6 storeys high to the east of the Sausalito building group, while there are obstacles in Ocean View; (2) in the situation of Ocean View, the gaps between buildings are large; (3) the layout of the Residential District of Sausalito is not as well arranged as Ocean View, as some buildings are located in a line parallel to the wind direction. In practice, because of the uncertainty and complexity of the freestyle layout, the simulation outcome may not follow the principles completely. The principles we summarized are for ideal situations. For detailed study in practical projects, what is needed are case-by-case studies on certain issues.

Sometimes many other factors may affect the ventilation have to be concerned. The main two factors are the site topography and the buildings surrounds the objective architectures. Because they have great influence on wind flow. The influence leads to the change of wind directions, speeds and velocities attribution. Then it concludes a different pre-condition for objective building groups, compare to the ideal surroundings.

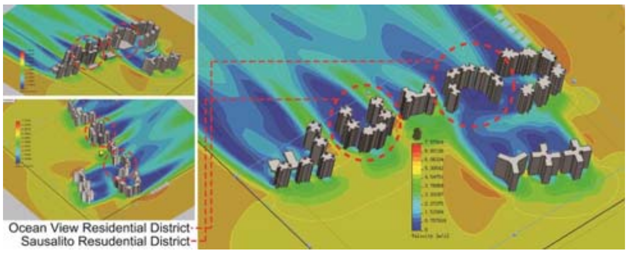

Fig.12. CFD Analysis of the entire area

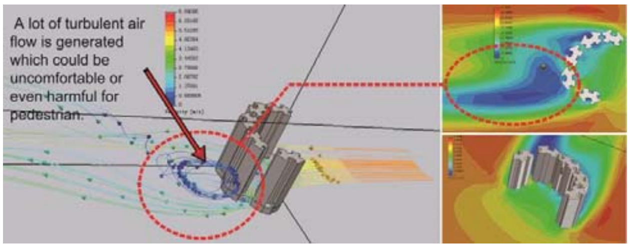

Fig.13. CFD Analysis of Ocean View District

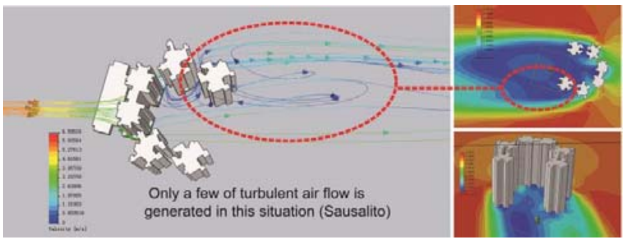

Fig.14. CFD Analysis of Sausalito Residential District

3. Conclusions

In this paper, the analysis of airflow and ventilation of non-standard curvilinear buildings based on Computational Fluid Dynamics (CFD) simulations has been presented and summarized. The Flow Simulation of Solidworks is well qualified for analysis. Further application in engineering has proved its potential helping with design in practical projects. In the third section, nonstandard and curvilinear shaped building arrangements are categorized and analyzed in respect to their performance of ventilation on street and mid-levels in the ideal circumstance. The simulation study concludes the principles that, for curved layouts, the convex-type in several situations have better performance in wind environment compared to the concave-type ones, especially in the uniformity of flow distribution, but also in rear region ventilation. To verify our principles, we did further case study of Sha Tin, Hong Kong.

Our findings show that curvilinear buildings lead to a more favorable ventilation environment since they have a smaller wind resistance. Non-standard curvilinear designs perform better in terms of general ventilation since the airflow around the buildings is faster and less turbulent. Based on these analysis cases, it is believed that in the curved plane group, using windward side to be the protruding part of the architectural community is more likely to lead to a favorable wind environment. Convex-shaped buildings have a better overall wind environment than concave-shaped ones. The foregoing examples have shown that convex layout type performs better in ventilation, illustrates that more uniform distribution of the air flow rate is faster, and less turbulent fluid is produced. It can be predicted that, to the situation in Hong Kong where its climate is usually damp and hot, when a building group has small wind resistance, the wind environment between buildings can be improved. According to our classification of various nonstandard curvilinear buildings that offer a general better airflow and ventilation due to their shape, it allows designer to understand quickly wind resistance, airflow, and turbulences that a non-standard curvilinear design has on the immediate environment.

4. References

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