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Quantitative Analysis of Height-Difference Ventilation in Residential Buildings: Application in Higher Education and Architectural Design in Shanghai

Lei Zhang[1], Xin Huang[2], Jie Zhong[1*], Hua Zhong[3]

[1] School of Architecture and Planning, Anhui Jianzhu University, Hefei 230601, China
[2] Department of Architecture, Tongji Zhejiang College, Jiaxing 314051, China
[3] School of the Built Environment and Architecture, London South Bank University, London SE1 0SW, UK

Corresponding Author Email: jiezhong@ahjzu.edu.cn

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ABSTRACT

This study investigates the ventilation performance driven by height differences in residential buildings within the Shanghai region, utilizing a quantitative experiment framework based on the Virtualwind (VW) platform. The research emphasizes the integration of a "wind performance-oriented design" (WPOD) paradigm, aimed at promoting sustainable architectural practices. A core objective of this research is to develop a robust set of quantitative control methodologies for height-difference ventilation, designed to streamline the traditionally complex and time-consuming process of case-by-case analysis into a series of precise and reliable wind performance metrics. These metrics are intended to be incorporated into the early stages of architectural design, functioning similarly to the control of sunlight spacing, and serving as critical guiding parameters that align architectural design with natural environmental factors. The WPOD approach is anticipated to optimize ventilation efficiency in residential environments, thereby enhancing the living conditions in densely populated urban areas like Shanghai. Additionally, the paper explores the application of the WPOD design paradigm in higher education, with a focus on its integration into architectural teaching curricula, aiming to equip future architects with the skills necessary to incorporate sustainable design principles into their practice. The results of this study are expected to provide a scientific basis for the development of architectural designs that harmonize with the natural environment, contributing to both the field of architecture and the advancement of sustainable living environments.

1. INTRODUCTION

In densely populated urban environments, the issue of ventilation has emerged as a critical concern. Given Shanghai's scarcity of land resources and its large population, the city's building density is exceptionally high. Within this context, exploring and implementing efficient strategies for indoor and outdoor natural ventilation holds significant practical implications for advancing the construction of low-carbon and ecological cities.

Recent research has indicated that Shanghai boasts a ventilation utilization rate of 35%, highlighting the immense potential and value of delving into natural ventilation technologies within the region [1, 2]. The wind environment performance of high-density urban blocks is primarily influenced by two major factors: firstly, the macro-level natural conditions, including the city's proximity to the sea and land, its larger-scale terrain features, and atmospheric circulation, which collectively shape the regional climate; secondly, the micro-level spatial configuration and terrain within the immediate neighborhood. Located on the middle and lower reaches of the Yangtze River Plain, Shanghai was formed by the alluvial deposits of the Yangtze River's estuary, resulting in a relatively flat terrain. Consequently, when designing and evaluating the wind environment at the urban residential level in Shanghai, the impact of external natural terrain is generally less significant, and the focus should instead be on the wind environment changes induced by the internal urban building layout, which are aspects that designers can actively adjust and intervene [3].

The primary task of evaluating the wind environment in high-density urban blocks involves studying how, based on the conditions and foundation of the larger-scale wind environment, to create a wind environment within and around buildings that meets human comfort requirements through rational urban block planning and building layout design. Additionally, this approach aims to support the reduction of energy consumption in heating and cooling systems by fulfilling the thermal comfort requirements within the built environment. The achievement of these goals will lay a solid foundation for constructing greener, more energy-efficient, and livable urban environments [4].

1.1 WPOD: A sustainable research paradigm of performance "intervention" design

Excellent architectural ventilation design is one of the key climate regulation strategies for building sustainable living environments. Residential wind performance is the ability of a residential building to naturally circulate indoor and outdoor air and meet the corresponding thermal comfort requirements without relying on active equipment. In the evaluation of outdoor wind environment performance, the main focus is on the wind environment comfort of public activity areas in residential areas and the impact of these areas on the surrounding urban wind environment. These two points constitute important indicators to evaluate the quality of outdoor wind environment [5].

As a residential design paradigm, WPOD aims to optimize indoor and outdoor wind performance [6]. This design paradigm mainly focuses on how wind performance analysis guides residential design itself, and the strategy of using active ventilation equipment to improve wind comfort is not discussed in depth in this paper.

An important application goal of WPOD research is to explore ways to establish an efficient link between wind performance simulation and building design, thereby avoiding the tedious process of complete scenario simulation. Its aim is to extract a guiding strategy, so that designers do not need to make repeated simulation adjustments, only with some relatively simple quantitative guidelines, you can have a more comprehensive grasp of residential wind performance design.

Existing studies typically involve specific Computational Fluid Dynamics (CFD) simulations for individual projects. This approach requires simulation for every necessary modification in each design project, which is time-consuming and requires the operator to have relatively high expertise and skills in wind environment [7]. Such skill requirements exceed the usual knowledge and skill range of architects, making it unfriendly and difficult to control for them [8, 9]. The research in this paper is a design method oriented towards a specific planning and design pattern of row housing in China. This method, tailored to specific meteorological parameters of a particular climate zone, summarizes and expresses the ventilation performance resulting from building height differences in a tabular form through pre-emptive CFD simulation experiments. Architects can directly obtain the general rules of ventilation resulting from building height differences during the early design stage of community planning and design by referring to the tables. This approach avoids multiple specific CFD simulation experiments for the design project [10].

At the theoretical level, this design approach has transformed the design workflow, overturning the traditional iterative design paradigm of concept design—software simulation—concept redesign—software re-simulation, and has established a new paradigm of WPOD that relies on a method of quickly consulting tables to obtain the patterns of ventilation performance due to building height differences. This new design paradigm offers several advantages at the application level: 1) Architects are typically not well-versed in the wind environment performance patterns of community design, and thus are unable to control wind environment performance in the early design stages. The WPOD design paradigm can assist architects in quickly understanding the ventilation performance patterns of height differences in specific climatic regions, thereby integrating the design concept of wind environment performance control into the early stages of design. 2) During the implementation of design projects, the application of the WPOD paradigm can save on the repetitive cycle of CFD simulation experiments, significantly reducing the design time cycle and associated costs.

1.2 Height difference ventilation: A study as a quantitative control indicator for green living

The quantitative experiment of residential height difference ventilation based on the VW platform is one of the main contents of the research on wind performance-oriented design of residential buildings in Shanghai. Research shows that in high-density residential environments represented by Shanghai, a large number of buildings at the same or similar heights will guide airflow across the upper parts of the building complex, making it difficult for the airflow to be directed between buildings, thus affecting the natural ventilation between buildings. cause negative impact [11-15]. The gradually ascending staircase design that follows the prevailing wind direction can effectively enhance the ventilation between the front and rear buildings (see Figures 1 and 2).

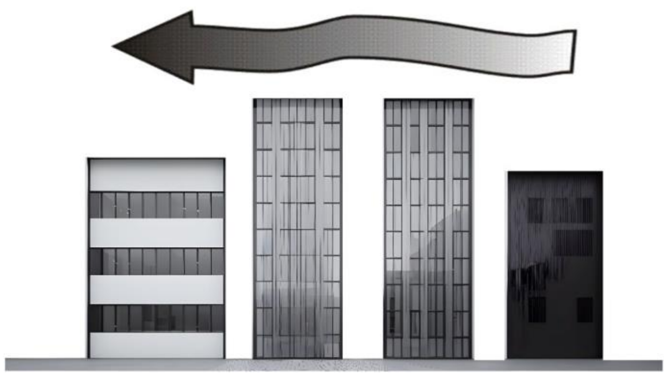


Figure 1. Airflow over the upper part of a building when the buildings are of similar height

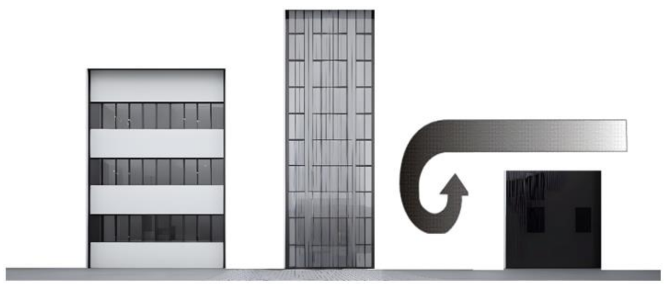


Figure 2. Downward airflow between buildings: Vector diagram showing downward airflow (arrows) after encountering taller buildings in the back row

Based on this principle, this study designed a set of quantitative guidance methods for wind environment in residential areas using the minimum height difference between adjacent residences as an indicator. The index control system for height difference ventilation draws on the current daylight spacing specifications to determine a method that combines quantitative guidance and special simulation analysis (for buildings with a height below 100 meters, the experiment gives quantitative indicators for height difference layer control;

higher than For a 100-meter building, special CFD simulations or wind tunnel experiments are required for the design plan to effectively control the wind environment of the residence [7, 16-27].

As the core part of this research, the following takes the row housing in Shanghai as an example to introduce the basic framework of CFD simulation experiments aimed at establishing a ventilation height difference index control system [20]. It should be pointed out that due to space limitations, the core of this article is to introduce and discuss the research methods and main experimental paths of wind performance "intervention" design. It is not intended to fully display the entire experimental results, so only some groups The data model illustrates the experiment.

2. QUANTITATIVE RESEARCH FRAMEWORK FOR RESIDENTIAL HEIGHT DIFFERENCE VENTILATION BASED ON VW PLATFORM

The research route of the quantitative method of height difference ventilation is to establish a set of simplified models of typical buildings and building groups, select appropriate experimental platforms for group simulation of typical models, and establish an exemplary data base through a large number of simulations and calibrations, so as to generate a more reliable critical index to meet the wind comfort of the green living environment, i.e., the minimum height difference of the building (in terms of the number of floors).

The quantitative study of high-difference ventilation is based on experiments. The following is a brief introduction to the experimental platform, the establishment of the experimental model, and a set of image data matrix as an example to introduce the output method of the quantitative index of wind comfort.

2.1 Experimental steps

With the previous wind environment simulation "results evaluation" function is different, the quantitative study of high difference ventilation is aimed at a large number of models in advance of the batch simulation, analysis, management, the complex and time-consuming and unstable results of the specific case study is simplified into a quantitative index of the wind performance, so that the wind performance, such as the sunshine performance, in a simple and easy to operate way "intervention" in the pre-design, become a "participatory" performance parameter. Wind performance, like sunlight performance, is "involved" in the pre-design stage and becomes a kind of "participatory" performance parameter.

The experiment is divided into three stages: model library establishment, experimental simulation, and batch processing of data. Specifically, it includes the following steps: Establishment of simplified model - Setting of airflow parameters - Group simulation - Result evaluation - -Matrix generation for quantification of height difference ventilation - Generation of minimum height difference index for ventilation - Analysis of results and strategy generation.

2.2 Experimental platforms

Due to the complexity of wind environment research, no single current platform can provide reliable and operable simulation experiments. Therefore, this study divided the simulation into three stages: CFD simulation, wind tunnel test and parameter verification. Among them, CFD simulation is the main experimental method and the basis for data generation, while wind tunnel experiments are mainly used for verification and CFD parameter correction. Due to the staged nature of the research, only a brief introduction to the CFD experimental platform is given below.

This experiment uses Virtualwind 2.1 software for simulation. Virtualwind's software development team is affiliated with the famous Canadian company RWDI. RWDI enjoys an international reputation in wind tunnel and wind power engineering and is a world-class wind engineering company. Virtualwind is an advanced simulation and visualization software that can be used to predict microclimate and wind environmental performance in a variety of environmental conditions, from low-density rural areas to medium-density urban suburbs to high- density urban core areas. Virtualwind not only provides a variety of simulation generators, but can also be used as a plug-in to directly connect with Google SketchUp software commonly used by designers, making Virtualwind very suitable for architects and planners. Like Ecotect software, which is widely used in the field of architectural design today, Virtualwind is a pre-design platform developed for architects and planners. Compared with professional software such as Airpak, Virtualwind is more in line with the working characteristics and usage habits of early designers, and is a good tool for architects and planners to carry out sustainable design in early design.

2.3 Basic airflow parameter settings

This experiment only examines ventilation conditions in summer. According to the meteorological data in the *Special Meteorological Data Set for China Building Thermal Environment Analysis*, in the experiment: the wind direction was selected as the maximum wind direction S (due south) in summer; the wind speed was selected as the average outdoor wind speed of 3.4m/s in summer; the rough environment type was Urban (Figure 3).

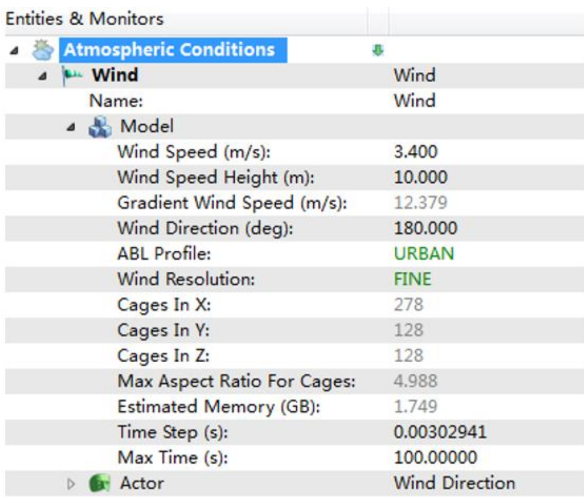


Figure 3. Virtualwind parameter settings [6]

2.4 Numerical modeling

Due to factors such as living habits and historical cultural traditions of the users, the planning and design of residential communities in China exhibit a strong characteristic of row arrangement. The vast majority of residential community planning and design in China adopts the row planning of parallel buildings [8].

The shape of new residential buildings in Shanghai is mostly slab- type, so the residential model is simplified to a rectangular volume in the experiment. The experimental model is two buildings in front and back. The incident wind direction is southward, and the south side of the house is the front row. In view of the requirement of preventing north wind in winter, this experiment only studies the case where the height of the building on the north side is greater than or equal to the height of the building on the south side, and does not consider the case where the height of the building is higher than the height of the building on the south side and lower than that of the building on the north side [7].

The parameterization of the experimental model dimensions consisted of the following 2 constants and 3 variables:

a) Constant 1: The angle between the wind direction and the building normal

Different building layout forms have different effects on the height difference ventilation. In this paper, we only give the quantitative guideline matrix when the building is facing north-south in the case of row-row layout, and the angle between the ventilation direction and the building's normal line is 0 degree at this time. This paper does not study the other angles of incident winds in rows and columns, as well as diagonal columns and angular layouts for the time being.

b) Constant 2: the depth of the residential building volume model

Through the collection and organization of common house plans, the depth of the residential building model is set to be 15 meters, which is similar to the depth of most newly-built houses. The depths of the front and back rows of the building volumes are kept consistent.

c) Variable 1: Width of residential building volume model

In the experiment, the width of the residential volume model is modelled at 15 meters, and four width values are set, namely 15 meters, 30 meters, 45 meters and 60 meters, which basically cover the range of common values of the total width of residential buildings.

d) Variable 2: Height of front row residential building

The height of the front row of buildings is set to vary from 10 to 100 meters in 10-meter increments, divided into 10 levels.

e) Variable 3: building spacing

The spacing between the front and back rows of residential buildings is set to vary from 10 meters to 50 meters in 5 meter increments. The building spacing is set with reference to the current Shanghai sunlight spacing standard. If the building spacing does not comply with the daylight spacing, the simulation will not be performed, and the final result matrix will be marked with "-". For example, when the building height of the front row is 20 meters, the residential building spacing of 10 meters and 15 meters do not meet the daylight spacing requirements and are not calculated in the experiment (see Table 1).

The experiments were divided into four large groups according to the width of the buildings (see Figures 4-7), corresponding to building widths of 15 m, 30 m, 45 m and 60 m. Each group was divided into 10 groups, corresponding to different front row building heights. Each group was divided into 10 subgroups, corresponding to different front building heights.

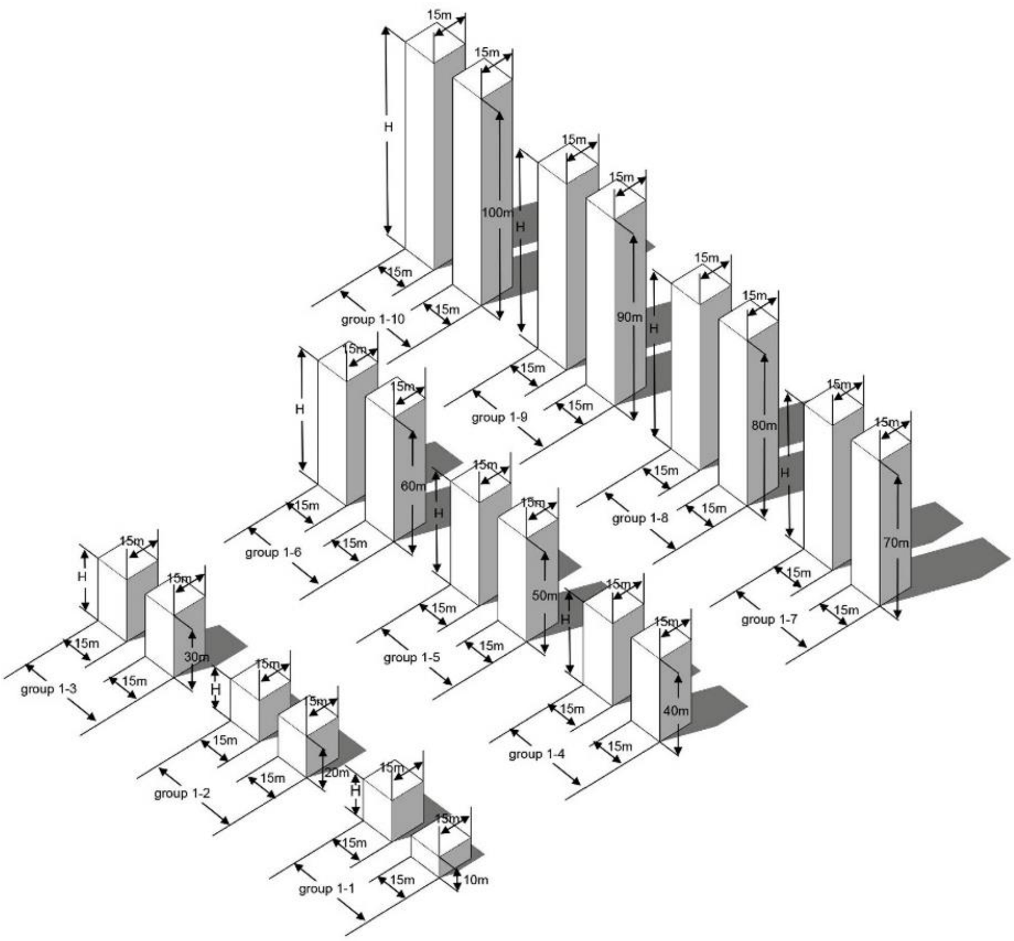


Figure 4. Schematic of the dimensions of the experimental model for group 1

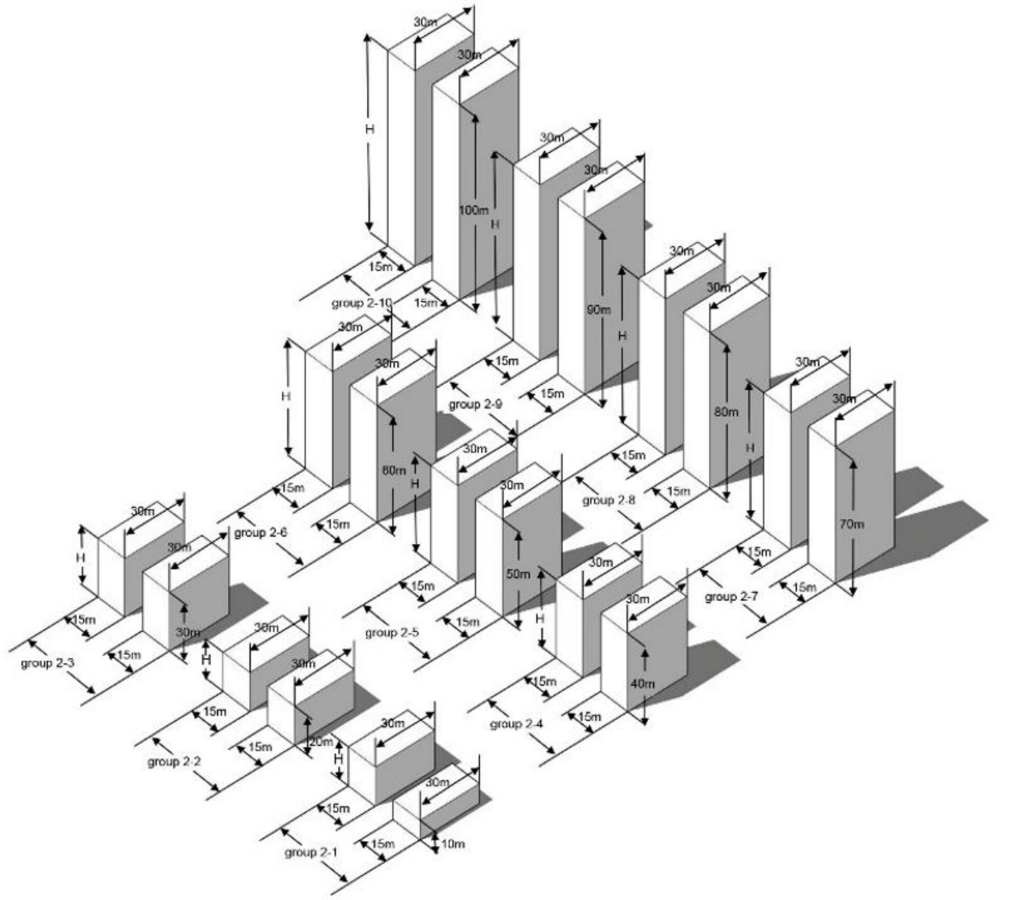


Figure 5. Schematic of the dimensions of the experimental model for group 2

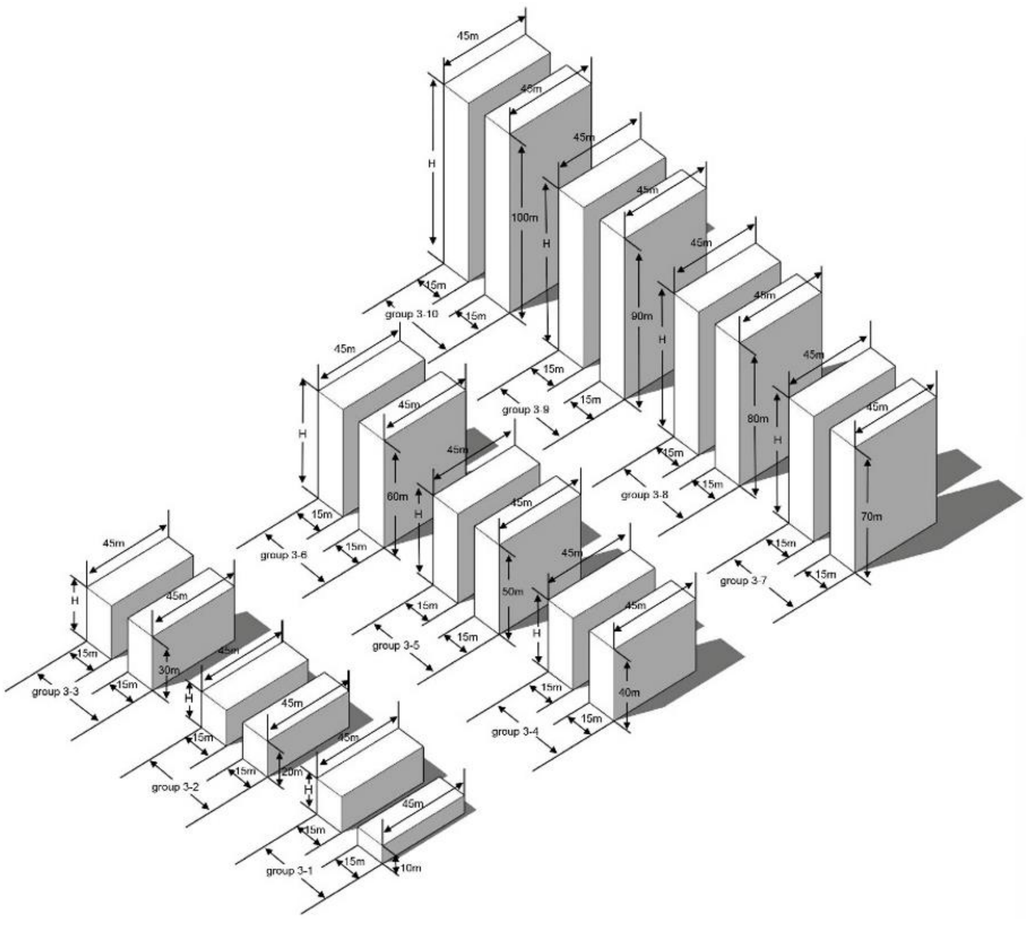


Figure 6. Schematic of the dimensions of the experimental model for group 3

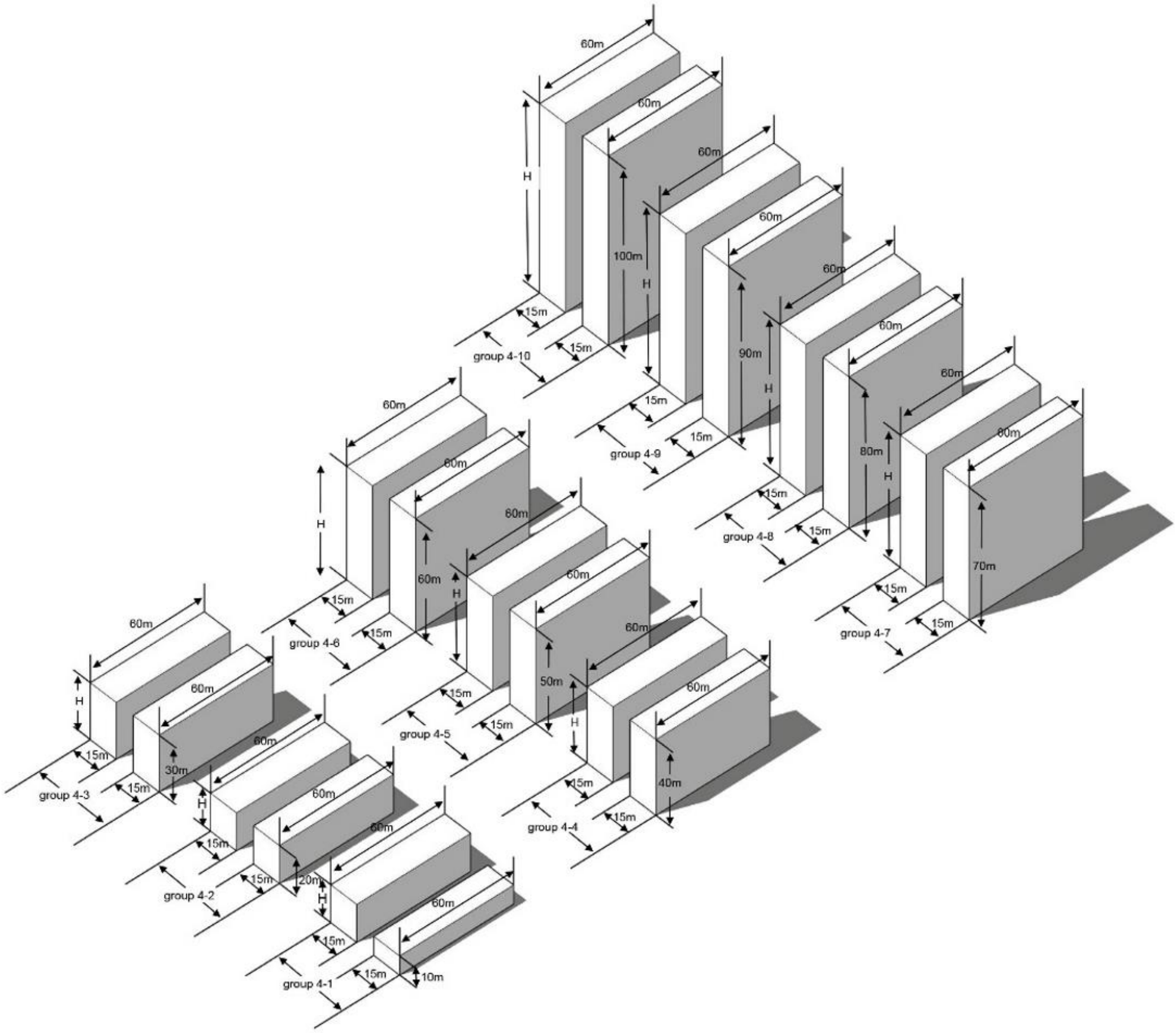


Figure 7. Schematic of the dimensions of the experimental model for group 4

Table 1. Parameters of the experimental model dimensions (Group 1)

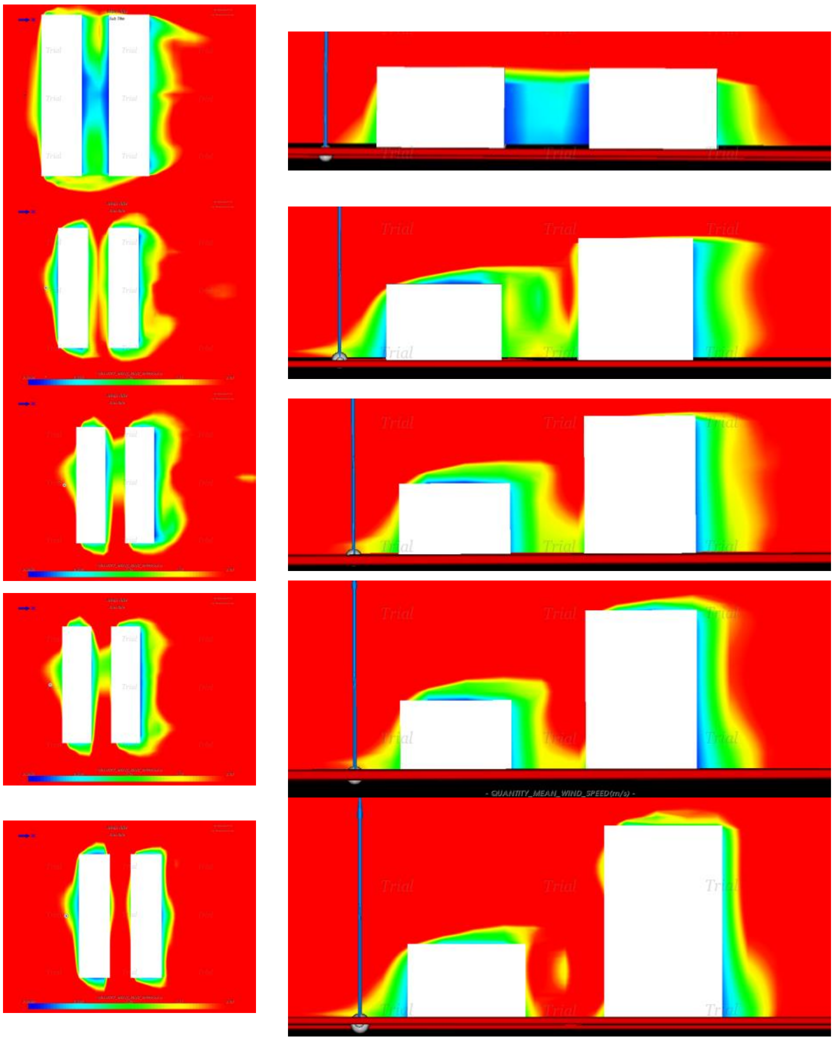
Constant 1	Constant 2	Variable 1	Variable 2	Variable 3	Target Parameter
Angle between the wind direction and the building normal (degree)	Depth of the residential building volume model (meter)	Width of residential building volume model (meter)	Height of front row residential building (meter)	Building spacing (meter)	Height-Difference (number of storeys)
0	15	15	10/20/30/40 50/60/70/80 90/100	10/15/20 25/30/35 40/45/50	

2.5 Output of quantitative residential wind comfort metrics based on minimum height difference

Virtualwind provides a variety of visual output modes, including color gamut diagrams, vector diagrams, etc. In order to clearly evaluate the simulation results, the result output in the experiment is in the form of a color gamut diagram, and the maximum value of the color gamut is set at 3m/s wind speed. At this time, the background color (red) indicates that the wind speed is greater than or equal to 3m /s area, and the remaining colors represent areas with wind speeds less than 3m/s. The criterion for judging the final result is set as a continuous 3m/s wind speed area on both the plane and the section [9].

The indicator control of the experiment is that the ventilation between houses should reach more than 3m/s. Since the ventilation goal of this experiment is to eliminate the enhanced heat island effect and reduced comfort caused by low outdoor wind speed, only a lower limit value of 3m/s wind speed under summer conditions was set. The discomfort and potential unsafety caused by the generally considered wind speed greater than 5m/s are not within the scope of this experiment and need to be studied separately [28-39].

Taking a set of experimental image data matrix with a width of 60 meters as an example (see Figure 8), it can be obtained that the model meets the minimum height difference of 5 storeys for wind environment control. Similarly, it can be derived from other heights and spacing in the same group of well-ventilated minimum height difference in the number of layer values (see Table 2, Figures 9 and 10).



The height of the rear building is the same as that of the front building

The rear building is 2 floors higher than the front building

The rear building is 3 floors higher than the front building

The rear building is 4 floors higher than the front building

The rear building is 5 floors higher than the front building

Figure 8. Simulated experimental images for buildings with width of 60 meters, a front building height of 10 meters and a building spacing of 10 meters

Table 2. The minimum number of height difference floors to meet the ventilation requirement of 3m/s when the building width on the south side is 60 meters (lower in the south and higher in the north)

Building Height / Building Distance	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
10m	5	--	--	--	--	--	--	--	--	--
15m	4	--	--	--	--	--	--	--	--	--
20m	4	4	--	--	--	--	--	--	--	--
25m	4	4	5	9	11	--	--	--	--	--
30m	3	3	5	6	9	9	--	--	--	--
35m	3	1	4	6	8	8	10	--	--	--
40m	1	0	5	7	9	9	8	--	--	--
45m	1	0	4	0	8	8	5	--	--	--
50m	1	0	0	0	8	8	3	2	0	0

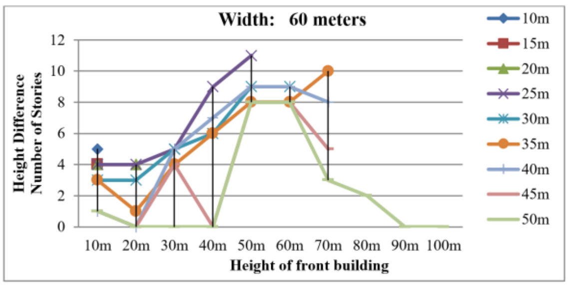


Figure 9. Height difference varies with the height of the front row building (The legend on the right shows the distance between the front and rear buildings)

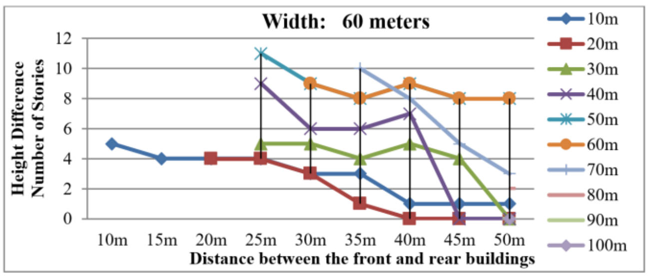


Figure 10. Height difference varies with the distance between the front and rear buildings (The legend on the right shows the height of front building)

When planning and designing residential areas, designers can look up tables to know what the minimum height difference between front and rear buildings should be to obtain relatively good outdoor wind environment performance. Urban planning departments can use this as a basis to proportionally control the outdoor wind environment. For example, new residential buildings are required to have more than 50% of the building meet ventilation height difference requirements. It should be noted that when the building height exceeds 100 meters, special CFD simulation experiments are required instead of table lookup to obtain the minimum height difference data.

3. APPLICATION IN HIGHER EDUCATION TEACHING

Residential buildings are a significant type of architecture in the Chinese design market. However, Chinese architects rarely consider wind environmental performance in their design work. Therefore, it is necessary to apply the WPOD design paradigm to the teaching of architecture courses in higher education institutions. Through such course teaching, students are taught to familiarize themselves with the principles and laws of wind environment performance, as well as its impact on architectural design. Furthermore, it helps students to consider more the impact of wind environment performance on residents in residential course design and future practical design work. The application in teaching can be carried out simultaneously in undergraduate and graduate courses. Undergraduate students in residential planning and design courses can master the changes in wind environment performance caused by building height differences through simple principle learning. In the course, graduate students can focus on learning how to simulate wind environment performance using software. The application of WPOD paradigm in the teaching of architecture courses in universities has a very positive impact on the sustainability of future built environments.

The WPOD design paradigm is suitable for residential planning and design courses for undergraduate students in their early years, helping them fully grasp the technical key points of carrying out residential community planning and design in China. Meanwhile, the WPOD model can also assist students in quickly mastering the wind environment performance of building complexes in urban design courses for senior and graduate students. These teaching sessions are aimed at helping students master the wind environment performance laws suitable for architects' technical characteristics without the need for tedious and technically demanding wind tunnel tests and wind environment software simulations. This new teaching model also faces some challenges. Firstly, this model places higher demands on teachers' abilities, requiring them to master the principles and techniques of the WPOD paradigm proficiently. Secondly, students need to spend more time acquiring relevant professional knowledge.

4. CONCLUSION

Shanghai is located in an area with hot summer and cold winter, so the wind environment research needs to take into account both winter wind protection and summer ventilation. Through the questionnaire survey and the reference to the related research in Hong Kong, this study concludes that the problem of wind protection in winter is not prominent in Shanghai, while the improvement of summer wind speed is the main topic of wind environment design in residential areas, which should be used as a controlling factor for the quantitative study of ventilation [40].

The study culminates in a numerical table that gives quantitative guidelines for the design of ventilation for residential height differences. The characteristics are as follows.

(1) Intervention in the pre-design stage. The intuitive parameter system (height difference ventilation) is intervened in the design conception stage in a way similar to the sunlight spacing specification, so as to change the current wind environment simulation only as a complicated, time-consuming and specialized means of checking in the design completion stage. Fitting the gap between wind performance simulation and traditional residential design.

(2) Intuitively simple and standardized. Through a large number of simulation experiments for the simplified model, a set of simple quantitative guidelines is finally formed, so that the design of the wind environment is free from the heavy physical simulation, and at the same time, it also avoids the confusion of experimental standards and results caused by the different experimental methods and means.

Due to design standards and other reasons, most Chinese urban residential planning and design are mainly based on determinants. Based on this situation, this new residential design paradigm is applicable to most Chinese cities. Different cities will have different meteorological conditions. When using the WPOD design paradigm, VW software can adjust parameters based on different meteorological data to complete CFD performance simulations for different cities, and then obtain a table of height difference ventilation performance laws applicable to local climate conditions.

This study has certain limitations. Due to limitations in research conditions and space, this experiment is only the initial stage of studying height difference ventilation control methods, and only examines the working conditions of two buildings with a single angle of incident wind. In the future, further research will be conducted on the arrangement of wind from other angles, such as oblique and angled layouts, as well as the performance of group wind environments.

Meanwhile, the application of the WPOD design paradigm in university curriculum teaching will cultivate more architects to pay more attention to the impact of wind environment performance and master the design techniques involved. This application will play a very important role in the sustainable development of the built environment.

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