A STUDY ON INDOOR NATURAL VENTILATION IN HIGH RISE HOUSING FROM THE PERSPECTIVE OF CARBON REDUCTION, SHANGHAI, CHINA

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By
Yuqing Han

DArch Committee:

Stephen Meder, Chairperson
Yiru Huang
William Chapman

Key Words: Residential Buildings, Natural Ventilation, Windows, Energy Consumption, Emission Reduction Effect

ABSTRACT

As a big country of carbon dioxide emissions, China's emission reduction situation is very grim, while the construction sector accounts for a considerable proportion of the country's carbon emissions. As a large number of residential buildings occupy a large proportion in the field of construction, the residential emission reduction has great potential and practical significance. Therefore, combined with the daily behavior characteristics of the residents in our country and the suitable temperature experience, to explore the relationship between indoor natural ventilation and energy saving and from low carbon perspective, and study the methods of optimal design of residential interior space from the perspective of carbon emission reduction, has become a research topic with urgency.

In this study, the residential area in Shanghai, which is located in the hot summer and cold winter zone in the Yangtze River Delta area, is taken as the research object. The main research methods are software simulation, empirical research, literature research and questionnaire survey. This study explores the influence of design factors such as location and size of doors and windows on the indoor natural ventilation of residential buildings. This study seeks to improve the design method of indoor natural ventilation, and to explore the relationship between indoor natural ventilation and residential energy consumption and carbon emissions in the whole life cycle. Based on this, the paper also tries to reveal the demand of residents for thermal comfort and the appropriate temperature range of thermal experience, and to study the correlation between energy saving, carbon saving and resident behavior.

The paper collects and arranges the previous theoretical research results that affect the natural ventilation inside the house. On the basis of that, the physical factors which affect the outside ventilation of doors and windows, which have the greatest influence on indoor natural ventilation, are selected as the object of study. First of all, it introduces the background, purpose and significance of the research, as well as the research questions, reviews and summarizes the relevant theories and literature, and discusses the relationship between the empirical data of building case and the energy consumption simulation data. Secondly, the paper studies the influence of exterior window changes on natural ventilation, including three aspects such as the location among the exterior doors and windows with the interior door, the different width of external doors and windows and the changes of summer outdoor natural wind flow direction. And it also analyzes the influence of the change of exterior doors and windows on building carbon emissions, including the annual energy consumption of building equipment system and the carbon emissions caused by the related outer structure materials. Finally, the dissertation has studied the influence of indoor natural ventilation on household emission reduction potential. This paper combines the results of the investigation of the residents' heat comfort behavior with the purpose of indoor natural ventilation, and uses the existing research results to simulate and estimate the related household behavior emission reduction potential. And it also gives the summary and outlook of this research.

This study makes a comprehensive evaluation and comparison of the conclusions drawn from the research in the fourth, fifth and six chapters. This study also concludes the potential and feasibility of this design approach to reduce the overall carbon emissions of residential buildings by natural ventilation in residential buildings.The result of the research shows that, through the natural ventilation design of residential buildings can not only create a reasonable natural wind environment and good quality of living in the cultural level, but also reflects the great potential in low carbon emission level. And, as far as possible, it can achieve relative balance in these two seemingly contradictory areas. It is hoped that through this study, we can further deepen the understanding of the good effects and importance of the natural ventilation of residential buildings to architects, real estate developers and government departments. At the same time, we hope that it can provide some reference for the future residents about the heat comfort experience and the relevant standards and design guidelines of the natural ventilation level of residential buildings. Taking into account energy-saving emission reduction at the same time to promote the quality of housing residents to optimize the promotion.

Key Words: Residential Buildings, Natural Ventilation, Windows, Energy Consumption, Emission Reduction Effect

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Chapter 1 | Introduction

1.1 Research Background

The factors that affect the carbon emissions and energy consumption of residential buildings in the whole life cycle are often determined by the design stage. Therefore, for the low carbon emission reduction of housing, at the beginning of design, only a relatively small effort, it is necessary to obtain a considerable cost at the end of the construction can achieve the effect. Under this condition, we should cultivate and strengthen designers' research awareness of energy consumption and carbon emissions in the process of design. In this regard, the design will have a profound impact on the various aspects of architectural design.

Currently, in the design of residential buildings in urban areas, architects often place emphasis on the requirements of people's living and living style for the design of functions and spaces within the single buildings. The rational research and calculation of typical residential design methods from the perspective of energy saving and low carbon emission reduction in China is not enough. Energy saving and emission reduction of residential buildings guided by architectural design is an important part of low carbon emission reduction in the whole society. So, starting from the perspective of carbon emissions to the living environment evaluation of residential buildings, revealing these design methods in relation to satisfy the people's living needs and to compare the energy saving and low carbon emission, is particularly important in the current society.

More worth mentioning is that as more and more industries begin to use the carbon footprint as a basis for judging sustainability, and the domestic and international carbon trading platform has gradually established, all of these changes are indicative of residential design concepts and standards must also be completed with the conversion of building carbon emissions. Therefore, taking into account the design of energy-saving at the same time from the perspective of low carbon emission reduction residential design methods to study is an important part to establish the existing evaluation mechanism and the link between carbon emissions.

Comprehensive analysis of typical residential ventilation design method of the mutual influence for social property, residential energy consumption and carbon emissions, qualitative analysis of the influence and significance of all aspects of the role, to explore how to achieve a balance between the quality of living and the pursuit of esidential energy-saving emission reduction, has a forward-looking significance to realize the development and transformation of residential design from the perspective of low carbon emission reduction.

1.1.1 The Status of Indoor Ventilation Design for Residential Buildings in China

After years of development, the research on the layout and spatial composition of residential buildings in our country is becoming rationalized and refined. For different size of residential units, the space organization in each room can also take into account the practical economic requirements. In recent years, with the continuous deepening of researches on residential buildings by major universities and design institutes in China, more and more optimized design methods for residential dwelling arrangements have been gradually formed and have their own systems for different climatic regions.

However, the mere consideration of spatial physicality while ignoring the user's experience of living in it is far from enough for residential buildings. With the rapid growth of world population, the city building density increases and the land resource constraints, some architects in residential design process, for the construction of energy-saving standard measures are often limited to research and enhance the physical properties of building material. Architects often use airtight designs and artificial air conditioning and ventilation systems. Although this reduces the energy consumption caused by the heat exchange between the external door and window openings, it also neglects the design for natural ventilation to a certain extent, resulting in a large number of indoor natural ventilation or indoor air turbulence is not suitable, prompting occupants tend to use mechanical ventilation ventilation, causing the deterioration of indoor air quality, and seriously affect the indoor thermal comfort environment. The resulting diseases such as Building-related Illness, Sick Building Syndrome and Multiple Chemical Sensitivity are not uncommon. [p1] The contradiction between the lag of indoor ventilation design and the continuous improvement of the quality of residential interior space will inevitably affect the overall quality of buildings and hinder the further optimization of residential experience. In fact, these defects in

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[1] Kuiting Wang. *"The Best Natural Ventilation [N]."* China Environmental News, 2004-12-17(6).

residential buildings can be addressed and compensated by improving or strengthening appropriate natural ventilation.

1.1.2 The Importance of Emission Reduction in Residential Buildings

In recent years, as the phenomenon of global warming becomes more and more serious, people have come to realize that reducing carbon emissions has become a major problem to be solved urgently in the world. To do this, many solutions have been put on the agenda, such as reducing the use of transport and replacing fossil fuels with clean energy. What is most surprising, however, is that in the total amount of carbon dioxide emissions, the construction sector in developed countries turned out to be the third largest contributor to greenhouse gas (GHG) emissions, before it is the industrial sector and the transport sector.

Figure1.1 The countries by carbon dioxide emissions in thousands of tonnes per annum

Source: https://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions

In the early 21st century, the architectural construction industry has gradually becomes one of the biggest energy consumption industries. A recent study shows that during the construction of buildings and the life of the buildings use, the architectural field took possession of more than half of resources in the global energy consumption—translating into 16 percent of the earth's freshwater resources, 30-40 percent of all kinds of energy supplies, and 50 percent of all of the raw and processed materials which is withdrawn from earth's surface.[2] Figure 1.1 illustrates the countries by carbon dioxide emissions in thousands of tonnes per annum, via the burning of fossil

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[2] Accessed July 15, 2016, https://global.britannica.com/art/green-architecture.

fuels all over the world. And the it also shows that China's carbon emissions are very large in the world. Therefore on this occasion, there is an urgent need of a new building type, which not only can meet the functional needs asked by people but also can reduce the emission of carbon dioxide.

Back in 2009, Premier Wen Jiabao made a commitment on behalf of China at the Fifteenth Local Conference of Parties to the UN Framework Convention on Climate Change held in Copenhagen, Denmark. By 2020, China's carbon emissions per unit of GDP will drop by 40-45% compared with the same period of 2005. Since then, China has consistently adhered to its commitment to implementing emission reductions. It not only officially became the IEA's Association Country in 2015 but also formally introduced carbon emission reduction into the national five-year development plan. All walks of life actively promote carbon emission reduction. In the already concluded "12th Five-Year Plan", it is the first time to include international cooperation in energy resources in China's five-year plan. In the 13th Five-Year Plan, China will also continue to practice this concept.

Figure1.2 Classification of CO_2 emission at construction stage in Shanghai

Source: *Theories and Methods of Low Carbon City Research and Shanghai Empirical Analysis*

Shanghai is an international metropolis and one of the fastest growing cities in China. As Shanghai's population continues to grow and urban density continues to increase, its demand for residential buildings is also on the rise. Data show that from 2000 to 2007, Shanghai's overall construction energy consumption increased at a rate of 10.2% a year, slightly lower than the economic growth rate. The total volume of CO_2 increased from 19,525,500 tons to 38,575,100 tons with an average annual growth rate of 8.6% (Figure 1.2).[3] This shows that the rapid economic growth with green and low-

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[3] Fei Chen, Dajian Zhu. "*Theories and Methods of Low Carbon City Research and Empirical Analysis in Shanghai*

carbon growth is of great significance to cities in Shanghai and even other rapidly developing cities in China where urbanization is accelerating.

Residential buildings and people's daily lives are closely related. In the current environment of increasing population, its energy consumption will also continue to grow. Under the increasingly serious problem of global warming, reducing the carbon emissions of residential buildings while improving human comfort is a necessary requirement to achieve low-carbon emission reduction and sustainable development in China and improve the global warming effect.

1.1.3 Transformation from Energy Consumption Perspective to Low Carbon Context

With the gradual establishment of carbon trading platform at home and abroad, more and more industries begin to use carbon footprint as the basis for judging sustainable development. From the perspective of energy consumption to the transformation of low-carbon context, the construction field can better adapt to the other industrial areas in carbon emission environment conditions. And, from the perspective of the life cycle of buildings, carbon emissions can show a very comprehensive assessment perspective, which can establish a more scientifically based green building evaluation system.

1.2 The Purpose and Significance of the Study

1.2.1 Research Purposes

The purpose of this study is to explore the natural ventilation of residences in the hot summer and cold winter area and how they affect the carbon emissions of buildings by acting on households from a low carbon perspective. As Christopher Alexander said in his book, "*Architecture Patterns Language,*" no architect can only consider an isolated factor in the design phase, but instead make a decision on a holistic perspective.

Similarly, when we are studying the issue of building low-carbon emission reductions, we can not just confine ourselves to an independent physical indicator of

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[J]." Urban Development Research, 2009, (10): 71-79.

"carbon emissions." Instead, we should integrate them completely with other factors, such as the living experience of residents Perhaps some design methods do not appear to be very beneficial to energy conservation and emission reduction in an intuitive way. However, in the long run, in combination with the concrete behavior of occupants, they will instead show their positive aspects in a dynamic process. The optimization of indoor natural ventilation in the design of windows is such a dynamic benign feedback mechanism. Its effect on residential low-carbon emission reduction is not the same as the problem - the balance of payments is the result, but after the combination with living habits and considering the residence time weighted, it will produce improvement effect for the residential building carbon emissions. More importantly, due to indoor natural ventilation condition is not only in isolation with carbon emission factors, it will bring the advantages of residential buildings can also be reflected in other aspects, such as improving indoor air quality and enhance the residents living experience etc. Although these are not directly related to emission reduction, they can bring better benefits from the perspective of Habitat, making the design of energy conservation and emission reduction more humane.

Based on this, this paper studies the effect of energy consumption and carbon emissions on indoor natural ventilation in typical residential buildings by combining the behavior habits of users with the results of preliminary simulation and quantitative analysis.

1.2.2 Research Significance

First, this study has some theoretical significance. In the past, the research on natural ventilation in residential buildings was often limited to simple correspondence of energy consumption. In addition to the traditional analysis of energy consumption, this study further translates into the natural ventilation design of residential interior and the multiple corresponding relationship of carbon emissions. Try to analyze its impact on carbon emissions in the light of its connection with residents 'social life and residents' thermal comfort experience. From a new point of view of carbon savings, we consider the improvement of natural ventilation effect of residential windows and the change of occupants' behavior under the condition of improved thermal comfort as well as changes in material and window-wall ratios that affect the building construction phase, changes in the energy consumption of construction equipment, and more. And then reveals the integrated results of the same design method in terms of energy conservation and carbon saving, finds out the relationship between these two aspects, and establishes the link between the energy and carbon saving of sustainable building.

Second, this study also has some practical significance. With the improvement of living standards, people in the pursuit of a more perfect living space with the function of style, but also pay more attention to improving the quality of living environment. However, as far as the present situation is concerned, the evaluation of indoor environment for residential buildings is seldom considered as a pre-design consideration, and the criterion of energy-saving evaluation is often only for meeting the green building assessment standards. Take China as an example, although some relevant codes have been introduced, many designers still do not know enough about natural ventilation simulation knowledge. If using computer simulation of indoor ventilation during the building design phase, the designer can properly adjust the unreasonable size and position arrangement of the outside windows to form a suitable indoor environment and take away the indoor heat load so as to reduce the building energy consumption. This study not only stays on the research of single ideal model, but analyzes the design elements and variables of different external doors and windows, combined with empirical test and investigation, concludes the indoor natural ventilation design method.

Finally, to bring residential carbon emissions into the early stages of the design phase, to give it a certain degree of foresight and control, to further allow residential building design based on human behavior needs to join the low-carbon emission reduction and other physical problems.

Indoor environment as one of the urban space environment closely related to people's life, the comfort level affects the quality of people's life to a great extent. A good indoor natural ventilation environment not only helps to improve the living environment and the quality of human life, but also conducive to improving indoor thermal comfort in the transitional season and hot season. Reasonable window arrangement can largely change indoor wind speed and wind turbulence field, which can greatly reduce the opening hours of air conditioners. It can also greatly reduce the air conditioning and cooling energy consumption of buildings, which is beneficial to the low carbon emission reduction of the residential buildings.

1.3 Research Scope and Research Content

1.3.1 Definition of Research Scope

In China's *"Civil Engineering Thermal Design Code"* (GB50176-2016) provisions, in order to meet the needs of thermal engineering design, the country is divided into five thermal areas. As shown in figure 1.3, respectively, they are severe cold area, cold area, hot summer and cold winter area, hot summer and warm winter area and mild area. Among them, hot summer and cold winter area has the largest area and the largest residential area, as shown in figure 1.4. From a national point of view, the climate is not the worst in the region. The summer outdoor temperature is slightly lower than that of the hot summer and warm winter area, and the winter outdoor temperature is somewhat milder than that of the cold area. Therefore, the hot summer and cold winter zone is designated as a non-heating zone in China, resulting in one of the worst indoor thermal environmental quality in the country.

Figure 1.3 China thermal partition diagram

Source: *Architectural Physics*

Figure 1.4 Residential area distribution map of different thermal zoning in China

Source: *Residential Energy Saving*

In recent years, with the continuous improvement of people's living standards in our country, the installation rate of air conditioners in that region is increasing year by year. Therefore, it shows that the research focus of this thesis is - to conduct effective natural ventilation guidance in the hot summer and cold winter area in order to improve indoor thermal experience and shorten the use time of air conditioning, which has great research potential and value.

Shanghai is one of the most developed cities in China and happens to be located in hot summer and cold winter area, so it is very representative of the study. Moreover, its economic growth rate is high throughout the country and even in the world. At the same time, the overall increase of building energy consumption in Shanghai is also very fast. Some studies show that its growth rate is only slightly lower than the economic growth rate. From this point of view, from the perspective of low-carbon energy saving, in order to improve indoor living quality as the goal of indoor residents in Shanghai to explore the thermal comfort and residential building energy-saving carbon issue is particularly important. Therefore, the scope of this dissertation is defined as the area of Shanghai in the hot summer and cold winter conditions in the Yangtze River Delta in China, and the natural ventilation design closely related to residents' daily life is selected as the main carrier for research and analysis.

1.3.2 Definition of Research Content

From the perspective of social development, promoting energy-saving design of buildings, especially residential buildings in the current society is the need to achieve the sustainable development of nature and society. But the building usually has been defined in its design phase of its energy and carbon saving effect and the ability to use renewable energy. Therefore, nowadays, architects often hope to take into account the premise of meeting the thermal comfort of occupants to maximize the use of renewable energy to adjust the indoor living quality. Quantitative analysis has done very little on how to make better use of natural ventilation to improve indoor microenvironment. In this study, after collecting, consulting and arranging the relevant documents, it is found that improving indoor natural ventilation is an important way to provide a good indoor thermal comfort environment as well as save energy and carbon emission.

Therefore, the main topics of this research include the following aspects:

1、The article will combine empirical data, and use the corresponding energy analysis software and CFD software for comparative analysis and simulation of a specific communities. Combined with the questionnaire survey in a large area of hot summer and cold winter areas and some actual measurements, we can summarize the status quo of ordinary residents' indoor natural ventilation and the suitable thermal comfort range. And in order to control the unity of the research factors, the indoor ventilation discussed in this study mainly focuses on the natural ventilation design of residential units, focusing on the selection of physical parameters related to the outer windows and doors as the main research object, not including the overall layout of residential areas and outdoor shelter factors and so on. In this study, we consider the survey results of occupants'behavior and combine with the previous research results of natural ventilation indoors in residential buildings. We will use CFD software-Fluent to compare with the numerical simulation method. Finally, the study is trying to obtain the optimal results of the indoor natural ventilation in the case building of specific community under the kinds of different design elements and physical variables.

2、Based on the appropriate outdoor windows improvements, the article will incorporate PKPM, the energy analysis software, and a product environmental statement for the building materials. The article will calculate the amount of carbon emissions that have been changed as a result of the improved design of the exterior doors and windows, such as to study the change of carbon emissions caused by the operation of the equipment system in order to maintain the constant environmental parameters during the building operation and maintenance phase; to study the change of carbon emission caused by the materialization and removal stages of the building envelope materials related to the research object, including the materials in the stages of production, transportation and construction, as well as demolition and recycling.

3、According to the appropriate measures for improvement of exterior doors and windows, the article will combine the findings of research on the thermal comfort behavior of residents and the findings of this study on the questionnaire on residential indoor natural ventilation and household behavior reduction. At the same time, the article will comprehensively analyze the potential of residents' behavior reduction produced by the improved indoor natural ventilation environment which can give residents suitable indoor thermal comfort experience.

To sum up, the problem (1) will be studied in the chapter 3 and 4 of this paper; problem (2) can be summarized as the physical impact of natural ventilation on the carbon emissions of residential buildings, which will be studied in the chapter 5 of this paper; problem (3) reflects the social impact of improved indoor natural ventilation on residential buildings and will be studied in Chapter 6 of this paper. The problems (2) and (3) comprehensively reflect the impact of this research project on the energy consumption of residential buildings, and the overall relationship between the changes in carbon emissions can be expressed as Formula 1.1:

$$\triangle E=\triangle E_{PHY}+\triangle E_{TCB}=\triangle E_{ESO}+\triangle E_{MPT}+\triangle E_{TCB} \qquad (1.1)$$

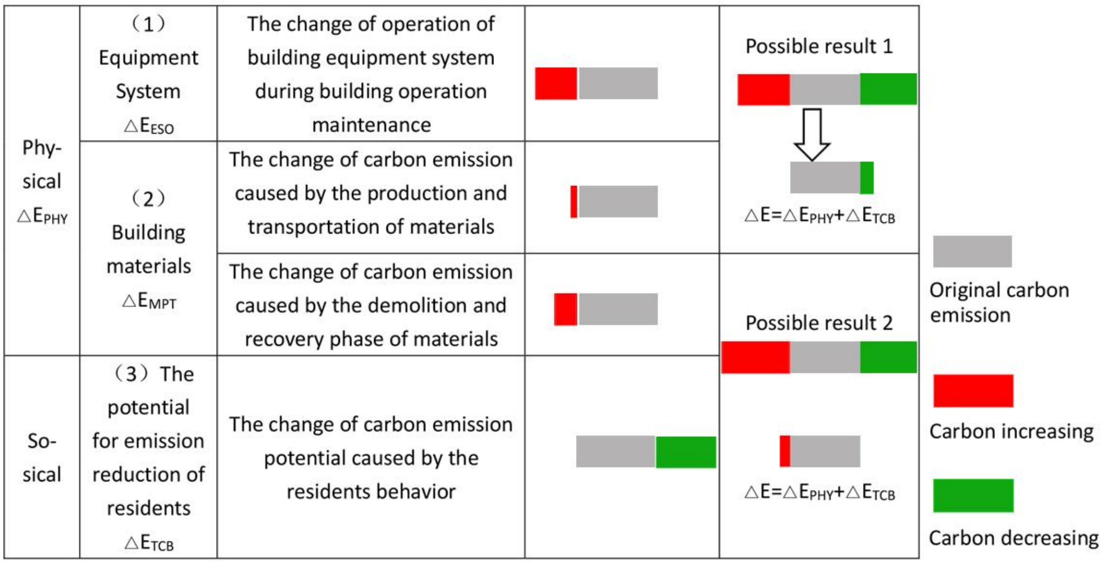
$\triangle E$ is the change of carbon emissions caused by changing the properties of residential windows(kgCO$_2$/ m^2);

△E$_{PHY}$ is the physical impact of window changes on carbon emissions of residential buildings(kgCO$_2$/ m^2);

△E$_{ESO}$ is the change of operation of building equipment system during building operation maintenance caused by the change of window(kgCO$_2$/ m^2);

△E$_{MPT}$ is the change of carbon emission caused by the change of window to relevant material production and transportation of external envelope(kgCO$_2$/ m^2);

△E$_{TCB}$ is the change of the potential of residents behavior emission reduction caused by the change of window by influencing the thermal comfort behavior of residents resulting(kgCO$_2$/ m^2).



Phy-sical △E$_{PHY}$	（1）Equipment System △E$_{ESO}$	The change of operation of building equipment system during building operation maintenance	🟥▨	Possible result 1 🟥▨🟩 ⇩ ▨🟩 △E=△E$_{PHY}$+△E$_{TCB}$
	（2）Building materials △E$_{MPT}$	The change of carbon emission caused by the production and transportation of materials	🟥▨	
		The change of carbon emission caused by the demolition and recovery phase of materials	🟥▨	Possible result 2 🟥▨🟩 🟥▨ △E=△E$_{PHY}$+△E$_{TCB}$
So-sical	（3）The potential for emission reduction of residents △E$_{TCB}$	The change of carbon emission potential caused by the residents behavior	▨🟩	

▨ Original carbon emission

🟥 Carbon increasing

🟩 Carbon decreasing

Figure 1.5 The matrix of 3 factors

Source: Author

In addition to studying above three problems with the qualitative analysis method, this dissertation will combine the quantitative calculation method to estimate the revenue and expenditure of energy consumption and carbon emission of residences after the design method of window is used, summarize the mechanism of the change of exterior window on above three factors as the conceptual relationship matrix, and finally make a summary and conclusion

1.4 Research Methodology

The purpose of this study is to explore the relationship between natural ventilation design and carbon emissions in residential buildings. The research methods used in this paper mainly include related theories and literature research, software simulation, data collection and integration, questionnaire investigation and empirical data integration.

(1)Related theories and literature research: the article mainly through a large number of access to relevant literature to understand the development of residential natural ventilation context and the research status quo at domestic and overseas, and summarize the factors affecting the indoor thermal environment suitable for living as well as existing achievements.

(2)Software simulation: because this topic will involve the simulation of indoor fluid environment CFD technology, so the paper will use fluid dynamics software-Fluent to simulate the indoor natural ventilation values. At the same time, the article will also use our independent research and development of energy analysis software-PKPM to model the case of residential buildings and simulate the overall energy consumption.

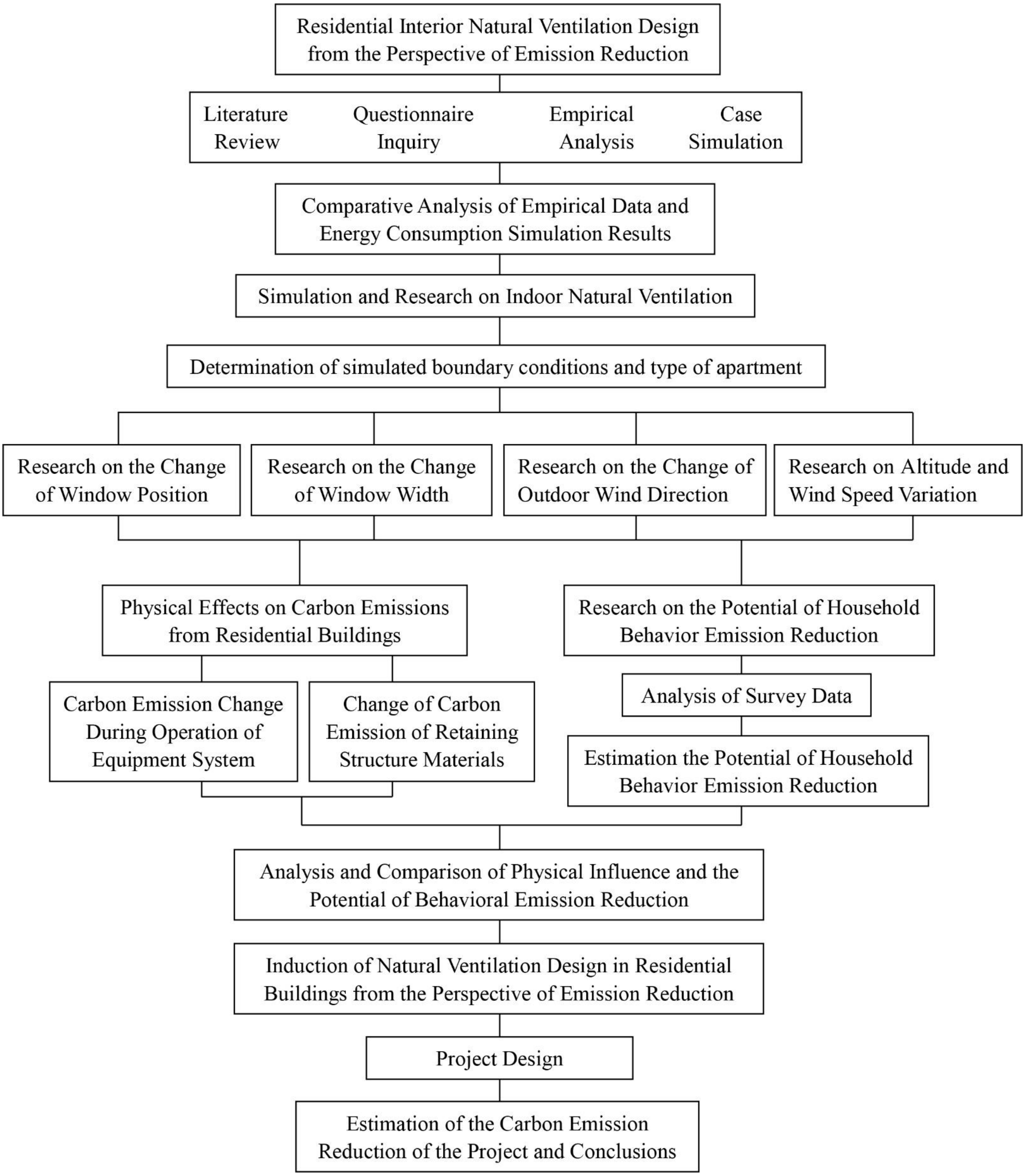
(3)Data collection and integration: the article mainly through the literature and various specifications to collect appropriate physical parameters related to the study of the indoor natural ventilation environment for reference, and collects relevant research results of household behavior reduction based on the thermal comfort experience of all kinds of suitable residents related to the research.

(4)Questionnaire investigation: based on the research object of this paper, the questionnaire of natural indoor ventilation design and residents' behavior habitat was designed, and were investigated to the community which the empirical data was conducted. It is used to collect the residents' behavior habits related to this research topic and make a comprehensive analysis based on the data collected to determine the more realistic and exact preference demand direction.

(5)Empirical data integration: by integrating empirical data of annual energy consumption of the corresponding case houses and analyzing the survey results, the article summarizes the real situation in the actual residential buildings as a support for emission reduction theory and also verifies the reliability and accuracy of the simulation software , draw the correction factor and then make the software simulation results more accurate.

In this study, the method of combining qualitative analysis and quantitative calculation was adopted to simulate and calculate the carbon emission benefits and expenditures after the optimization design of residential buildings with external windows and openings.

1.5 Research Framework



Chapter 2 | Theoretical Research and Literature Review

2.1 Study on the Theory of Residential Indoor Ventilation

2.1.1 Domestic and Foreign Research on Indoor Natural Ventilation in Buildings

There are many researches on indoor natural ventilation in residential buildings in our country. The earliest began in the 90s of last century, and since the twenty-first Century its association with green building and energy-saving environmental protection literature gradually increased. In 2003, Xiaowen Ma in the *"Shenzhen Residential Buildings in Summer Natural Ventilation Cooling Experimental Study"* article investigated the Shenzhen residential building in summer indoor thermal environment. She chose six kinds of buildings with different layouts as test objects, explored the outdoor climate and the temperature and humidity of the inner surface of the building envelope under different ventilation conditions, and analyzed the feasibility of using natural ventilation to cool residential buildings in summer. By comparing the strengths and weaknesses of both continuous and intermittent natural ventilation, she put forward the conditions for using natural ventilation to adjust indoor thermal comfort and where improvements should be made in architectural design. In 2003, Xiong Yongmei found out the proportion of the minimum window opening area for residential buildings in the hot summer and warm winter area to meet the indoor comfort through computer simulation in the article *"The Influence of Windows on the Indoor Air Quality in Natural Ventilation Rooms"*. In 2006, Wei Zhu put forward in his paper *"Indoor Environment and Natural Ventilation"* that the indoor thermal comfort environment formed by natural ventilation is conducive to residents' thermal experience. The influence of indoor natural ventilation on the indoor air quality and thermal environment was analyzed. The design strategy of using natural ventilation to improve the indoor environment of the building was explored and corresponding methods were put forward. The results show that reasonable natural ventilation can effectively improve the indoor thermal environment and air quality. In 2007, Kai Duan used CFD software to analyze the effect of indoors natural ventilation under different window-opening conditions in his article *"The Influence of Ventilation Position on Indoor Natural Ventilation Effect"*. The results show that if the location and size of the window are reasonable, it will have a good effect on improving indoor air quality and wind turbulence. In 2008, Fei Guo passed a simulation analysis of three typical floor plans in Shanghai high-rise residential buildings in his article *"Research on Design of Natural Ventilation and Energy-saving for High-rise Residential Buildings in Shanghai"*. The paper summarizes the influence of different planar layout on natural ventilation, and selects typical high-rise residential examples for natural ventilation simulation optimization design to further explore the natural ventilation is how to reduce building energy consumption, so as to achieve the goal of 65% energy saving reference. In 2009, Li Nan, in *"The Influence of Natural Ventilation in Residential Buildings on Indoor Thermal Environment"*, shows that even in cities with poor wind resources, rational use of natural ventilation in the design of residential buildings can not only save building energy consumption but also greatly improve the indoor thermal environment. In 2010, Wei Yin put forward the concept of "natural ventilation and energy-saving rate" in his article *"Research on Prediction and Energy-saving Evaluation Model of Natural Ventilation and Utilization of Buildings"*. Through the energy-saving evaluation of the model, he has been able to more accurately distinguish the ventilation effects quantified by different architectural forms, outdoor wind environment, climate zone, window size and orientation, and the different people's behaviors on opening the windows. It provides certain reference data for the initial plan of building, which is beneficial to the more extensive and effective application of indoor natural ventilation technology.

In 2011, Liang Wang, in his article *"Analysis of the Influence of Window Opening Mode on Natural Ventilation in a Home"*, showed that the window opening mode has a great influence on the natural ventilation inside a residential building. Through the use of different ways to open windows to restrict and guide the indoor air, indoor air flow can play a very significant role in the control. Using the method of analog comparison, he analyzed the influence of different opening modes of windows on the natural ventilation inside the building, and proposed the optimization scheme of the window opening. In 2012, Junli Zhou explored the effect of building windows on indoor natural ventilation through the use of Airpak software in her article *"Simulation of Building Opening Effects on Natural Ventilation and Building Energy Consumption"*. She used fluid dynamics software and *Design Builder* energy simulation software to analyze the impact of building openings on its energy consumption. Based on the typical annual meteorological data of Changsha, China, she analyzed the effect of window on the natural ventilation and energy consumption of the building indoor in different opening positions and orientations. Finally, based on the simulation results, a new comprehensive evaluation criterion for building design was put forward. Based on this criterion, different buildings were simulated and analyzed, and the optimal combination of building orientation and opening location was obtained. In 2012, Tianwen Yang used the CFD software to conduct a comprehensive simulation analysis of wind speed, wind direction, window position and opening size which are the key factors among the natural indoor ventilation in the article *"Research on the Optimization of Indoor Airflow Structure in Natural Ventilation Buildings"*. The results show that outdoor wind speed is most suitable between 1.3 and 2.5 m / s, and the best wind speed is 1.5 m / s; it is advisable to open windows in the middle of the wall considering the lighting and natural ventilation; appropriate reduction in the area of north-facing window openings of residential buildings is conducive to the formation of a good wind turbulence field in the naturally ventilated building; on the basis of ensuring that the buildings meet the energy-saving standards, appropriately expanding the south-facing window area is conducive to natural ventilation. In 2013, Ziling Xie used the building energy consumption software IES-VE to simulate the energy consumption of air-conditioners in a residential building in Wenzhou, China, in his article *"Analysis of the Correlation of Residential Natural Ventilation Energy Saving Rate and Its Window Opening Behavior"*. Because the behavior of the residents to open the outer window is controlled by the climatic parameters of outdoor temperature, wind speed and outdoor relative humidity, the outdoor temperature range which control outer window opened during the simulation is 26-28°C and the outdoor air humidity range is 80% 100%, the lower limit of wind speed control range is 0-1.5m/s. Through calculation and analysis, the natural ventilation can reduce the air conditioning energy consumption by at least 30%. The energy saving rate increases with the increase of the outdoor temperature and humidity upper limit when the window can open, and decreases with the lower limit of the wind speed.

In 2016, Danfeng He used CFD software to simulate the influence of building windows and indoors natural ventilation in residential buildings in a paper entitled *"The Study of the Influence of Building Opening and Facing on Natural Ventilation in Residential Buildings"*. He comprehensively analyzed the influence of window-wall ratio, wind direction (building orientation) and height of windowsill on the indoor environment of the building. Firstly, taking the wind speed, temperature, air age and PMV-PPD thermal comfort standards into consideration, the indoor microenvironment changes were explored and the best architectural design parameters were found. Subsequently, DeST software was used to study building energy conservation, which simulated the annual energy consumption under the optimal architectural design parameters and compared with the pre-optimization building energy consumption. The results show that the window design is most reasonable when the window-wall ratio is

0.3, the outdoor wind direction is 30 °, and the height of the windowsill is 900 mm. Under this condition, the indoor natural ventilation effect in the building can be greatly improved, and the living quality is improved. Indoor temperature is reduced by as much as 2.23 °C, and the annual energy saving rate of the building under this design parameter reaches 14.4%. His essay helps designers provide a reference to a rational natural ventilation organization as they carry out architectural graphic design. In 2016, Zhijuan Liu used the CFD software Phoenics to simulate the residential window and natural ventilation in Shanghai's Chifeng district in a paper entitled *"CFD simulation of wind and natural ventilation in a residential building"*. The results show that when the relative position of the outer window is constant, the larger the ratio of the openable window area to the open area, the higher the ventilation rate of indoor air, the smaller the total indoor air age; when the window ratio is maintained, the relative position of the outer window is larger, the indoor ventilation rate is almost unchanged, but the air age tends to decrease greatly; the change in the height of the windowsill has little effect on the indoor ventilation efficiency and the air age.

There are also many researches on natural ventilation in the world, and there has been a long history of research on natural ventilation outside China. Results are also more significant than those in China. It is mainly through the numerical evaluation of indoor thermal comfort. The earliest model used to judge the thermal comfort of building ventilation in foreign countries is the human body heat balance model. Richard J. Dear and Gail S. Bragger et al studied the indoor comfort of a total of 160 air-conditioned buildings and natural ventilation buildings and found that human thermal comfort response differs greatly between natural ventilation and air-conditioning. In the natural ventilation environment, the thermal comfort zone should be significantly wider than the air-conditioned environment, that is, under the conditions of natural ventilation, the human body can withstand higher indoor temperatures. And the air flow rate can also improve indoor thermal comfort, which can also be seen as a compensation effect of wind speed on the indoor temperature. Iftikhar A. Raja conducted thermal comfort tests on 15 naturally ventilated buildings in Aberdeen, England and Oxford. The results show that natural ventilation can indeed play a role in cooling. Compared with other indoor ventilation methods, the indoor ventilation can reduce the indoor temperature by about 1.5 °C due to the natural ventilation in the interior of the tunnel. Carrilho da Graca, Q. Chen, L.R, et al. Selected two homes in Beijing and Shanghai respectively for natural ventilation experiments. After doing a numerical analysis of human thermal comfort, they concluded that the maximum permissible wind speed in the room was 2 m/s.

2.1.2 Indoor Ventilation Development of Residence in China

With the continuous development of China's economy, living environment is more and more superior, the population is also increasing year by year. As the basic necessities of life and the population grows, the demand for residential buildings in the field of construction is also on the rise. With the escalating global energy crisis, all countries in the world have correspondingly introduced various types of energy-saving design standards for buildings in line with their respective national conditions. China also gives corresponding design standards for energy efficiency of residential buildings under different thermal conditions according to different climatic regions, as shown in Figure 2.1.

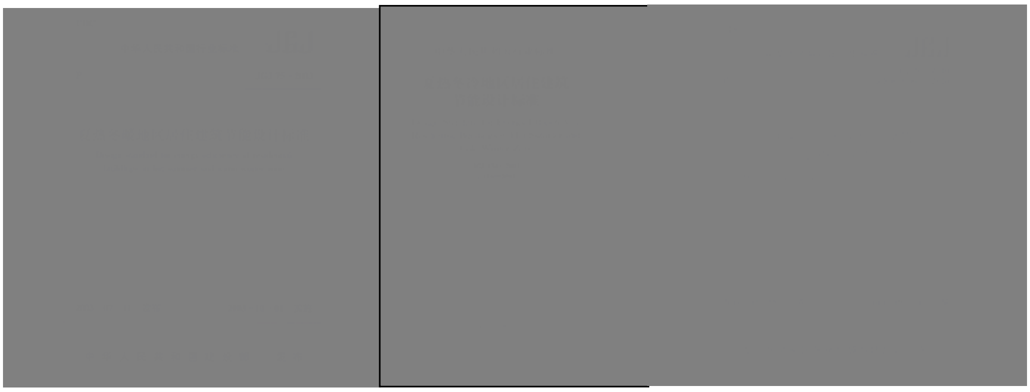


Figure 2.1 Energy-saving design standards for residences in different thermal zones in China

Source: https://baike.baidu.com

As people's living standards continue to improve, air conditioners, as household appliances that regulate indoor micro-climate, have seen their penetration rate rise year after year. Taking Shanghai as an example, the application of residential air conditioners is very common. According to the survey and analysis, the average number of air conditioners installed per household is 2.72, as shown in Figure 2.2. According to the calculation of an air conditioner in each room, at present, the installed capacity of residential buildings in Shanghai is 78.3%, and the proportion of energy consumption in residential buildings is very large.[4] In the meantime, it can be seen from the above analysis that in the transition season and the summer season, using natural ventilation to adjust the indoor micro-environment in residential buildings can not only reduce the great energy consumption compared with air-conditioned rooms, but also improve the

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[4] Shun Zheng, Xiang Zhou, Jingsi Zhang et al. *"Investigation and Analysis of Residential Air Conditioning Energy Consumption in Shanghai in summer [J]."* HKV, 2016, (03): 38-41.

indoor thermal environment and improve the living quality. However, as far as the current situation is concerned, the current status of indoor ventilation design in China is still not very satisfactory. The reasons for this are summarized as follows:

Figure 2.2 Air conditioning installation quantity proportion in Shanghai area

Source: *Investigation and Analysis of Residential Air Conditioning Energy Consumption in Shanghai*

(1)At present, the requirements of energy conservation norms for indoor natural ventilation just mentioned that residential buildings should deal with the organization of indoor air flow and improve the ventilation efficiency. There is no more detailed standard.

(2)There is not a standard that suits China's national conditions to evaluate the quality of indoor wind environment in residential buildings. Relying solely on existing single standards such as "health ventilation rate" or "indoor air age" can hardly accurately or appropriately measure the indoor ventilation environment under the combined effect of various factors.

(3)Although many international organizations have put forward standards related to the indoor ventilation environment,such as the ASHRAE standard proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, the ISO7730 international standard proposed by the International Organization for Standardization (ISO), and the Chinese standard *"GB 18049-2000-T PMV and PPD index for moderate thermal environment and thermal comfort conditions Provisions"*.These mentioned the criteria for judging the thermal comfort conditions of indoor ventilation. And these guidelines all try to judge and analyze four environmental variables such as air temperature, average radiation temperature, relative humidity, air velocity and two human variables such as human activity and clothing. However, the test population that formulates these standards is mainly Europe and the United States, which is not very suitable for Asian people with different living habits.

In summary, China's current development of indoor natural ventilation is not very satisfactory. In energy-saving design, architects often do not pay too much attention to the impact of natural ventilation on energy conservation. Mostly, they achieve energy-saving targets by strengthening the perimeter envelope. Therefore, it has become one of the important topics to improve the quality of living how to combine the daily behavior characteristics of residents and the appropriate feeling of thermal comfort to better explore the relationship between natural ventilation and energy conservation and emission reduction in residential interior from the viewpoint of low-carbon emission reduction.

2.2 Theoretical Study of Indoor Thermal Comfort Requirements

Human thermal comfort is the result of a combination of multiple influencing factors and can change as outdoor climate changes. In the 55-56 standard, ASHRAE defines a thermal comfort environment in which a person is satisfied with the state of mind. Thermal comfort usually refers to the people's sub-indifferent subjective feelings about the micro-environment in which they live. It is a subjective reflection of people under the combined effect of many influencing factors. It also involves a large range of influential factors. After extensive research both at domestic and overseas, the main influencing factors of human thermal comfort can be summarized into six categories, of which: four variables, air temperature, average radiation temperature, relative humidity and air velocity, are related to the environment; human activity, clothing thermal resistance of the two related to people.[5]

2.2.1 Two Perspectives on Thermal Comfort

In daily life, we often encounter many concepts, but we do not necessarily know its true meaning, thermal comfort is just such a concept. There is no point in terms of indoor thermal comfort environment, purely for the pursuit of its meaning, whether broad or narrow, essential or superficial. However, from a methodological point of view, only by clearly recognizing the true connotation of the subject to be studied can we appropriately select the appropriate research methods and methods. Therefore, it is

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[5] Yan Mao. *"Study on Climate Adaptability of Human Thermal Comfort [D]."* Xi'an University of Architecture and Technology, 2007.

necessary to discuss what is thermal comfort. Up to now, there are many kinds of explanations for thermal comfort, but in essence they can be divided into two categories: steady state and transient state. Steady-state view that thermal comfort and thermal feeling is exactly the same, in other words, neither hot nor cold (thermal neutral) is the thermal comfort. Of course, the effect of air humidity and wind speed will also be taken into consideration, but the thermal comfort in this environment refers to the feeling of being cold or hot. The transient view is that thermal comfort does not exist or remain in a stable state, only in the dynamic process is reflected, more specifically, thermal comfort is not a state but a process.

For example, when the body temperature is higher than the thermal neutral range, moderate cold stimulation will make people have a pleasant response. If you continue to maintain body temperature at this moment, then people's subjective thermal feeling will be in thermal comfort range. But this is from the steady-state point of view, from the transient point of view this is not a real sense of comfort, can only be called "undifferentiated thermal state." The above change process is shown in Figure 2.3:

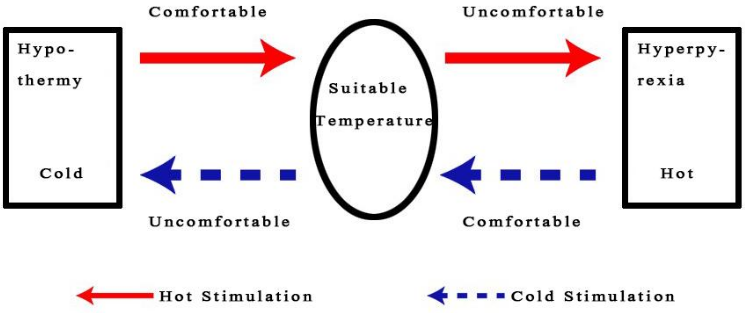

Figure 2.3 Different responses to hot and cold stimuli under dynamic conditions

Source: Author

However, we can also see from the figure that comfort and discomfort are alternated under dynamic conditions, in other words, comfort and discomfort are mutually exclusive. Discomfort is the premise of comfort, including expectations of comfort; on the contrary comfort is uncomfortable premise, contains the exclusion of discomfort, only from the comparison to understand what is comfortable. Therefore, from the transient point of view that the thermal neutral has been maintained in a steady state is unfounded, it can only be called a non-discriminating non-stimulating state. And from a hygienic point of view, some studies so far have shown the long-term concern that heat neutrality is beneficial to the human body and pointed out that the constant temperature in a room is actually detrimental to the health of the occupants.[6]

Although the current international mainstream view of human thermal comfort is the steady-state view, its discussion with the transient view is not over. Houghton, Yaglou, Gagge, Fanger et al., Who support the steady state viewpoints, and Ebbecke, Hensel, and Cabanac et al., Who support the transient viewpoints. Because the transient point of view is from a time and dynamic point of view, the concept is more focused on the relationship between process and state. For the purpose of this research topic, natural ventilation is a dynamic environment. It focuses more on occupants' behavioral feedback on the thermal comfort environment, and the research methods adopted are empirical, investigative and experimental simulations. This article therefore prefers the second transient view. For thermal comfort can not be an exact temperature or wind speed limit, but should be a suitable range of the boundary interval.

2.2.2 Analysis of Human Thermal Comfort Adaptability

Thermal fitness of the human body can be taken as the root cause of discrepancies between the thermal comfort laboratory simulation study and field measurements. In laboratory research, people are passive recipients of the environment. In the field of adaptive measurement, human social attributes are more emphasized and become the initiative to create their own favorite hot environment.

There are three parts of human body adaptive behavior: behavioral adjustment, psychological adjustment and physiological adjustment.[7] These three parts do not exist in isolation, work alone, but act together on the human body's subjective assessment of the thermal environment, as shown in Figure 2.4. Residents of the subjective feelings of the environment may be comfortable or uncomfortable, but after the technical adjustment of environmental elements and the behavior of individual elements to adjust to satisfaction. On the other hand, the thermal environment, local climatic conditions and social background that residents have been experiencing have a great impact on the expectation of thermal comfort. Physiological conditioning is based here on all physiological changes that occupants are acclimatized to when occupants are

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[6] A. Auliciems. *"The atmospheric environment: A study of comfort and Performance."* University of Toronto Press, 1972.

[7] Mingzhi Luo, Baihan Li, Jie Zheng. *"Human Body Thermal Adaptability And Thermal Comfort."* Refrigeration and air conditioning. 2OO5 (l): 75-78.

exposed to a hot environment; mental conditioning is a reflection of the organ's adaptive response to past thermal expectations. Thus, it is determined that the personal optimum comfort temperature values of occupants in different climatic zones are not the same. Among them, behavioral regulation plays a leading role in maintaining individual thermal comfort.

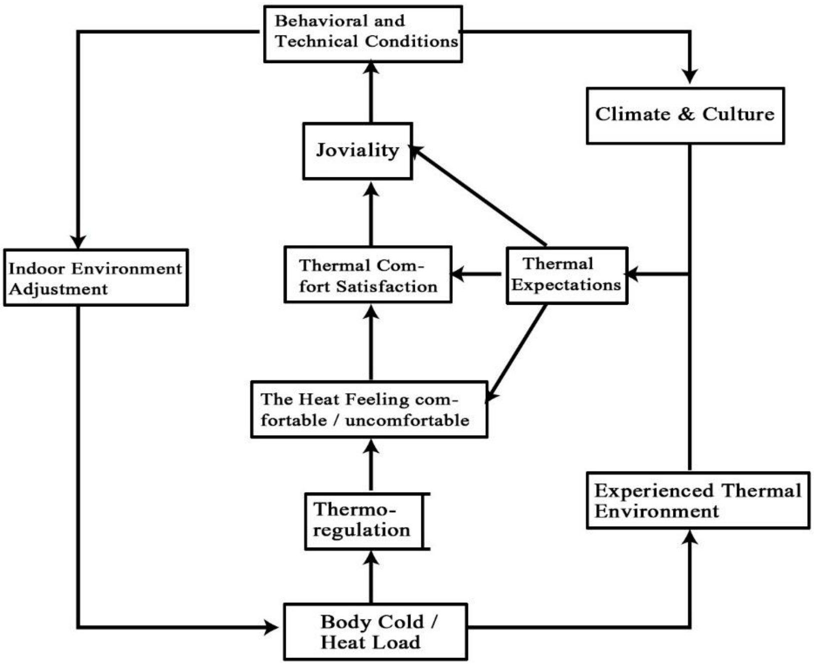

Figure 2.4 Mutual Mechanism of Hot Adaptive Behavior

Source: Author

2.2.3 Influence of Ventilation on Thermal Comfort

Studies have shown that increasing indoor air flow in residential buildings is one of the best ways to improve indoor thermal comfort in hot weather.[8] It tests the experimental population's perception of the air flow (DSV) and statistics them, and performs linear simulations at different natural ventilation rates (v) in combination with different outdoor temperatures. The regression equation results obtained are shown in Table 2.1. It can be concluded from Table 2.1 that all the P-values of the linear simulation equations are less than 0.05, so that there is a good correlation between the air-flow sensation (DSV) and the indoor ventilation rate (v). It can be seen that as the indoor temperature increases, the higher the indoor ventilation flow rate, the faster

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[8] Raja I A, Nicol J F, McCartney K J et al. *"Thermal Comfort: Use of Controls in Naturally Ventilated Buildings."* Energy and Buildings, 2001, 33(1): 235-244.

and more able to maintain the thermal comfort of occupants; in the case of low temperature, the body's sensitivity to wind speed is higher, in other words, the higher the temperature, the weaker the sensitivity to wind speed. [9]

Table2.1 Relationship between air flow and natural ventilation rate

[redacted]

Source: *Thermal Comfort and Adaptability of Houses in Hot Summer and Cold Winter Area*

2.3 Literature Research on Residents' Thermal Comfort Behavior

Through the above analysis of various types of literature and research, we can conclude that the basic standard for evaluating indoor ventilation in residential buildings is the indoor thermal comfort environment. Residents' adaptability to indoor thermal comfort environment can be divided into three categories: behavioral, psychological and physiological adaptation. Among them, the psychological adaptation is based on past experience or the expected value which has led to changes in the sensory response. Because of the vastness of our country, people in all climatic regions under different thermal conditions are different for indoor thermal comfort expectations or for environmental tolerance. Physiological adjustment process is the most basic and complex process in the body's adaptability to thermal comfort. The human body, as a complex organic entity, exchanges the matter and energy with the external environment without interruption in order to achieve a natural balance.

Therefore, this adjustment varies from person to person, depending on the individual's physical fitness and health, from the design point of view is difficult to simulate and control. And the individual's behavior regulation is the most important in

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[9] Wei Yang. *"Summer Residential Thermal Comfort Conditions and Adaptability in Hot Summer and Cold Winter Area [D]."* Hunan University, 2007.

the resident's thermal comfort adaptation behavior. Compared with the other two adjustment factors, individual behavioral research is also the only one that has the highest correlation with the design perspective, and can conduct data collection, recovery analysis and simulation studies.

2.3.1 Literature Study on the Influence of Ventilation on Residents' Thermal Comfort

In China, research on the impact of ventilation on comfort has been going on for decades. These studies mainly include two aspects: one is to study the cold ventilation of residents in the air conditioning environment; the other is the acceptability of the ventilation in indoor thermal comfort environment. The second case can also be divided into: occupants for random and uncertain indoor natural ventilation and the feeling of monotonous mechanical wind. In his article *"Subjective Investigation and Objective Evaluation of the Effect of Hair Dryer on Comfort"*, Qingxian Jia did a great deal of research and analysis on the different experiences of natural and mechanical wind across China. The results are shown in Table 2.2:

Table2.2 Subjective feelings of different ventilation methods survey results statistics

Source: *Subjective Investigation and Objective Evaluation of the Influence of Ventilation on Comfort*

It can be seen from the table that the preference of residents for natural winds is obvious. In the sample population, 88.3% of the people liked the natural ventilation. Compared to the cool environment with air conditioning, the number of people who choose electric fans is still 34.0% even for a bit hot environment. However, in the same environment, most people (84.0%) still choose natural wind instead of air-conditioned environment as long as natural wind exists. 79.0% of the surveyed people are inclined to "swinging and ventilating", that is, to change the direction of the ventilation of the fan, which is favored by the people. It is also unique to natural ventilation and one of the major differences from mechanical ventilation. From the above table, we can draw two conclusions: First, whether working or leisure, people tend to choose the natural wind environment, which is not only conducive to the health of occupants but also conducive to low-carbon energy saving; second, people feel great difference between natural wind and mechanical wind.

In his article *"Simulation of Natural Wind Research and Its Thermal Comfort Assessment"*, Jun Chen simulated the difference between natural and mechanical winds in terms of airflow characteristics and evaluated the thermal comfort of the sample population in both environments. He also used the form of subjective experiment tests and voting evaluation of questionnaires to evaluate the blowing sensation, thermal environmental comfort, thermal sensation index (TSV) and thermal comfort index (TCV) of different air supply modes. Its research shows that compared with steady mechanical wind, natural wind can better meet the wider thermal comfort for different people, and people are more willing to accept the simulation of natural wind and the dynamic indoor thermal environment formed by it.

2.3.2 Literature Research on Natural Ventilation and Thermal Comfort of Residents

In the article entitled *"Multi-solution Phenomenon and Potential Analysis of Building Natural Ventilation"*, through lots of subjective questionnaires and objective tests, Lina Yang analyzed in detail the potential of natural ventilation for hot summer and cold winter area to regulate indoor thermal comfort and its relationship with residents' thermal comfort. The most important of these is to analyze the outdoor temperature limits when using various types of ventilation equipment. These data reflect the natural outdoor temperature range that residents can adapt to as shown in Table 2.3:

Table 2.3 Outdoor temperature statistics using HVAC equipment

[redacted]

Source: *Multi-solution Phenomenon and Potential Analysis of Building Natural Ventilation*

As can be seen from the analysis in Table 2.3, the outdoor average temperature of the fan is 27.7 °C, while the average outdoor temperature of the air conditioner is 30.8 °C. From the data analysis in Figure 2.5, it can be seen that in summer, about 40% of the residents with a fan start using at 27 °C -29 °C, and 25% of residents use it at 29 °C -30 °C. For air conditioners, only about 13% of residents began using them before 29 °C. More than half of residents began to use air conditioners above 33 °C. Some 40% of residents used air conditioners above 35 °C.

[redacted]

Figure 2.5 Outdoor temperature distribution using refrigeration equipment in summer

Source: *Multi-solution Phenomenon and Potential Analysis of Building Natural Ventilation*

Table 2.4 Statistics of window opening time of main rooms in different seasons

[redacted]

Source: *Multi-solution Phenomenon and Potential Analysis of Building Natural Ventilation*

Tables 2.4 and 2.6 show the window-opening statistics of the main rooms of the surveyed units in different seasons. Statistics from the data shows that the living room window opening time is generally greater than the bedroom, the summer window opening rate is higher than the transition season, as well as the transition season window opening rate is higher than the winter. It can be seen that there is a great potential for enhancing summer natural ventilation in hot summer and cold winter area, and it does have a great impact on the thermal comfort of residents.

Figure 2.6 Probability of window opening time distribution of main rooms in different seasons

Source: *Multi-solution Phenomenon and Potential Analysis of Building Natural Ventilation*

2.3.3 Literature Study on Residents' Window Opening Behavior and Indoor Thermal Comfort Environment

Windows as one of the main components of the building, there is an important relationship between residents' window opening behavior and indoor thermal comfort status. In the article *"Hot Summer and Cold Winter Area, Summer Thermal Comfort and Residents' Windowing Behavior"*, Weihuang Chen analyzed the impact of different factors on the thermal comfort and window opening behavior of residents in both natural ventilation rooms and air-conditioned room rooms. It uses a Binary Logistic regression model to establish a model of residents' window opening behavior and linearly approximates the predicted value of the windowed probability to the actual survey. It is found that the predicted value of window opening probability is in good agreement with the measured value, which verifies the correctness of the simulation. At the same time, it also shows that residents' window behavior has a great relationship with indoor and outdoor temperature, and its window opening probability increases with the increasing temperature of indoor and outdoor temperature.

2.4 Relevant Theory and Reference Standards for Carbon Emissions

2.4.1 Carbon Emissions Theory and Related Standards in the World

In the field of carbon emissions, many developed countries in the world have already formed a variety of well-established and widely-used green building evaluation systems in many years of research and exploration. Through the continuous practice and exploration in actual projects, they have gradually formed the effective standard for measuring carbon emission status in the construction industry and have been gradually maturing. These existing research systems have provided strong theoretical support for this study. Currently, the most widely used carbon emission theoretical system in the world are *Green Guide for Healthcare (GGHC), Living building Challenge, Labs 21, CO_2 Balancing, Ecological Footprint, Natural Step, SB Tool from International Initiative for a Sustainable Built Environment (IISBE), Life Circle Assessment (LCA), LEED* in USA, *BREAM* in UK and *CASBEE* in Japan and so on.

In the field of international carbon emissions, the United Kingdom has been in a leading position. The British Standards Institute (BSI) holds a significant place in the international carbon emission standard. In October 2008, based on the international carbon emission standards such as *ISO / TS14048*, BSI released the *"Criteria for Public Access to the 2050: 2008 Life Cycle GHG Emission Standards for Goods and Services"*, making it the world's first carbon footprint standard. Based on this platform, the calculation method of building carbon emission basically eliminates the uncertain factors in the process of production, transportation, construction and recovery, and the calculation method is more clear and definite.[10] Two years later, BSI once again released the *Public Access Code 2060: 2008 Implementation of Carbon Neutrality Reference Specification*. PAS 2060 proposed that in order to reduce carbon emissions, in addition to reducing greenhouse gas emissions can take this approach, but also can be achieved through some means to offset the carbon emissions to achieve energy-saving emission reduction targets. For example, carbon neutralization and eventual carbon reduction can be achieved by introducing ways to offset residual greenhouse gas emissions.

The whole life cycle assessment system (LCA) is currently one of the most widely

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[10] Lei Zhang, Yiru Huang, Xin Huang. *"Building Life Cycle Carbon Evaluation Based on Standard Computing Platform [J]."* Huazhong Architecture, 2012, (06): 32-34.

adopted carbon emission assessment systems in the world. The LCA assessment system measures the environmental impact of a building's entire life cycle from production, transport, construction, demolition and recycling. At present, many building materials, building products and construction monomers have a full life cycle database. At the same time, the environment is also affected by many different factors and substances. For example, greenhouse gases that have an impact on *global warming potential (GWP)* may consist of a mixture of gases such as CO_2, CH_4, and CFC. Therefore, to facilitate calculation and research, LCA gives the equivalent conversion of CO_2 for each gas, and classifies all GHGs as CO_2 emissions as shown in Table 2.5:

Table 2.5 Centennial GWP of six greenhouse gases

[redacted]

Source: *Environmental Statement of Roofing Products*

The whole life cycle of the statistical methods for the understanding of carbon emissions is very favorable, making the impact of building products on the environment is no longer confined to the material production process. Because of this, *the whole life cycle theory (LCA)* not only applies to the construction field is also widely used in various other industries.

2.4.2 China's Carbon Emission Standards

China started its research on carbon emissions relatively late. The carbon emission standard in the construction sector is called *"Low Carbon Building Method" (referred to as LCBM)*. This is one of the ways to evaluate greenhouse gas emissions during the construction activity cycle. In addition, China also promulgated the *"Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment" (GB / T24040-1999)* in 2002, which is a translation of the *ISO 14040* series of international standards. Since then, on December 1, 2014, China's first *"Building Carbon Emissions Measurement Standards" (CECS374: 2014)* was promulgated. This standard is a combination of ISO international carbon emission standards and China's construction activities in the field of carbon emissions in the main features of the unit. This standard uses the whole life cycle theory of buildings to analyze the data of building carbon emissions and provides a theoretical basis for the data accounting of China's building carbon emissions. And because "building carbon emission measurement standards" has the credible data, the scientific calculation method and the concise calculation process, so it has high reliability and versatility.

2.4.3 Data Sources for Carbon Emission

This paper focuses on the impact of the design method of physical design optimization on the exterior window on the carbon emissions of residential buildings. It covers the entire life cycle of buildings, including the production, transport and construction of building materials, the using stage of construction equipment and the phase of dismantling and recycling of building materials.

(1)Sources of carbon emissions statistics for the production of building materials

In this part of the evaluation of changes in construction carbon emissions, from the above evaluation system, the database selected for this study is Athena LCA Software, which is widely used in the world one of the most credible carbon emissions evaluation system, which is one of the most widely used and most credible carbon emission evaluation systems in the world at present. It is a series of carbon emissions software developed by the Athena Sustainable Materials Institute in Canada, a not-for-profit organization in Canada. It mainly includes four kinds of software such as Impact Estimator for Buildings, Impact Estimator for Highways, EcoCalculator for Commercial Assemblies and EcoCalculator for Residential Assemblies. The EcoCalculator for Residential Assemblies selected for this study is software that evaluates the entire building and its components based on the LCA algorithm. This database covers the environmental impact of dwelling buildings over their entire life cycle, except for operational energy use during the use phase, ie the environmental impact indicators for the various phases including material production, transport, construction and eventual demolition and recycle .

(2)Sources of carbon emissions statistics for the construction phase of the building

Carbon emissions at the construction stage of a building mainly include the transport energy consumption of materials transported to the construction site and the carbon emissions from the operation of construction machines when the building materials are assembled. And the transport energy consumption of materials transported to the construction site is relatively important at this stage. Carbon emissions from the operation of construction machines when building materials are assembled is not easily estimated due to the different types of construction equipment they are used in, so is often omitted. The carbon emissions from the transportation of construction materials can be calculated in the EcoCalculator for Residential Assemblies.

(3)Sources of carbon emissions statistics for using stage of the building

Often, the sources of carbon emissions from the use of buildings mainly include the lighting, HVAC and household appliances, and eventually the amount of electricity they consume to the equivalent amount of carbon emissions. The data of greenhouse gas emissions from residential buildings that are required by this study to maintain the specifications at their own operating stage are obtained from PKPM, a building energy analysis software developed by the China Academy of Building Research. Considering that the software only simulates the energy consumption of the building air-conditioners in the ideal room, during the heating and air-conditioning periods. However, in fact, due to the different habits of individual living in households, coupled with the complexity of energy consumption caused by air conditioning, lighting and various household appliances in buildings, the actual case of building carbon emissions during heating and air conditioning period should be some differences between software simulation results. Thus, this study will compare the results of the original energy consumption of residential houses simulated by the PKPM software with the empirical data below to obtain the correction coefficients to correct the calculated values of the simulation software so as to make the simulation results more realistic and accurate.

(4)Sources of carbon emissions statistics for the dismantling of building materials

The calculation of the change of carbon emission in the dismantling phase of the building involved in this study mainly includes the carbon emissions from the operation of construction machinery when the related building materials are dismantled and the transportation energy consumption of materials transported to the treatment plant. Similarly, the transport energy consumption of materials is relatively important at this stage, and the carbon emissions from the operation of construction machinery at the time of dismantlement of construction materials is also not easily estimated due to the different types of construction machinery used, so is usually omitted. The carbon emissions from the dismantling of building materials can also be calculated in the EcoCalculator for Residential Assemblies.

In addition, this study also included the potential for abatement of residents caused by changes in residents 'behavior caused by changes in exterior windows and doors, such as changes in residents' use of summer air conditioners. This study seeks to examine the impact of natural ventilation in residential homes on carbon emissions from a relatively macro perspective.

2.5 Chapter Summary

Through the study of this chapter, it can be seen that the full use of indoor natural ventilation in residential buildings is of great significance to the low-carbon emission reduction of buildings and its research and development potential is also huge. First of all, this chapter combs the development of the natural ventilation design method. Residential interior natural ventilation has been a product of the interaction between residential needs and architectural design since ancient times. And with the continuous reduction of the world's natural energy, the issue of building energy saving and emission reduction gradually becomes a key link in the architectural design phase. Because of the huge potential of natural ventilation for energy saving and emission reduction, it has been more widely concerned and applied in China. Even today, although the importance of natural ventilation is self-evident, there is still a lack of application of its evaluation system and specific design methods in the early stages of architectural design.

Afterwards, this chapter starts with the demand theory of indoor thermal comfort and expounds the best judgment factor as the relationship between indoor natural ventilation and residents' indoor experience. And summarizes the criteria for evaluation. It is open to discussion for the existing control boundary (eg indoor summer of 26 °C and winter of 18 °C), and its boundary control limits (such as temperature and wind speed) should also be a suitable boundary range , not a temperature point or wind speed limit value.

Subsequently, this chapter begins with the relevant literature about the residents' demand for thermal comfort experience, and reveals and elaborates a series of human demand theories for indoor thermal comfort environment. These needs are related to the adjustment of human mind, physiology and behavior. Based on the previous studies on the relationship between residents' fenestration and indoor thermal comfort, it can be seen that the change of natural ventilation in residential buildings caused by the change of exterior doors and windows has a great potential for reductions in thermal comfort among residents. This is also the key entry point of this thesis. This article also introduces the related literatures about resident fenestration and indoor thermal comfort environment The purpose of this study is to find out whether the indoor ventilation environment in residential buildings can be improved by improving the physical properties of exterior doors and windows. Which in turn can create an indoor thermal comfort environment that meets the residents' needs for thermal comfort so as to achieve the objective of enhancing the low-carbon emission reduction effect of residential buildings.

Finally, the chapter reviews the theory and measurement of carbon emissions involved in this study, paving the way for the subsequent calculations of carbon emissions and expenditures. In summary, the literature theory in this section lays a theoretical foundation and feasibility for the study of the physical factors of external doors and windows changes, the indoor natural ventilation unit involved in carbon emissions and the emission reduction effect of residential buildings. At the same time, the connection and influence between natural ventilation and residents' thermal comfort and carbon emissions can also be fully recognized.

Chapter 3 | Case Study Based on Empirical Analysis and Energy Consumption Simulation

This chapter will utilize the energy consumption analysis software PKPM to simulate annual energy consumption of the building, but according to the limitation of simulation software, the result is calculated under the completely ideal situation and many influence factors are neglected, especially for daily living habits of residents. To get close to reality and obtain more accurate result, this chapter will combine with actual electricity consumption and actual household evaluation to do empirical detection and study for the simulated cases, trying to explore the internal relation between daily consumption of architectural equipment system and daily living habits of residents.

3.1 Basic Information of Case Building

Based on the above-mentioned chapter, Shanghai in hot summer and cold winter thermal zone, located in the Yangtze River Delta Area, is defined as the research object for study and discussion. As the central city of the Yangtze River Delta Area, quality of the residential building in Shanghai increasingly becomes the focus of attention. Meanwhile, as an important means to improve residential quality, suitable indoor natural ventilation is also concerned. On the basis of the existing data collection and investigation, this study selects the drawings of existing residences and energy-saving calculation sheets in Shanghai, as well as three highly identical residential buildings as the research objects for software simulation and calculation analysis. The three selected case buildings are respectively located in: ① Songjiang District, Shanghai; ② Putuo District, Shanghai; ③ Putuo District, Shanghai.

The construction of the case was from 2009 to 2010, and their construction drawings and corresponding energy-saving calculation sheets have referred to relevant documents used by the design units in practical engineering. Now, the basic information of case buildings are summarized as follows:

The Case 01 is shown in Table 3.1:

Table 3.1 The basic information of No.10 building in a residence community in Songjiang District, Shanghai

Location	Shanghai(31.31°N，120.61°E)
Thermal Partitions	Hot summer and cold winter zone
Building Orientation	South
Structure Tyoe	Brick-concrete structure
Shape Coefficient	0.41
Building Area	3167.25m^2
Building Volume	9212.25m^3
Building Surface Area	3792.62m^2
Building Storey	7 (Including the closure layer)
Number Of Households	24
Storey Height	2.90m
Building Height	20.30m
Exterior Wall Construction (From Outside To Inside)	Cement Mortar (20.0mm) + Powder Polystyrene Particle Slurry (50.0mm) + ALC Aerated Concrete Block 240 (240.0mm) + Cement Mortar (20.0mm)
Exterior Window Structure	Insulated Metal Profile Low-E Multi-chamber Sealing Window(6+12A+6)
Window-Wall Ratio	East 0.06; South 0.35; West 0.08; North 0.28

Source: Author

It can be observed from Table 3.1 that the Case01 building is located in Songjiang District, Shanghai. It is the mid-tall storey housing with 7 floors (including a unreachable roof). The structure is the brick-concrete structure. The overall floorage is 3167.25m^2.

The Case 02 is shown in Table 3.2:

Table 3.2 The basic information of No.7 building in a residence community in Putuo District, Shanghai

Location	Shanghai(31.31°N，120.61°E)
Thermal Partitions	Hot summer and cold winter zone
Building Orientation	South west 4.1 °
Structure Tyoe	Shear wall structure
Shape Coefficient	0.33
Building Area	4699.35m^2
Building Volume	13628.12m^3

Building Surface Area	4489.00m^2
Building Storey	15
Number Of Households	28
Storey Height	2.90m
Building Height	43.50m
Exterior Wall Construction (From Outside To Inside)	Cement-Based Composite Insulation Mortar (W Type) (30.0mm) + Reinforced Concrete (200.0mm) + Cement-Based Composite Thermal Insulation Mortar (L Type)
Exterior Window Structure	Aluminum alloy general hollow glass window(5+6A+5)
Window-Wall Ratio	East 0.03; South 0.35; West 0.03; North 0.31

Source: Author

It can be observed from Table 3.2 that the No.2 building is located in Putuo District, Shanghai. It is the high-rise housing with 15 floors. The structure is the shear wall structure. The overall floorage is 4699.35m^2.

The Case 03 is shown in Table 3.3:

It can be observed from Table 3.3 that the No.3 building is also located in Putuo District, Shanghai. It is the high-rise housing with 13 floors. The structure is the shear wall structure. The overall floorage is 3442.17m^2.

Table 3.3 The basic information of No.6 building in a residence community in Putuo District, Shanghai

Location	Shanghai(31.31°N，120.61°E)
Thermal Partitions	Hot summer and cold winter zone
Building Orientation	South
Structure Tyoe	Shear wall structure
Shape Coefficient	0.39
Building Area	3442.17m^2
Building Volume	10451.11m^3
Building Surface Area	4119.31m^2
Building Storey	13
Number Of Households	26
Storey Height	The first floor is 4.20m, others are 3.00m
Building Height	41.40m
Exterior Wall Construction	Cement Mortar (20.0mm) + EPS (P = 18) (30.0mm) + B06 Aerated

(From Outside To Inside)	Concrete Block (200.0mm) + Cement Mortar (20.0mm)
Exterior Window Structure	Insulated aluminum alloy Low-E insulating glass window(6+12A+6)
Window-Wall Ratio	East 0.05; South 0.35; West 0.05; North 0.35

Source: Author

According to regulations in the Code for Civil Building Heat Design GB50176, Shanghai is located in the hot summer and cold winter zone. The average temperature in the coldest month of winter for years in succession is 0-10°C, while the average temperature in the hottest month of summer is 25-30°C. Hence, the residential buildings in this climate zone must meet summer thermal insulation requirements and give consideration to water heat preservation. To have the definite requirements in the thermal climate zone is the precondition that this study accurately and mechanically applies relevant design standards.

3.2 Introduction to Energy Consumption Simulation Based on Case Building

3.2.1 Introduction to Relevant Regulatory Requirements

The mode of construction and area in external envelope structure of buildings, as well as shape of buildings determine the energy brought by climate changes and energy consumption of changing internal energy into refrigeration and heating. The external envelope structure of buildings will accept lots of thermal radiation energy in summer to bring energy load for refrigeration. Similarly, thermal radiation energy of the external envelope structure in winter also results in energy load of indoor heating. Moreover, the human behavior style and the external envelope structure of buildings determine gains and losses of heat in ventilation process. As refrigerating in summer and heating in winter, the envelope structure will warm or cool indoor air, for the sake of balancing the temperature difference between indoor and outdoor. The energy load will be slightly reduced when the indoor is deserted. For purpose of greatly studying the relation between the building energy consumption and building shape, Depecker proposed the building shape coefficient—the specific value between buildings' exterior surface area and enclosure volume.[11] The latest Residential Building Energy Conservation Design in Shanghai (DGJ08-205-2015) published in 2015 in Shanghai, the stipulation on shape coefficient of residential buildings was adjusted. The specific situation is shown in Table 3.4:

Table 3.4 The limits of shape coefficient for residenrial buildings

Buildings	3 ≤ Height ≤ 10m	4 ~ 11 Floors (Or Height ＞ 10m)	Floors ＞ 12
Shape Coefficient	≤0.55	≤0.45	≤0.40

Source: Author

If the building does not meet the requirements of this provision, it is also necessary to conduct a comprehensive assessment of the thermal performance of the envelope of a particular building.[12] The integrated judgment can be realized by measuring the annual dynamics(AD) of a building through computer energy consumption simulation software. Moreover, the simulated design energy consumption is compared with the standard reference energy consumption to judge whether this building meets energy-saving standards.

In Shanghai, building energy consumption takes place in two stages. The one is the air-conditioning refrigeration in hot summer and the other one is the heating period in cold winter. The dynamic energy consumption simulated by energy consumption simulation software PKPM applied in this study targets at two periods for measurement. The *Residential Building Energy Conservation Design Standards in Hot Summer and Cold-Winter Zone* JGJ134-2001 and *Residential Building Energy Conservation Design in Shanghai* stipulate the indoor thermal environmental calculation parameters of residential buildings as follows: The heating period ranges from December 1st of that very year to February 28 of the following year, while the air-conditioning period ranges from June 15 to August 31 in the same year. At the same time, the indoor calculating temperature in the entire air-conditioning area is stipulated. The whole-day temperature in winter is 18°C, while the whole-day temperature in summer is 26°C. The building to be tested only requires for meeting standard requirements in shape coefficient or AD, thus it can be considered as meeting energy consumption design

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[11] Qi F, Wang Y. *"A New Calculation Method for Shape Coefficient of Residential Building Using Google Earth[J]."* Energy and Buildings, 2014, 76: 72-80.

[12] *"Shanghai Residential Building Energy Conservation Design Code" (DGJ08-205-2015)*

standards. It can be observed from the above-mentioned section, the height and shape coefficient in three buildings are shown in Table 3.5. By combining with the Table 3.4, it is proven that it conforms to the requirements of energy conservation design specifications.

Table 3.5 Data collection of shape coefficient of case buildings

	Case 01	Case 02	Case 03
Building Height	20.30m	43.50m	41.40
Total Floors	7	15	13
Shape Coefficient	0.41	0.33	0.39

Source: Author

For convenient simulation calculation, the standards referred in this study include the *Thermal Code for Public Building Design* GB50176-93, *Carbon Emission Measurement Standard* CECS374-2014, and *Residential Building Energy Conservation Design Standard in Hot summer and Cold winter Zone* JGJ134-2001.

3.2.2 The Introduction of Energy Consumption Simulation Software

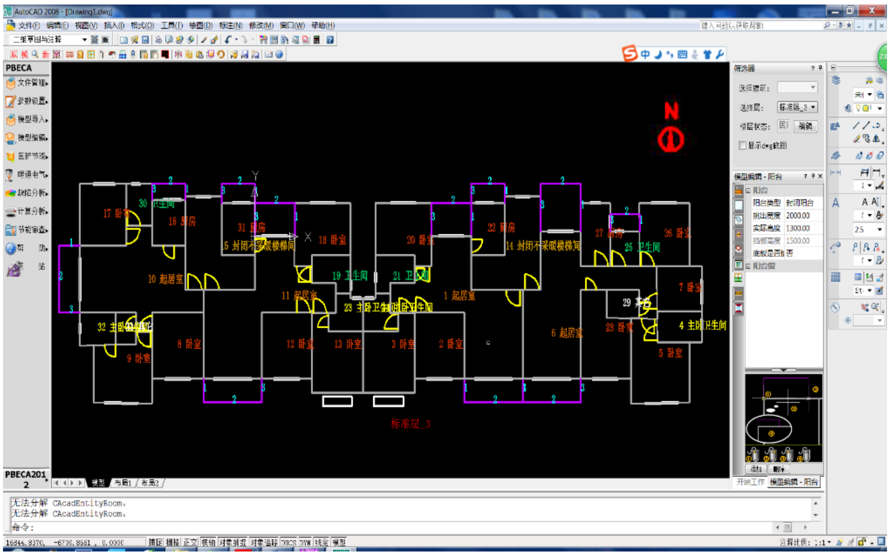
Currently in the field of building energy simulation, Energy Plus, PKPM energy conservation software PBECA, DOE-2 and DeST or other domestic and overseas software can conduct the simulation calculation on energy consumption in the building operation stage. In the above-mentioned software, PKPM energy conservation design analysis software PBECA is the energy consumption simulation software independently developed in China, covering more than 80 national standards and relevant local energy conservation design standards issued by China. Moreover, this software is developed on the basis of AutoCAD, thus it has the favorable compatibility. It is convenient for data connection with the construction drawing, so this study selects PKPM series energy consumption simulation software PBECA to simulate and measure annual energy consumption value for the buildings involved.

3.2.3 The Process of PKPM Software Simulation Analysis

In this study, the modeling materials, structure, door and window size in the energy consumption software completely refer to the corresponding construction drawing of the practical project for setting. Now, the modeling process of PKPM software is briefly introduced as follows:

(1)The Construction of Case Building Model

The reference model of the case building respectively refers to the buildings in the established communities of Songjiang District and Putuo District, Shanghai introduced in the above-mentioned section. First of all, the AutoCAD construction drawing plane of each case building is inputted to respectively input window and door schedule of buildings. According to the general layout, the compass direction is selected. By referring to the plane drawing, the corresponding structure columns, walls, doors and windows are inputted. Moreover, the construction attribute of PBECA model is endowed to generate each standard layer of the corresponding residential building. In the standard layer, the model is further deepened to perfect the separating wall, balcony and room type (shown in Figure 3.1). Afterwards, the storey height is established. Finally, the datum mark is selected to connect with each floor in accordance with the plane sequence in the drawing and assemble it into the complete building model. By checking the 3D model and making a comparison with the drawing, it is necessary to check whether it has careless omission (as shown in Figure 3.2).



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Fugire 3.1 Standard layer modeling interface display of PKPM software

Source: Author

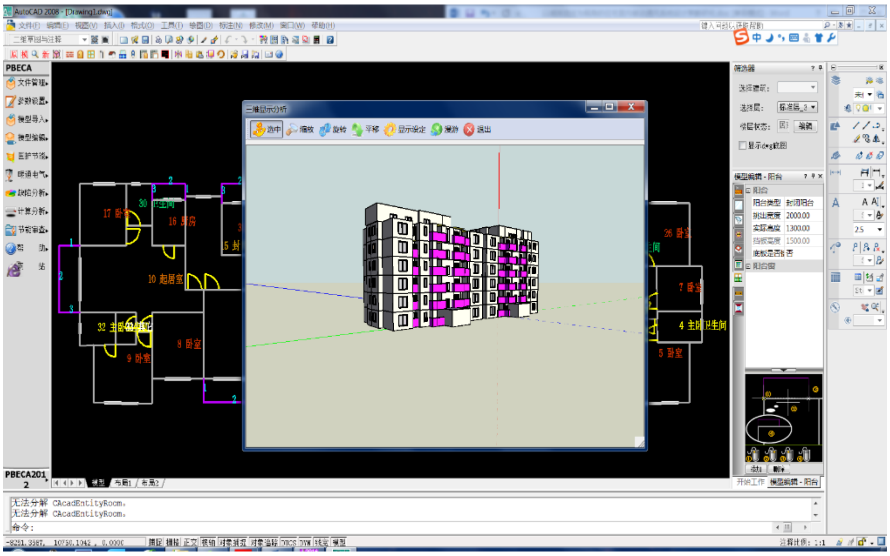

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Figure 3.2 3D model interface display of PKPM software

Source: Author

(2)The Compilation of model materials

After finishing preliminary model construction, the next step is to compile thermal insulation component materials of each building component involved in the model, including the roof, wall, door, window, thermal bridge, common floor and overhead floor, as shown in Figure 3.3. The selection and mode of construction for size in each structural material strictly refer to the construction drawing of the practical project for compilation and setting, ensuring that the thermal material performance in building envelope structure can maximally get close to the physical situation of case buildings.

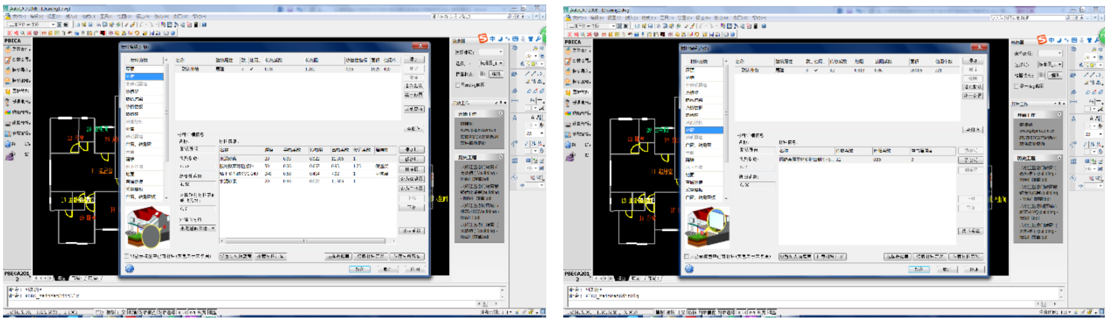

Figure 3.3 Material editing interface display of PKPM software

Source: Author

(3)Simulation Calculation of Energy Consumption

Through the above-mentioned steps, modeling is completed. Next section will discuss the core part of the software simulation—“energy consumption simulation calculation”. According to stipulations, the operational process of engineering practice should firstly conduct the prescriptive index checking for the model. If the result can’t meet standard requirements, it needs to continue weigh calculation. On the contrary, the building is considered as conforming to standards. If it still can’t meet the standards, it needs to return to the energy conservation design process to correct each construction node of the building and increase the thermal insulation performance until it can satisfy standard requirements. The change of carbon emission for building equipment system in this study is mainly reflected in the external envelope structure. Since the size change of outer door and window hole will alter the window-wall ratio of the building and finally change the annual energy consumption simulation value of the building. After finishing the original model energy consumption calculation for three case buildings, PKPM software will automatically generate the report corresponding to the model. Afterwards, this study will conduct the detailed study and analysis on the simulation result by combining with the measured data.

3.3 Case Building Energy Consumption Calculation Based on the Empirical Electricity Data

This study aims to explore the influences of outer doors and windows’ physical property changes on indoor air ventilation environment, thus the thermal indoor comfortable environment will satisfy residents’ thermal comfort behavior requirements and improve carbon-saving potential of residents. As a result, the behavioral habit of residents has the important status in this study. However, the energy consumption data simulated by the energy consumption simulation software is completely ideal. The building operation time is 24h and the result is obtained by neglecting the intervention situation of human factors. Therefore, in order to improve the reliability and accuracy of software simulation results, depend on the support of Natural Science Foundation of China (NSFC) and Tongji University, and cooperate with the regional State Grid Corporation of China(SGCC), this study gains the anonymous practical power data in the above-mentioned residential buildings in 2016. This data have included power consumption at ordinary times and valley of each month in 2016 of each household.

After eliminating the abnormal data, measured data and simulated data are compared to explore the difference law between them. Based on the Formula 3.1 and Formula 3.2, the correction factors of simulation data are obtained to correct the difference brought by the calibration software simulation, trying to make research results become more practical and accurate.

$$C = \frac{C_1 + C_2 + C_3}{3} = \frac{\frac{E_{R1}}{E_{S1}} + \frac{E_{R2}}{E_{S2}} + \frac{E_{R3}}{E_{S3}}}{3} \tag{3.1}$$

$$E_R = \frac{E_T}{FA} = \frac{E_A x U}{FA} \tag{3.2}$$

C is the simulated data correction coefficient relative to the empirical data;

C_1、C_2、C_3 are the correction coefficients of the three case buildings for their respective simulation data;

E_{R1}、E_{R2}、E_{R3} are the energy consumption of the three case buildings through their respective empirical data(kWh/m^2);

E_{S1}、E_{S2}、E_{S3} are the energy consumption of the three case buildings respectively through the PKPM software(kWh/m^2);

E is the annual total electricity consumption of each case building unit(kWh);

E_A is the measured average annual electricity consumption of each household in each case building unit(kWh);

U is the total number of households contained in each case building unit;

FA is the total construction area of each case building unit.

3.3.1 Electricity Consumption Analysis and Energy Consumption Calculation of Case Buildings

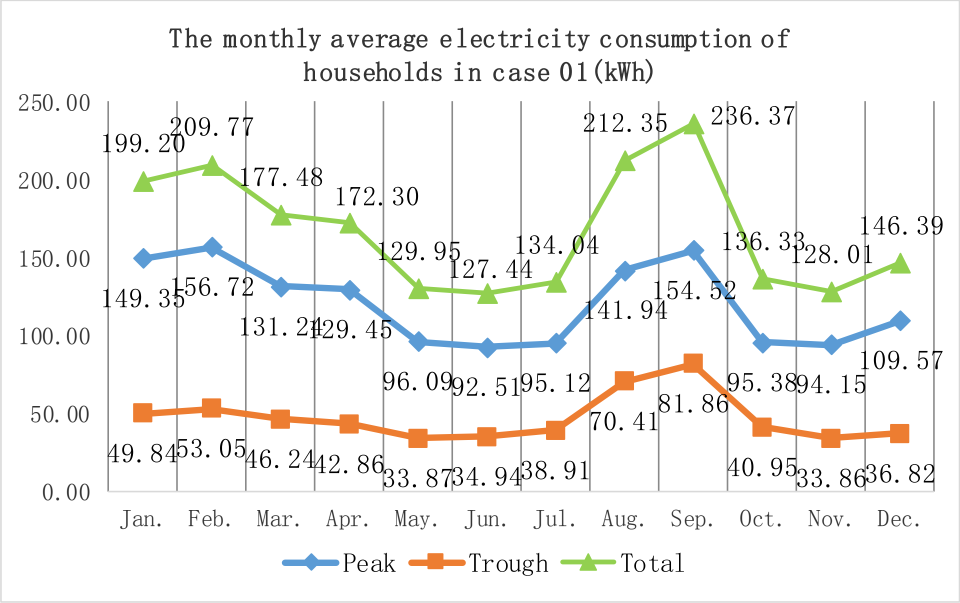

Figure 3.4 The monthly average electricity consumption of building tenants in Case 01

Source: Author

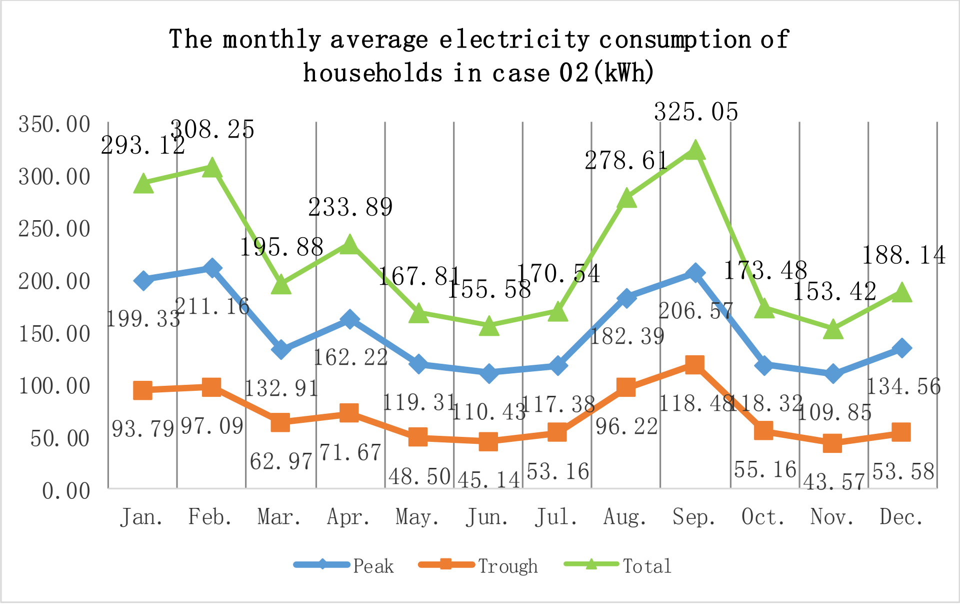

Figure 3.5 The monthly average electricity consumption of building tenants in Case 02

Source: Author

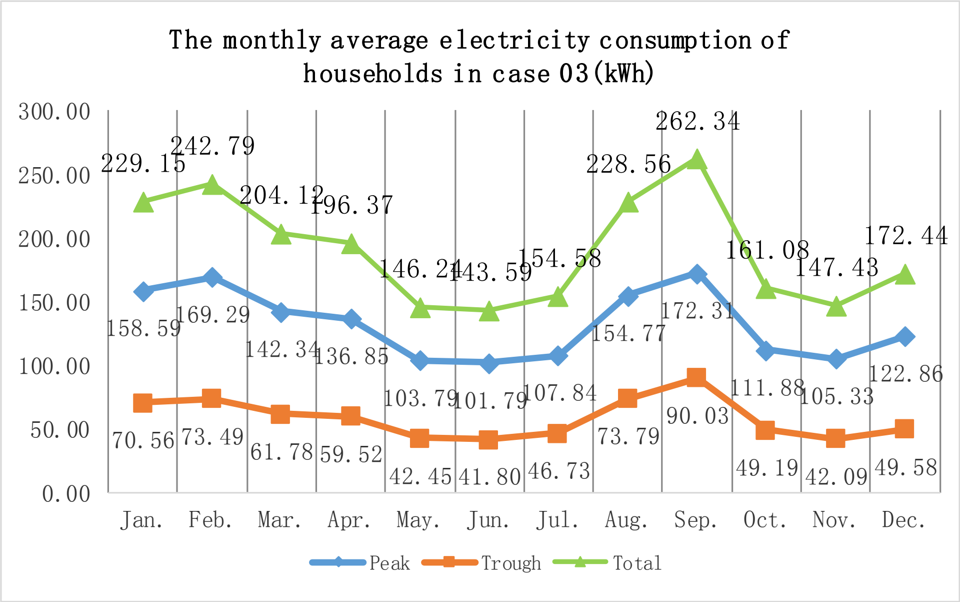

Figure 3.6 The monthly average electricity consumption of building tenants in Case 03

Source: Author

By briefly analyzing the monthly average power consumption data of households in each case building, it can be found that the average total power consumption in Jan, Feb, Mar, Apr, Aug and Sep of three case buildings is dramatically higher than other months. By combining with life experience, it can be observed that several months in the beginning of the year are the coldest seasons in Shanghai, while Aug and Sep are the hottest seasons in this area. Moreover, in addition to use heating and refrigeration equipment for coldness and hotness, daily household appliances in buildings are seldom affected by seasons. As a result, according to measured data, it approximately thinks that the months with dramatically increasing power consumption and average power consumption difference with other months of the same year are attributed to residential heating and refrigeration equipment, thus the annual heating energy consumption of households in each case building uses the difference between monthly average power consumption with the obviously increasing winter power consumption and monthly average power consumption in spring and autumn (transition seasons) to multiply by months with dramatically increasing power consumption in winter. Similarly, it can be observed that the annual refrigeration power consumption of households in each case building uses the difference between monthly average power consumption with the obviously increasing summer power consumption and monthly average power consumption in spring and autumn to multiply by months with dramatically increasing power consumption in summer. According to the Formula 3.2, it shows that the households' average equipment power consumption of each case building multiplies by the corresponding households divide by the corresponding gross floor area to obtain the annual empirical power consumption data under the unit area of each case building, as shown in Table 3.6:

Table 3.6 The summary of annual energy consumption of each case building

Category	Case 01	Case 02	Case 03
Average Household Heating Consumption(kWh)	223.98	358.49	255.53
Average Household Cooling Consumption(kWh)	181.34	267.34	182.45
Total Electricity Consumption Per Household(kWh)	405.32	625.83	437.98
Number of Households	24	28	26
Construction Area(m^2)	3167.25	4699.35	3442.17
Heating Energy Consumption Per Unit Area(kWh/m^2)	1.70	1.98	1.93
Cooling Energy Consumption Per Unit Area(kWh/m^2)	1.37	1.48	1.38
Energy Consumption Per Unit Area(kWh/m^2)	3.07	3.46	3.31

Source: Author

3.3.2 Energy Consumption Correction Factor of Case Building

Table 3.7 is the statistical result obtained by using the energy consumption software PKPM to do energy consumption simulation in line with building information for the above-mentioned three buildings:

Table 3.7 The annual simulated energy consumption summary of each case building(kWh/m^2)

Category	Case 01	Case 02	Case 03
The Simulated Heating Energy Consumption Per Square Meter	32.35	29.61	37.04
The Simulated Cooling Energy Consumption Per Square Meter	21.11	25.45	21.72

Total Energy Consumption of Simulation Operation Per Square Meter	53.46	55.06	58.76

Source: Author

It can be observed from Table 3.6 and Table 3.7 that the empirical energy consumption of three case buildings under the unit area is widely apart from the simulated energy consumption. The simulated value is higher dozens of times than measured data. Relevant causes are attributed to the following factors: heating and refrigeration equipment of case buildings under the PKPM software simulation state is based on national relevant specification. Within three months of heating period and two and a half months of refrigeration period, the corresponding equipment maintains the constant expected indoor temperature and will conduct continuous working within 24h. This has a great difference from residents' actual service situation of heating and refrigeration equipment in their daily life. In real life, heating and refrigeration equipment is often affected by numerous factors, including different residents' behavioral habits and equipment energy consumption. As a result, it is normal that the simulated energy consumption has a large difference from energy consumption data calculated by empirical power consumption. In the end, by combining with the Formula 3.1, Formula 3.2, Table 3.6 and Table 3.7, the energy consumption correction factors of three case buildings are obtained respectively:

(1)The total energy consumption per square meter of **Case 01** is 3.07kWh / m^2, while the total energy consumption per square meter of simulated operation is 53.46kWh / m^2, thus the energy consumption correction coefficient is:

$$C_1 = \frac{3.07}{53.46} \approx 0.057$$

(2)The total energy consumption per square meter of **Case 02** is 3.46kWh / m^2, while the total energy consumption per square meter of simulated operation is 55.06kWh / m^2, thus the energy consumption correction coefficient is:

$$C_2 = \frac{3.46}{55.06} \approx 0.063$$

(3)The total energy consumption per square meter of **Case 03** is 3.31kWh / m^2, while the total energy consumption per square meter of simulated operation is 58.76kWh / m^2, thus the energy consumption correction coefficient is:

$$C_3 = \frac{3.31}{58.76} \approx 0.056$$

3.3.3 Correction Factor of the Simulated Data for the Case Buildings

Figure 3.7 The measured and simulated percentages of energy consumption in three cases

Source: Author

It can be intuitively observed from Figure 3.7 that there is the large difference between measured value and simulated data of each case building, but by combining with correction factors of energy consumption C1, C2 and C3 in three case buildings, the proportion of measured data in simulated data is approximately equal in each building. Moreover, the energy consumption percent proportion between measured data and simulated data is also approximately equal, thus it can be deduced that under the measured data obtained by using the Formula 3.1, the accuracy and reliability of coefficient factors for PKPM software simulation data are very high. In order to make the subsequent data calculation more accurate, coefficient factors of the above-mentioned case buildings are conducted weighted average. Besides, the decimal digits of correction factors are retained to the thousands, namely 0.059:

$$C = \frac{0.057 + 0.063 + 0.056}{3} \approx 0.059$$

3.4 Analysis of Results of Indoor Ventilation Questionnaire Based on Case Building

3.4.1 The Purpose of the Questionnaire

By combining with the energy consumption service habit study of households in residential buildings, in order to obtain the indoor air ventilation evaluation in each building involved for judging accuracy of the software simulation and practical reference significance, this study designs an empirical behavior questionnaire on ventilation evaluation and energy consumption with pertinence (Appendix A) and leaves for each empirical community for the field investigation. The investigation purpose of this questionnaire is to measure the actual ventilation situation of case buildings through household evaluation, combine it with actual energy consumption for analysis and construct the corresponding connection among empirical energy consumption data, actual ventilation situation and software simulation energy consumption results, trying to further verify the simulation results and expand research width.

3.4.2 Statistical Analysis of Questionnaire Results

In order to create the reference value and ensure accuracy for the investigation samples, the building households that are the same with case buildings are particularly selected as investigation samples as granting questionnaires in each case building. Finally, 200 questionnaires are granted. **Case 01** building, **Case 02** building and **Case 03** building recycle 53 questionnaires, 56 questionnaires and 58 questionnaires, respectively. The above-mentioned recycled effective questionnaires are systemized to do horizontal comparative study and cross-over analysis. For changing subjective feeling of households into the intuitive data conveniently, the scoring system is established in the questionnaires. The results can embody the subjective feeling of each index by using high-low scores. Satisfaction is scored as 5 and dissatisfaction is scored as 1. The evaluation in each middle stage is successively marked as 4, 3 and 2. The final questionnaire results are present from Figure 3.8 to Figure 3.10:

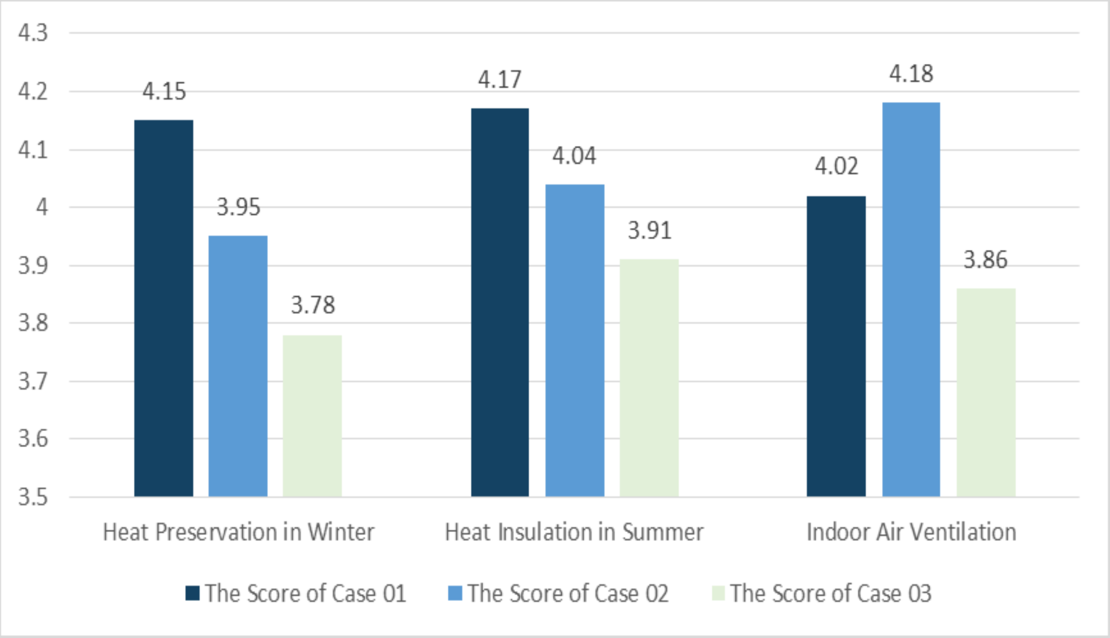

Figure 3.8 The integrated household scoring situation of each index in case buildings

Source: Author

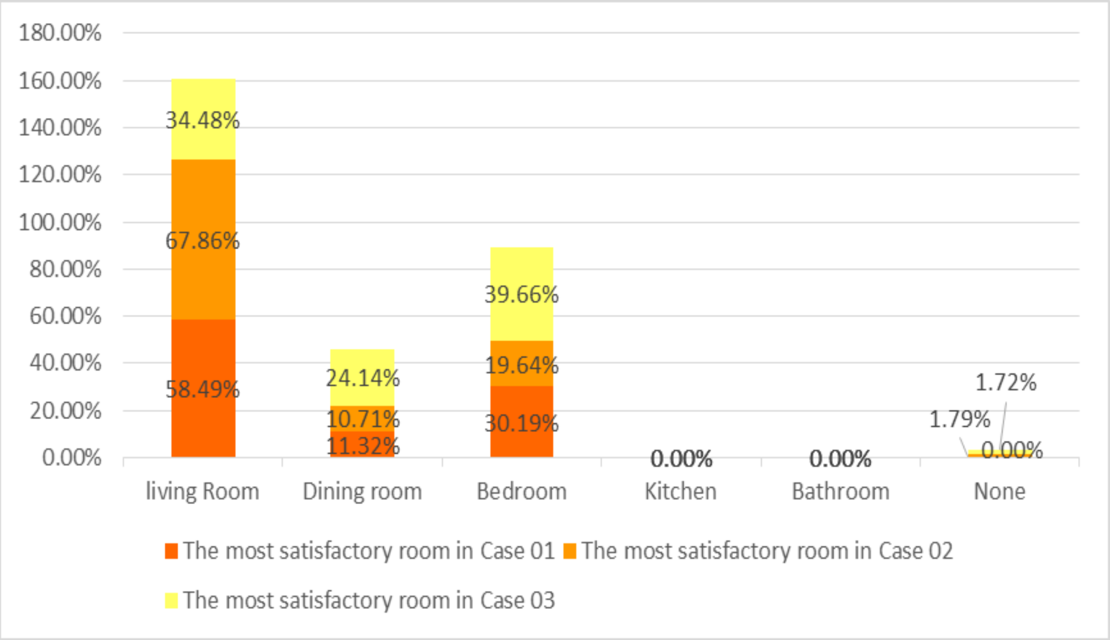

Figure 3.9 The most satisfactory room situation of households in case building

Source: Author

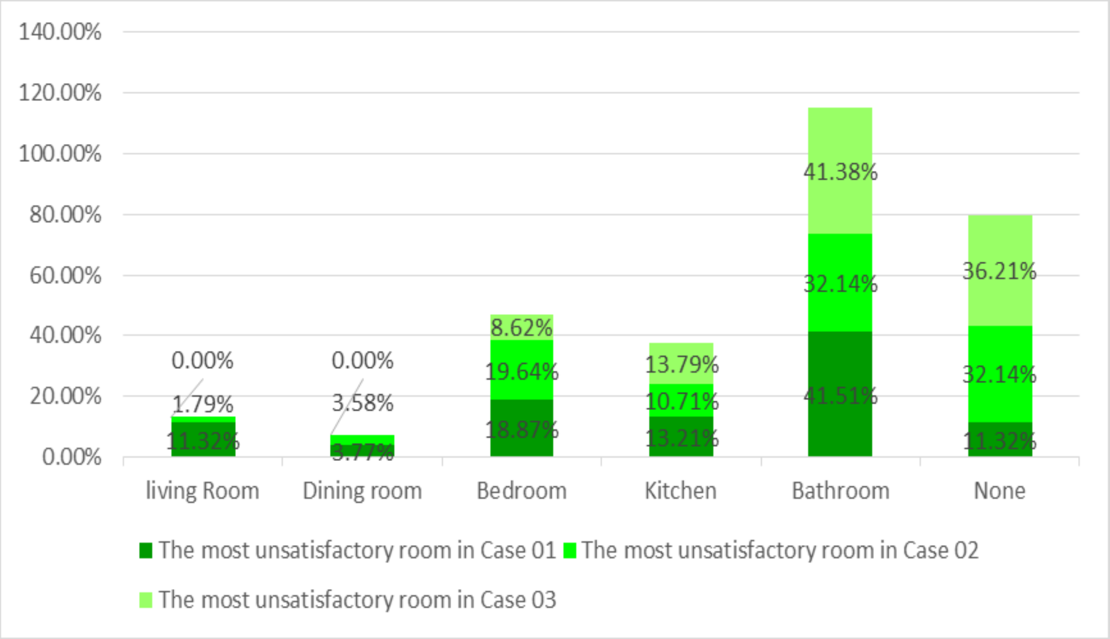

Figure 3.10 The most unsatisfactory room situation of households in case building

Source: Author

The following conclusions can be obtained from the questionnaire results: thermal insulation and heat insulation measures of Case 01 are superior to the other two cases. Based on three integrated scores, Case 01 building is the best one, while each score of Case 03 building is minimal. Rooms that satisfy households in indoor air ventilation in three buildings involved are concentrated on living rooms, dining rooms and bedrooms. Living rooms are the best, followed by bedrooms and dining rooms. Moreover, the satisfaction rate of living rooms in Case 01 and Case 02 buildings is dramatically higher than dining rooms and bedrooms. The satisfaction rate of living rooms and bedrooms in Case 03 building basically holds the line and it is higher than the dining rooms. In the statistics of the most unsatisfactory rooms, 11.32% of households in Case 01 building select living rooms, while almost 0% of households in Case 02 and Case 03 buildings select it. Making a general survey of various unsatisfactory rooms, except for toilets, unsatisfactory proportion of all rooms in Case 03 building is minimal. In the highest unsatisfactory room selection in three buildings, toilets have the minimal score. More than 30% of residents in Case 02 and Case 03 buildings think that there is no dissatisfaction in indoor air ventilation of residences and it is dramatically higher than 11.32% of Case 01 building. To sum up, the high-low ranking of indoor air ventilation evaluation in each room of Case 01 building is shown as follows: living rooms> bedrooms> dining rooms> kitchens> toilets. The room evaluation ranking of Case 02 building is shown as follows: living rooms> dining rooms> bedrooms> kitchens> toilets. And the room evaluation ranking of Case 03 building is shown as follows: bedrooms> living rooms> dining rooms> kitchens> toilets.

As a whole, the scoring situation of Figure 3.5 in ventilation scoring of each room in Case 03 building is less than Case 01 and Case 02 buildings, but the subsequent room satisfaction evaluation has a difference form such an opinion. The integrated index of Case 03 building is the best. The satisfaction of main used space, such as living rooms, bedrooms and dining rooms, is relatively average. Moreover, residents think that the proportion of unsatisfactory rooms at most gets close to 40%. As a result, in subjective evaluation, there is no theoretical corresponding relation between residential scoring and room satisfaction, due to various influence factors, such as subjective scoring preference of households, and so on.

3.5 Chapter Summary

This chapter introduces the three typical residential buildings studied in this study, selects PKPM software as the energy consumption simulation tool used in this study and uses three selected case buildings for the corresponding initial energy consumption simulation. In the end, by combining with the empirical power consumption data in 2016 of three case buildings and making a comparison with software simulation results, a correction factor that includes residents' behavioral influence factors for correcting PKPM simulation software calculation energy consumption data is obtained as 0.059. Afterwards, by designing the evaluation questionnaires of indoor air ventilation for relevant households in empirical case buildings, the ventilation satisfaction and relevant physical performance evaluation of buildings involved can be obtained as the ventilation design evaluation indexes of the empirical case buildings. Moreover, by combining with the actual annual energy consumption obtained by empirical research and making a comparison with energy consumption results simulated by PKPM (Table 3.8), the following conclusions can be summarized below:

Table 3.8 The summary of relevant indexes and simulated data in case buildings

Related Indicators	Case 01	Case 02	Case 03
Winter Insulation Score	4.15	3.95	3.78

Actual Heating Energy Consumption(kWh/m^2)	1.70	1.98	1.93
Simulated Heating Energy Consumption(kWh/m^2)	32.35	29.61	37.04
Summer Insulation Score	4.17	4.04	3.91
Actual Cooling Energy Consumption (kWh/m^2)	1.37	1.48	1.38
Simulated Cooling Energy Consumption (kWh/m^2)	21.11	25.45	21.72
Actual Operation Of Total Energy Consumption (kWh/m^2)	3.07	3.46	3.31
Simulation Of Total Energy Consumption (kWh/m^2)	53.46	55.06	58.76
Indoor Ventilation Score	4.02	4.18	3.86

Source: Author

In energy consumption, the high-low sequence of households involved for the subjective scoring of heat insulation is successively shown as Case 01, Case 02 and Case 03, which is also proven by the total energy consumption simulated by PKPM. The high-low energy consumption of buildings involved is present in Case 01, Case 02 and Case 03. Moreover, from actual heating and refrigeration energy consumption and simulated heating and refrigeration energy consumption, value of Case 01 building is less than Case 03 building. Data comparison also conforms to this tendency, proving that the PKPM energy consumption simulation software selected in this study has the high reliability. Furthermore, through the comparative analysis among three case buildings, the simulated total energy consumption and actual total energy consumption of Case 01 and Case02 buildings are less than Case 03 building, but the satisfaction of indoor air ventilation is higher than Case 03 building, proving that in design level, relatively excellent indoor air ventilation and relatively lower carbon emission can be both realized.

In real life, except for the lower simulated heating energy consumption, data of Case 02 building are higher than Case 01 and Case 03 buildings, but the indoor air ventilation is the maximum, successively followed by Case 01 and Case 03 buildings. By making a large difference between simulated energy consumption and measured energy consumption, it is deduced that different behavioral habits of residents are assignable carbon emission influence factors in the building operation, revealing that for idealization and theorization, the model neglects the inevitable limitation brought by other factors in real life.

In order to make the study have the wider universal applicability and the better practical reference value, the chapter six of this study will conduct the in-depth study on potential and possibility of households’ behavioral emission reduction, try to find out the relation between indoor air ventilation design of residential buildings and residents’ behavioral emission reduction and explore the multi-aspect carbon emission potential owned by indoor air ventilation of residential buildings under the support of relevant theories as much as possible.

Chapter 4 ❙ Indoor Natural Ventilation Simulation of the Variation of Exterior Door and Window

4.1 The Determination of the External Conditions and the Type of Apartment of Natural Ventilation Simulation

Based on the comparison results obtained by measured and simulated simulation data, correction factors are obtained. Since the year of construction in three case buildings is close and the corresponding energy conservation specification is referred in the design process, there is the simulation universality. Next, this study will select the Case 01 building to deeply analyze and simulate the relation between physical properties of doors and windows and indoor air ventilation. Considering that outer door and window materials of this building can be used as the influence factors improving indoor air ventilation, they are combined for consideration. As mentioned above, the residential indoor ventilation discussed in this study focuses on the ventilation design of the residential building. The research object is concentrated on relevant physical parameters of doors and windows in this building involved, excluding general layout and outdoor shield of the building. Similarly, since the Case 01 building plane belongs to two-household in a floor. Left and right house types are symmetric, thus a single household in the standard layer is selected as a simulated object to be simulated. From the section 3.1 above, the building height of Case 01 building is 2.90m, thus the research rooms selected are located in fourth floor of this building involved. The height is almost equal to the free air height defined by China Meteorological Administration for each region in line with the 10m height of standard meteorological observational site. And the test level of indoor space is of 1.5m height.[13]

When the boundary condition of indoor wind environment simulation is established, thermal performance design zoning of Case 01 building belongs to the hot summer and cold winter thermal zone—Shanghai and it is kept in the empty room state. According to the *"Shanghai Building Environment Numerical Simulation Technical Regulations" (DB31 / T 922-2105)*, the recommended value of outdoor wind environment calculation temperature in summer natural ventilation is 31.2°C, while the

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[13] *"Wind Power Rating" (GB / T 28591-2012)*

outdoor wind velocity is calculated as the height direction in line with the “Exponential Law” in Formula 4.1:

$$\frac{V}{V_0} = \left(\frac{Z}{Z_0}\right)^a \tag{4.1}$$

V is the wind speed at height Z(m/s);

V_0 is the wind speed at the reference height Z_0(m/s). According to the standard to take the wind speed at a height of 10m(3.1m / s);

Z is the reference plane for simulating the results of a simulation in a room and is known to be at a height of 1.5 m of the active area of the occupants according to the standard. Because the height of the story in Case 01 is 2.90m and the selected unit is on the fourth floor, the reference plane is approximately 10m above ground level;

Z_0 is the reference height(10m);

a is the surface roughness index, because the Case 01 is located outside the Shanghai Outer Ring Road in Songjiang District, so take 0.15.

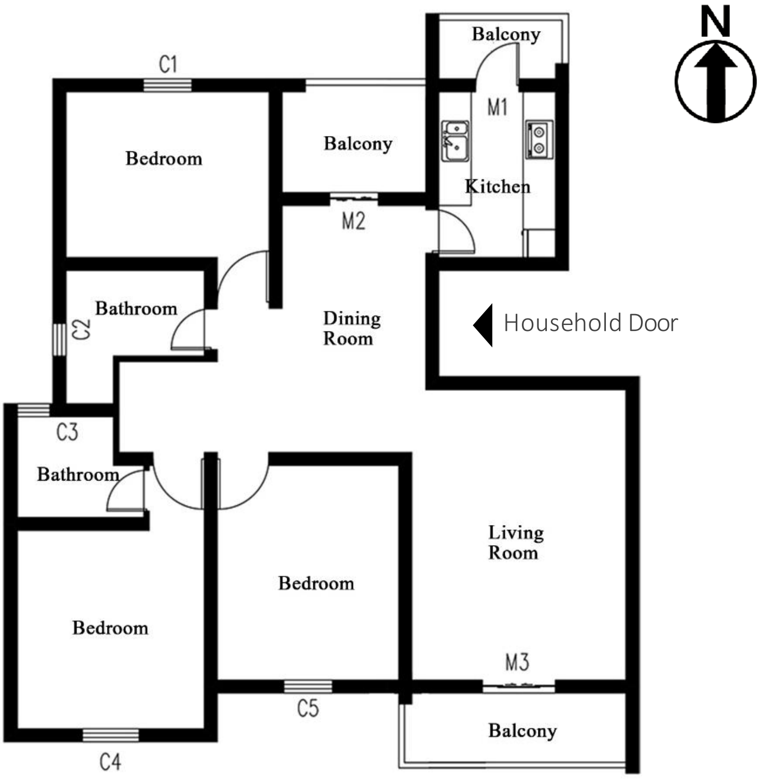

Figure 4.1 The simulated floor plan of Case 01

Source: Author

According to the Formula 4.1, the simulated outdoor velocity is taken as 3.1m/s. The simulated house type plane and window and door schedule in Case 01 building are present in Figure 4.1 and Table 4.1:

Table 4.1 The size of doors and windows

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
Actual Width	1800	600	600	2100	1800	800	1800	2700
Simulated Width	900	600	600	1050	900	800	900	1350

Source: Author

4.2 Determination of Natural Ventilation Simulation Conditions

Based on the scholars' research results in the literature review chapter, it can be observed that under the circumstance of not changing the physical properties of outdoor natural ventilation, wind velocity flowing through the room and even distribution of wind turbulence have the biggest influence on thermal comfort degree of indoor residents. Factors which are related to physical properties of outer door and window ventilation mainly include the several aspects: outer door and window position, window-wall ratio (window area) and sunshade component of outer doors and windows. In top two aspects of the above-mentioned variables, the windowing position and window-wall ratio are important design means to be controlled in early-stage building design, thus they are considered as the important parameter variables for analysis and study. In addition, factors that affect physical properties of outdoor natural ventilation including outdoor sunshade component are excluded in this study. For purpose of studying the summer indoor natural ventilation effect of different outer door and window position and windowing size in this case building, the influences of outdoor wind direction and wind speed changes are also considered. Now, the windowing position and size change of this house type are attached to the wind direction and wind speed influence factors, which can be divided into outer door and window position, outer door and window width and wind direction, wind speed of outdoor natural wind to respectively give the corresponding outdoor ventilation effect simulation and carry out the horizontal comparison on results.

Through the field investigation, it can be found that the outer doors and windows of this building belong to the horizontal pull type and the maximal opening area proportion is 50%, thus door and window size should be established as the half of the actual window in simulation analysis. The detailed alternation is shown in Table 4.1. It can be observed from Figure 4.1 that C2 and C3 are high windows in toilets, while M1 is a horizontal door of the kitchen. For indoor furniture limitation, there is no any change in this simulation.

4.2.1 The Changes of Relative Position of Exterior Doors and Windows with Indoor Doors

The first category of comparison refers to the relative position comparison between openable outer windows (doors) internal doors in each main room, thus the existing outer door and window size should be unchanged as well as the outdoor natural wind direction and wind speed. In simulation, outdoor wind direction is the south. According to the opening width distance in a room, five changeable positions are equally divided. The relative position of outer doors and windows and the corresponding internal doors of the room ranges from the nearest one to the farthest one. It is successively established as five working conditions: CASE01, CASE02, CASE03, CASE04 and CASE05. Moreover, the door and window size of each working condition is present in Table 4.2:

Table 4.2 The window and door schedule of the first category of comparison

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
Simulated Width	900	600	600	1050	900	800	900	1350
Acreage(m^2)	1.08	0.36	0.36	1.26	1.08	1.92	2.16	3.24

Source: Author

(1)CASE01:

Under this working condition, the relative position between outer doors and windows and internal doors in the corresponding room is the nearest. The specific position is arranged in Figure 4.2:

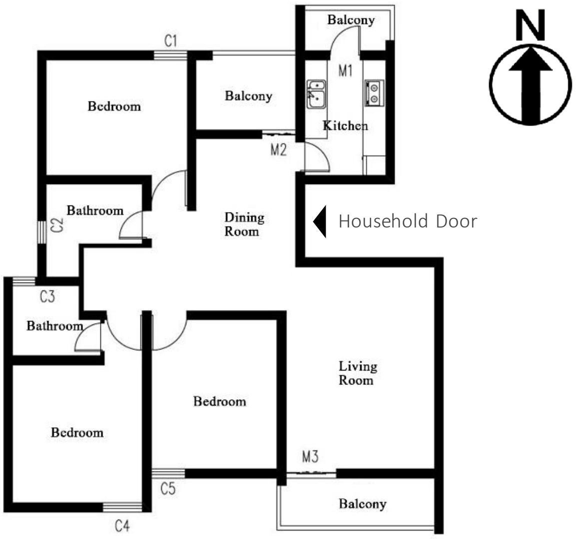

Figure 4.2 The location layout of door and window for CASE01

Source: Author

(2)CASE02:

Under this working condition, the relative position between outer doors and windows and internal doors in the corresponding room is slightly further for an equal segment by comparing with CASE01. The specific position is arranged in Figure 4.3:

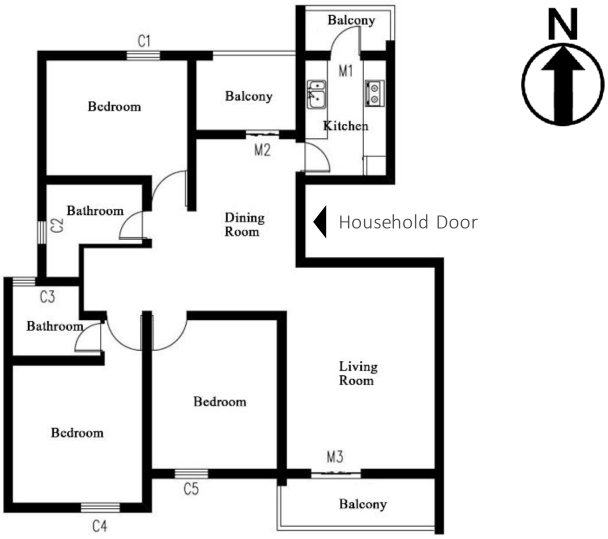

Figure 4.3 The location layout of door and window for CASE02

Source: Author

(3)CASE03:

Under this working condition, the relative position between outer doors and windows and internal doors in the corresponding room is further for an equal segment by comparing with CASE02. Under this circumstance, the doors and windows are exactly located in the middle of the outer wall. This is the commonest design method used by designers in the daily design. The specific position is arranged in Figure 4.4:

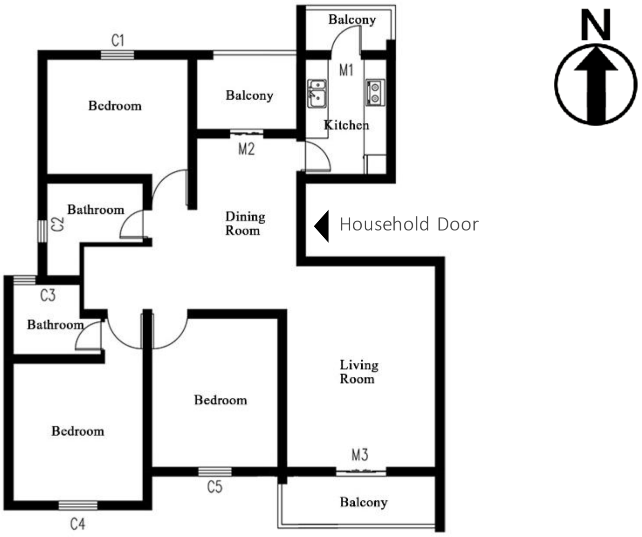

Figure 4.4 The location layout of door and window for CASE03

Source: Author

(4)CASE04:

Under this working condition, the relative position between outer doors and windows and internal doors in the corresponding room is also further for an equal segment by comparing with CASE03. The specific position is arranged in Figure 4.5:

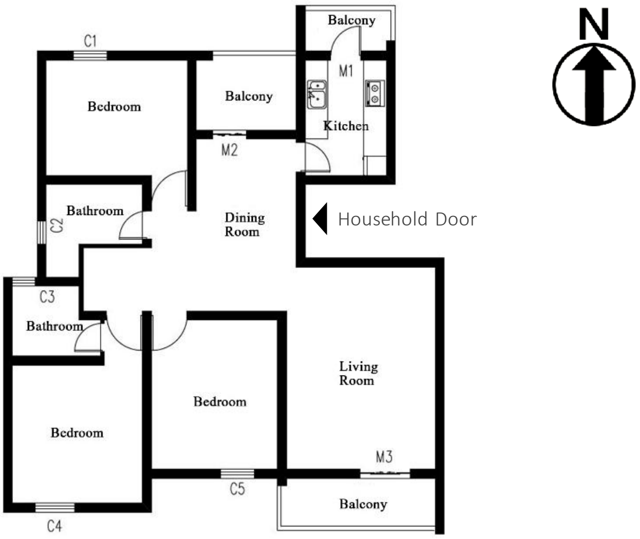

Figure 4.5 The location layout of door and window for CASE04

Source: Author

(5)CASE05:

Under the working condition, the relative position between outer doors and windows and internal doors in the corresponding room is the furthest by comparing with the previous four working conditions. The specific position is arranged in Figure 4.6:

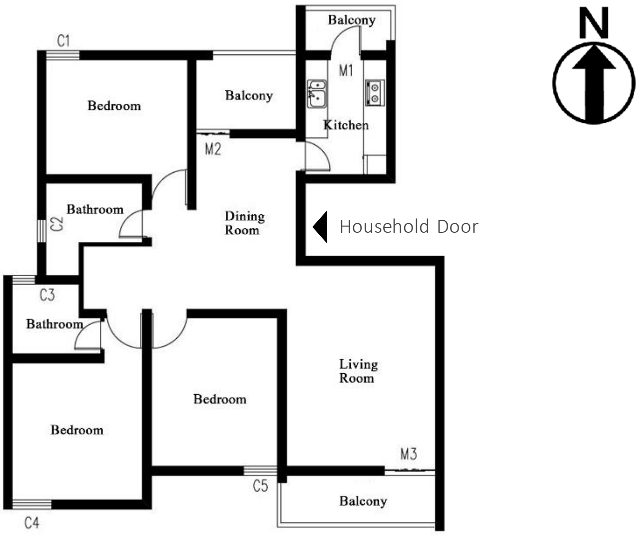

Figure 4.6 The location layout of door and window for CASE05

Source: Author

4.2.2 The Changes of Width Ratio of Exterior Doors and Windows

The second category is the relative proportion change of the simulated outer door and window opening width in the opening width of the corresponding room. Under this circumstance, the relative position between the outer doors and windows and internal doors of the rooms is unchanged and so as to the natural wind direction and the wind speed. The simulation time also takes the south as the outdoor window direction. Door and window position of CASE05 is randomly selected as the reference in the first category of working condition to change correspondingly. Moreover, it can be observed from the preamble that the maximal opening area of the outer doors and windows in the building involved is 50%, thus the maximal opening width proportion of outer doors and windows is also 50% of the opening area in the corresponding area. In the second category of comparison, the relative proportion of door and window opening is 10%, 20%, 30%, 40% and 50%, respectively, which are successively established as five working conditions, including CASE06, CASE07, CASE08, CASE09 and CASE010.

(1)CASE06:

Under this working condition, the opening width of outer doors and windows accounts for 10% of the opening width of the corresponding room. The specific position and door and window size are present in Figure 4.7 and Table 4.3:

Figure 4.7 The location layout of door and window for CASE06

Source: Author

Table 4.3 The size of doors and windows for CASE06

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
10% Width(mm)	376	600	600	364	336	800	266	396
Acreage(m^2)	0.45	0.36	0.36	0.44	0.40	1.92	0.64	0.95
Change In Acreage (m^2)	-0.63	0.36	0.36	-0.82	-0.68	1.92	-1.52	-2.29

Source: Author

(2)CASE07:

Under this working condition, the opening width of outer doors and windows accounts for 20% of opening width in the corresponding room. The specific position and door and window size are present in Table 4.4 and Figure 4.8:

Table 4.4 The size of doors and windows for CASE07

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
20% Width(mm)	752	600	600	728	672	800	532	792
Acreage(m^2)	0.90	0.36	0.36	0.87	0.81	1.92	1.28	1.90
Change In Acreage (m^2)	-0.18	0.36	0.36	-0.39	-0.27	1.92	-0.88	-1.34

Source: Author

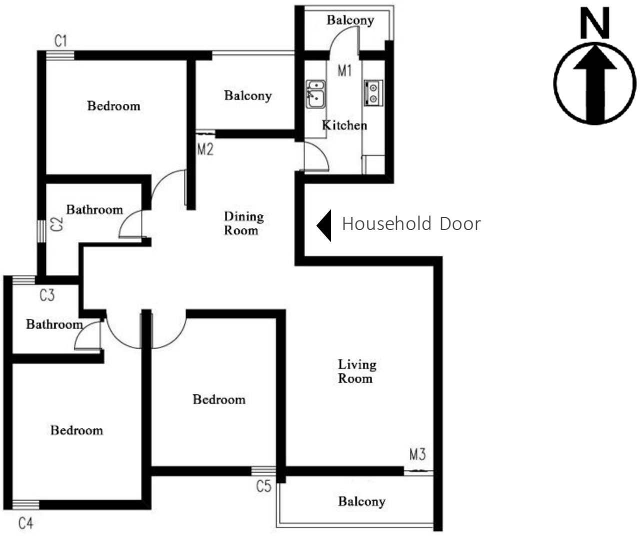

Figure 4.8 The location layout of door and window for CASE07

Source: Author

(3)CASE08:

Under this working condition, the opening width of outer doors and windows accounts for 30% of opening width in the corresponding room. The specific position and door and window size are present in Table 4.5 and Figure 4.9:

Table 4.5 The size of doors and windows for CASE08

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
30% Width(mm)	1128	600	600	1092	1008	800	798	1188
Acreage(m^2)	1.35	0.36	0.36	1.31	1.21	1.92	1.92	2.85
Change In Acreage (m^2)	+0.27	0.36	0.36	+0.05	+0.13	1.92	-0.24	-0.39

Source: Author

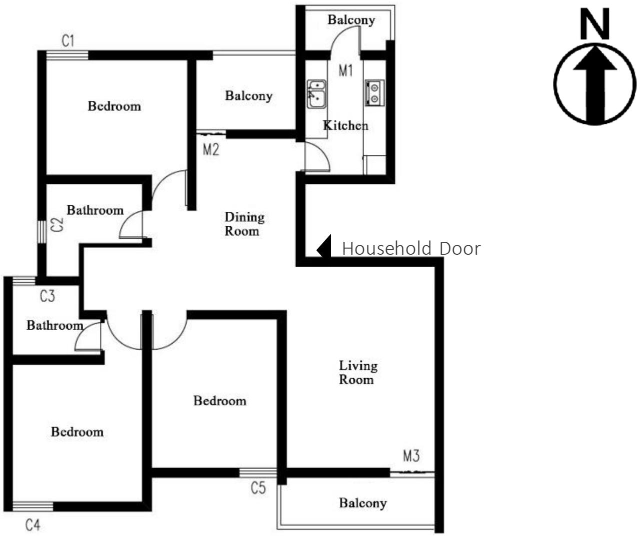

Figure 4.9 The location layout of door and window for CASE08

Source: Author

(4)CASE09:

Under this working condition, the opening width of outer doors and windows accounts for 40% of opening width in the corresponding room. The specific position and door and window size are present in Figure 4.10 and Table 4.6:

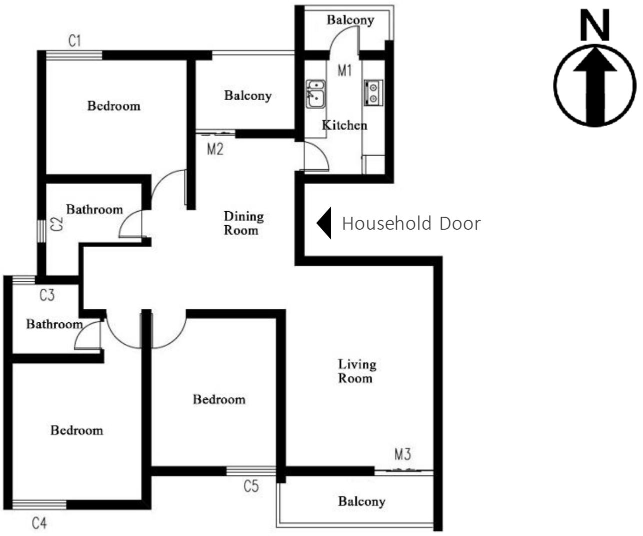

Figure 4.10 The location layout of door and window for CASE09

Source: Author

Table 4.6 The size of doors and windows for CASE09

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400

Windowsill height	600	900	900	600	600			
40% Width(mm)	1504	600	600	1456	1344	800	1064	1584
Acreage(m^2)	1.81	0.36	0.36	1.75	1.61	1.92	2.55	3.80
Change In Acreage (m^2)	+0.72	0.36	0.36	+0.49	+0.53	1.92	+0.39	+0.56

Source: Author

(5)CASE010:

Under this working condition, the opening width of outer doors and windows accounts for 50% of opening width in the corresponding room. The specific position and door and window size are present in Table 4.7 and Figure 4.11:

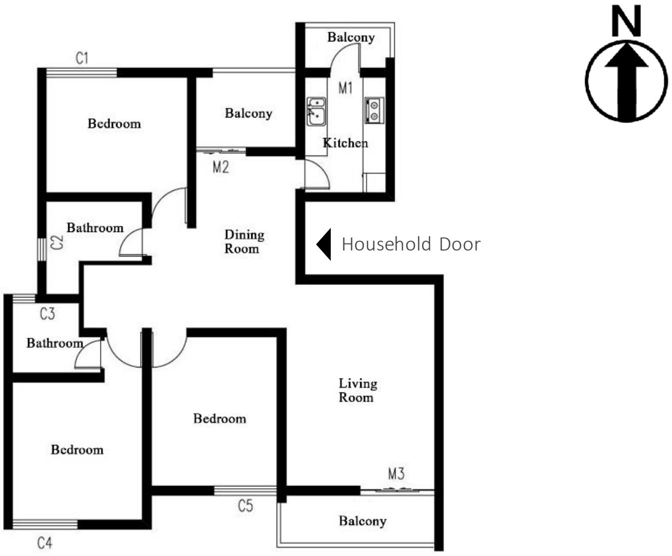

Figure 4.11 The location layout of door and window for CASE10

Source: Author

Table 4.7 The size of doors and windows for CASE10

Parameters(mm)	C1	C2	C3	C4	C5	M1	M2	M3
Window Height	1800	1500	1500	1800	1800	2400	2400	2400
Windowsill height	600	900	900	600	600			
50% Width(mm)	1880	600	600	1820	1680	800	1330	1980
Acreage(m^2)	2.26	0.36	0.36	2.18	2.02	1.92	3.19	4.75
Change In Acreage (m^2)	+1.18	0.36	0.36	+0.92	+0.94	1.92	+1.03	+1.51

Source: Author

Meanwhile, by integrating with the door and window size data from Table 4.2 to Table 4.7 that the relation between the gross area of original doors and windows in

Case01 building and five working conditions in the second category is shown as follows: CASE06< CASE07<CASE08< original width<CASE09<CASE10. In other words, the window-wall ratio of CASE06, CASE07 and CASE08 is less than the case building, while CASE09 and CASE10 are greater than that, and CASE08 has the most similar window-wall ratio to the case building.

4.2.3 The Angle Changes of Outdoor Wind Direction

The third category of comparison simulates the comparison of different summer outdoor natural wind directions. Under this circumstance, the relative position between outer doors and windows and indoor internal doors and opening width proportion of outer doors and windows are unchanged, and also make the natural wind speed maintained constant. In top two categories of working conditions, this study randomly selects physical properties of outer doors and windows in CASE08 as the reference. The southern wind direction simulates the corresponding change in accordance with the different south elevation angles of the case building. Since the left and right house types of the Case 01 building are symmetric, the simulated wind direction range is 0°-90°. The wind direction is eastward and 15° is used as the interval, obtaining 15°, 30°, 45°, 60°, 75° and 90° (this working condition is CASE08). Moreover, these six working conditions are successively established as: CASE11, CASE12, CASE13, CASE14 CASE15 and CASE16. Also the door and window size and position of those six working conditions are the same with CASE08, as shown in Figure 4.9 and Table 4.5.

4.2.4 The Changes of Outdoor Natural Wind Speed

The above three types of changes can all be said to be horizontal level simulation and analysis from a two-dimensional perspective and at a relative altitude of 10 meters. However, architectural design is not limited to two-dimensional world, but a three-dimensional project. Therefore, in order to better explore the relationship between indoor natural ventilation and architectural design, this study focuses on the simulation and analysis of the fourth type of changes under the increasing outdoor wind speed because of the changes of floors and its impact on indoor ventilation environment. According to the Formula 4.1 of the exponential law of outdoor natural wind speed among the changes of height mentioned in Section 4.1 of this chapter and the story height of 2.9 meters in combination with the case building, the curve of the outdoor wind speed in Shanghai with the height changed can be obtained and shown in the Figure 4.12:

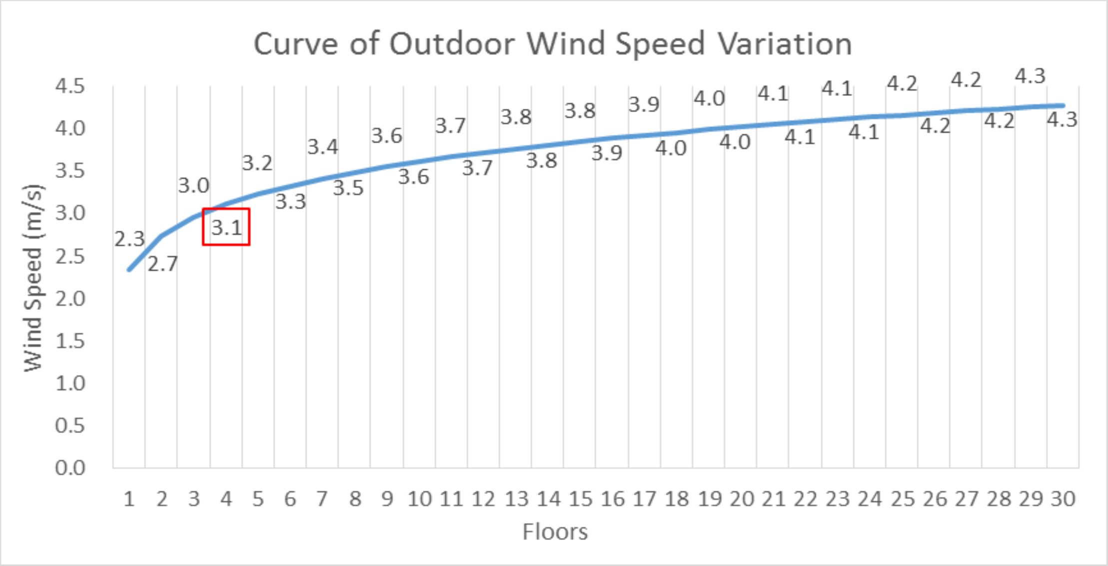

Figure 4.12 Curve of Outdoor Wind Speed Variation

Source: Author

The wind speed shown in Figure 4.12 represents the wind speed at a 1.5m elevation in the interior of the corresponding storey and corresponds to a reference wind speed of 3.1m/s at a height of 10m. Because according to the Chinese standard, the reference plane height used for judging the simulation result is 1.5m height of indoor activity area. As can be seen from Figure 4.12, as the floors continue to rise, the corresponding outdoor wind speed also becomes larger, but the rate of change is getting smaller and smaller. In reference to *"Shanghai Engineering Construction Code residential design standards" (DGJ08-20-2001)* shows that ten-storey and above are high-rise residential. The specific residential classifications are shown in Table 4.8:

Table 4.8 The classification of residential building

Residential Classification	Low-rise Dwelling	Multi-stores Dwelling	Medium High-rise Dwelling	High-rise Dweling
Floors	1-3	4-6	7-9	⩾10

Source: *Shanghai Engineering Construction Code residential design standards*

In order to make the results of this study more universal, the simulation floor is expanded to 20 floors, so the corresponding outdoor simulation wind speed range is 2.3m/s to 4.0m/s according to Figure 4.12. In order to ensure that a single variable in the simulation process, in such changes to maintain the relative position of the outer door and window with the inner door, the width of outer door and window and the outdoor wind direction are unchanged, and also take the outdoor wind is positive south. In this study, the physical properties of CASE08's exterior doors and windows was randomly selected from the first three categories of conditions as a benchmark for this change. Taking into account the wind speed and floor height in Figure 4.12 and Table 4.8, the simulation patterns for this type of change are classified into six types as shown in Table 4.9. The window size and position arrangement of the six working conditions are the same as CASE08, as shown in Figure 4.9 and Table 4.5.

Table 4.9 The classification of working conditions

Types	CASE17	CASE18	CASE19	CASE20	CASE21	CASE22
Wind Speed	2.7m/s	3.1m/s	3.4m/s	3.6m/s	3.8m/s	4.0m/s
Floors	2	4	7	9-10	13-15	18-20

Source: Author

4.3 The Introduction of CFD Software

The Computational Fluid Dynamics (CFD) analyzes the system of relevant physical phenomena including heat conduction and flow through computer simulation calculation and image display. The basic principle of CFD can be briefly summarized as: the continuous physical quantity field in the spatial domain and time domain, such as wind velocity field and temperature field. The set of variable value on a series of limited quantity discrete points is used for replacement. Some principles and methods are used for establishing the relational algebraic equation set between field variables of these discrete points. Then, a computer is used to solve the fluid flow's system of partial differential equations for value calculation. Moreover, quantitative analysis and qualitative analysis are used to describe the flowing physical phenomena.[14]

Fluent is internationally popular commercial CFD software package. It is often used for simulating the complicated flow from incompressible fluid to highly compressible fluid. The flexible unstructured grid, mature physical model based on self-adaptive network technology and powerful pre-processing and post-processing capacity enable Fluent to be widely used in Turbulence and turning, multi-directional flow, rotating

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[14] Ruijin Wang, Kai Zhang, Gang Wang. *"Fluent Technology Fundamentals and Applications [M]."* Beijing: Tsinghua University Press, 2007.

machinery, dynamic/variable grid, environmental engineering and safety engineering.[15] This software was officially introduced to Chinese market in 1998 and it has become the mainstream CFD software. The Fluent software structure mainly includes pre-processing, solver and post-processing. Gambit is used as the specialized pre-processing software and it is equipped with the grid division of multiple forms. The solver module is the core part of Fluent software. Moreover, the mathematical model of this module is based on Navier-Stokes equation set and various turbulence models, in addition to multi-phase turbulence model, free surface grid model and non-Newtonian model, combustion model and chemical response model. Considering that Fluent software applies multiple grids, including triangle and quadrangle in the 2D level, tetrahedron, hexahedron and pyramid in 3D level, as shown in Figure 4.13, bringing the great convenience to early-stage model processing and also laying a good foundation on the subsequent model analysis.

Figure 4.13 The Basic grid form diagram of Fluent software

Source: *The Influences of Window Position and Size on Indoor Natural Ventilation and Effect Evaluation*

As conducting grid division in Gambit, for considering the limitation of computer memory and calculation speed, as well as research purpose of indicating the effect of

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[15] Fan Jiang, Peng Huang. *"FLUENT Advanced Applications and Case Studies [M]."* Beijing: Tsinghua University Press, 2008.

indoor natural ventilation, the grid size in the indoor wind field area is 60mm. In the process of using Fluent software to do relevant simulation analysis, the key is to correctly set up the simulated boundary condition and this is the precondition of correct result calculation. Fluent provides dozens of boundary condition types. The typical ones include velocity-inlet, pressure-inlet, mass-flow-inlet, pressure-outlet, and outflow. It can be observed from section 4.1 that the entrance boundary condition of this study applies the velocity-inlet. The simulated outdoor wind velocity is 3.1m/s and temperature is 31.2°C. The outlet boundary condition is the normal atmosphere for the boundary pressure, thus the outlet boundary condition is established as pressure-outlet.

4.4 CFD Numerical Simulation and Result Analysis of Various Working Conditions

According to *the numerical simulation technique specification of Shanghai building environment (DB31 / T 922-2105)*, it can be observed that for residential buildings, the indoor natural ventilation flow is relatively stable at the height of 1.5m. The velocity and indoor temperature change gradient are not large. Similarly, this height is also the position that various physical environments directly contact with the human body. Therefore, this study selects the plane position with 1.5m of indoor height as the analysis reference surface of velocity and wind turbulence for study.

4.4.1 Analysis of the First Type of Simulation Results

(1)The simulation and analysis of the 1.5m height horizontal section of CASE01, as shown in figure 4.14:

It can be observed from the wind field slice map of indoor natural ventilation in Figure 4.14 that the velocity field distribution at 1.5m of CASE01 working condition is extremely uneven. The outer doors and windows and internal doors of the rooms are completely aligning. The “cross-ventilation” effect is excessively obvious, thus majorities of airflow flowing from the southern inlet window will directly and quickly flow through the primary indoor space, such as bedrooms and living room. Also, it shows from the turbulence that the velocity distribution of turbulence is extremely unbalanced. There are three columns of obvious “cross-ventilation” airflows in the north-south direction. Moreover, the remaining part in the primary indoor life space almost has no ventilation effect. As a whole, local velocity in indoor wind field of CASE01 is too concentrated, flow velocity is fast and distribution is uneven. Window opening for ventilation in summer will result in unsuitable indoor ventilation environment for residents and it is not good for providing the favorable comfortable indoor environment.

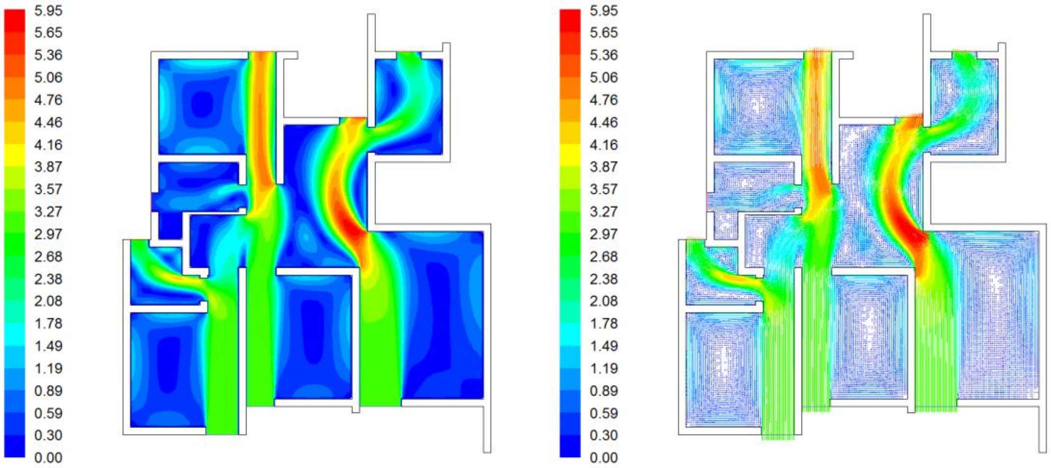

Figure 4.14 Wind velocity and turbulence field of CASE01 under indoor natural ventilation

Source: Author

(2)The simulation and analysis of the 1.5m height horizontal section of CASE02, as shown in figure 4.15:

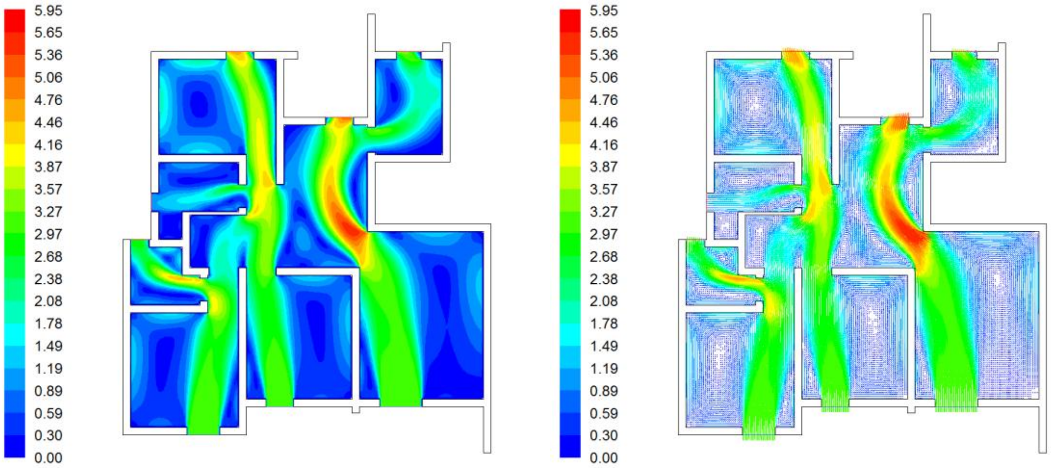

Figure 4.15 Wind velocity and turbulence field of CASE02 under indoor natural ventilation

Source: Author

According to the wind field slice map at 1.5m of indoor natural ventilation in Figure 4.15, relative to CASE01, the relative position between outer doors and windows and indoor internal doors is changed. The strong “cross-ventilation” effect in indoor still exists, but it obviously shows that airflow path flowing through the indoor is obviously lengthened. Compared with CASE01, locally concentrated airflow density slows down to some extent and velocity also slows down. The concentrated velocity in the middle dining rooms is obviously reduced. Moreover, it can be observed from wind turbulence that airflow distribution is relatively more even. The local velocity of indoor wind field is still concentrated, flow velocity is fast and distribution is uneven. Opening window for ventilation in summer also results in unsuitable indoor ventilation environment for residents. And it is not good for providing the favorable indoor thermal comfortable environment. As a whole, the indoor natural ventilation effect of CASE02 is superior to CASE01.

(3)The simulation and analysis of the 1.5m height horizontal section of CASE03, as shown in figure 4.16:

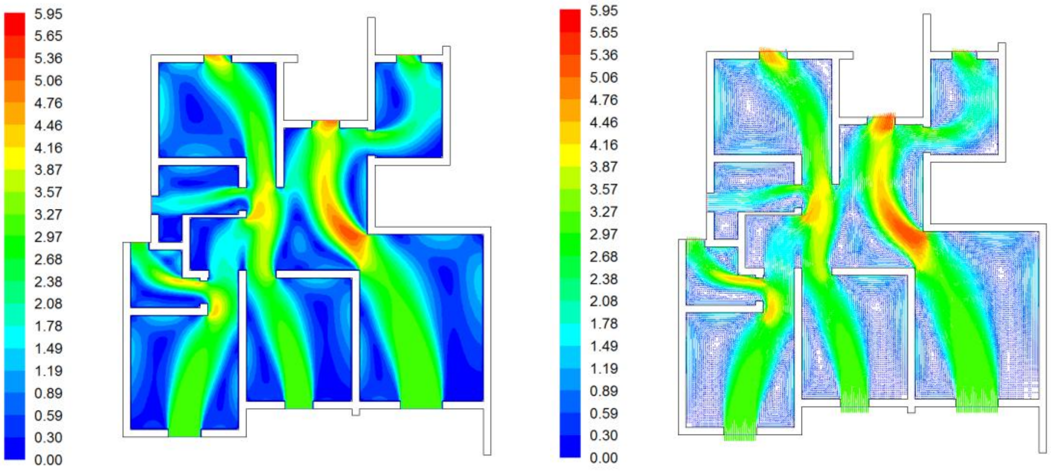

Figure 4.16 Wind velocity and turbulence field of CASE03 under indoor natural ventilation

Source: Author

The position setting of outer doors and windows in CASE03 is the most zealous for architectural designers and it is located in the center of each exterior wall. It can be observed from wind field slice map of indoor natural ventilation in Figure 4.16 that relative to CASE02, the indoor natural ventilation of the working condition further makes progress. The abnormally obvious “cross-ventilation” airflow in the previous working condition gradually slows down. By making a comparison with CASE01 and CASE02 working conditions, the concentrated wind velocity obviously slows down. It can be obviously observed from CASE03 working condition that three strong airflows originally passing through the rooms start evenly expanding to each wind hole of rooms, thus indoor natural ventilation environment is slightly improved by comparing with two previous working conditions. However, such a working condition still can't provide the favorable indoor natural ventilation environment for households.

(4)The simulation and analysis of the 1.5m height horizontal section of CASE04, as shown in figure 4.17:

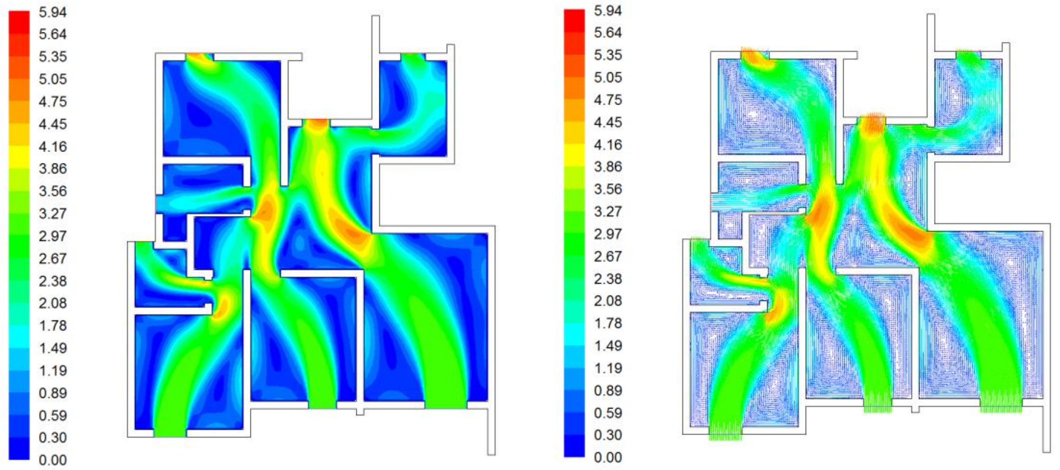

Figure 4.17 Wind velocity and turbulence field of CASE04 under indoor natural ventilation

Source: Author

It can be observed from Figure 4.17 that there is an obvious change: in top three working conditions, especially for CASE01 and CASE02, "cross-ventilation" with the high flow velocity almost disappears. The two bedrooms on the west side of the suite have good natural ventilation and the longer air flow paths make the wind speed appropriate. This kind of ventilation makes indoor heat dissipation effect more obvious in summer. The only obvious airflow means that relative to bedrooms, north-south all-transparent degree of living rooms and dining rooms is greater. This is called by the smaller windage in indoor furniture facilities. By making a comparison between Figure 4.16 and Figure 4.17, it can be found that indoor average velocity of CASE04 is superior to CASE03. The main indoor activity space gains the better ventilation effect. Based on the wind turbulence, it shows that three southward rooms of CASE03 and CASE04 have the turbulence in two directions. This is not good for natural ventilation experience of residents, thus comparing to the wind turbulence, the CASE04 has the better ventilation effect than the CASE03, but the ventilation effect still needs improvement.

(5)The simulation and analysis of the 1.5m height horizontal section of CASE05, as shown in figure 4.18:

It can be found from Figure 4.18 that the relative position between outer doors and windows and indoor internal doors is maximum. Similarly, natural ventilation path flowing through the indoor is also the farthest. From the perspective of indoor wind field strength average, CASE05 is optimal. By combining with the questionnaire results and this working condition’s wind turbulence in chapter three of this study, it shows that CASE05 is the only main indoor life space, especially for southward living rooms and bedrooms. The same room only has a kind of turbulence phenomenon. Because the indoor wind field belongs to microenvironment, it is not easy to change in each point. So the CASE05 in the first major category is the best one.

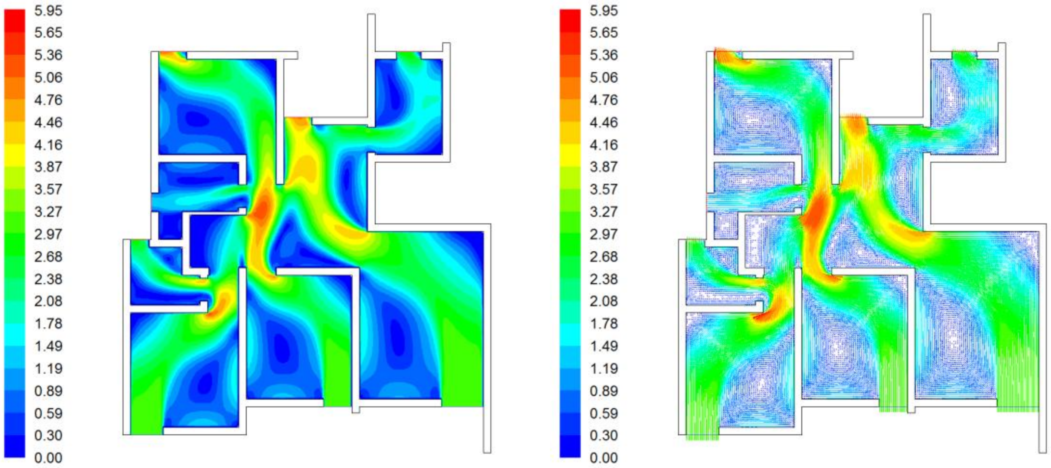

Figure 4.18 Wind velocity and turbulence field of CASE05 under indoor natural ventilation

Source: Author

By summarizing the first category of working condition comparison, it shows that if the relative position of outer doors and windows and indoor internal doors is larger, the airflow route flowing through the indoor will be longer. Wind velocity distribution will be evener. And wind turbulence distribution will be better.

4.4.2 Analysis of the Second Type of Simulation Results

(1)The simulation and analysis of the 1.5m height horizontal section of CASE06, as shown in figure 4.19:

It can be observed from Figure 4.19 that when opening width of outer doors and windows is 10% of room opening, indoor supply air rate is very small and wind velocity is too low. The northward rooms almost have no ventilation quantity, because by making a comparison between small air inlet and fast outdoor wind velocity, it is hard to introduce outdoor wind to the indoor space. The entire space is similar to a closed cavity. It seems that turbulence is even, but the distribution law—the airflow coverage flowing through the indoor is too small. Too low or even almost zero wind velocity of indoor ventilation environment is extremely unfavorable for residents. Hence, this working condition can't offer the suitable indoor natural ventilation environment to households.

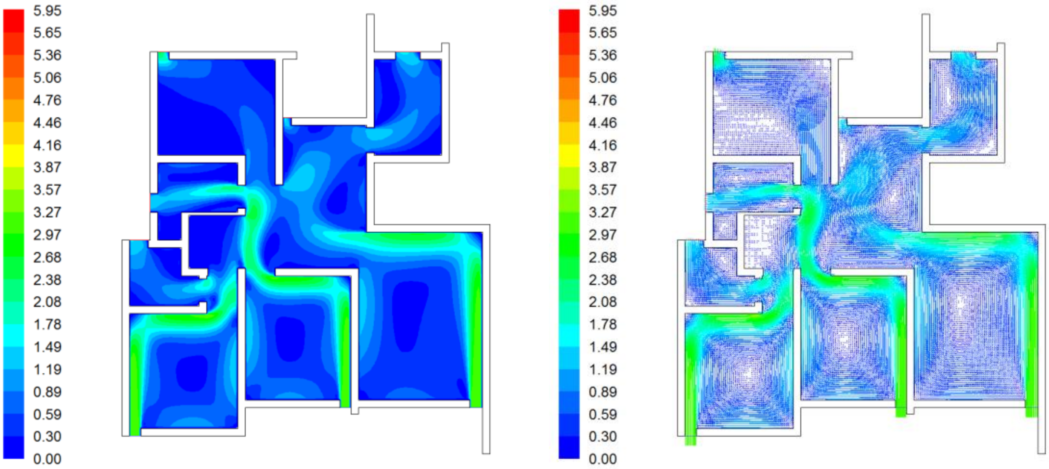

Figure 4.19 Wind velocity and turbulence field of CASE06 under indoor natural ventilation

Source: Author

(2)The simulation and analysis of the 1.5m height horizontal section of CASE07, as shown in figure 4.20:

It can be found from the wind field slice map at 1.5m of indoor natural ventilation in CASE07 that when the opening width of outer doors and windows is 20% of room opening, air inflow of natural air in the suites is obviously improved and wind velocity is also enhanced. At the same time, it reveals that there is the airflow path of urgent wind velocity in one side of the living rooms. Based on the wind turbulence, it indicates that main indoor life space has uneven airflow distribution. The airflow velocity in the southwest of living rooms is slow. Moreover, the airflow path distribution of three bedrooms is also uneven. Considering the overall effect, CASE07 is better than CASE06, but this working condition still can't give the suitable indoor natural ventilation environment to households.

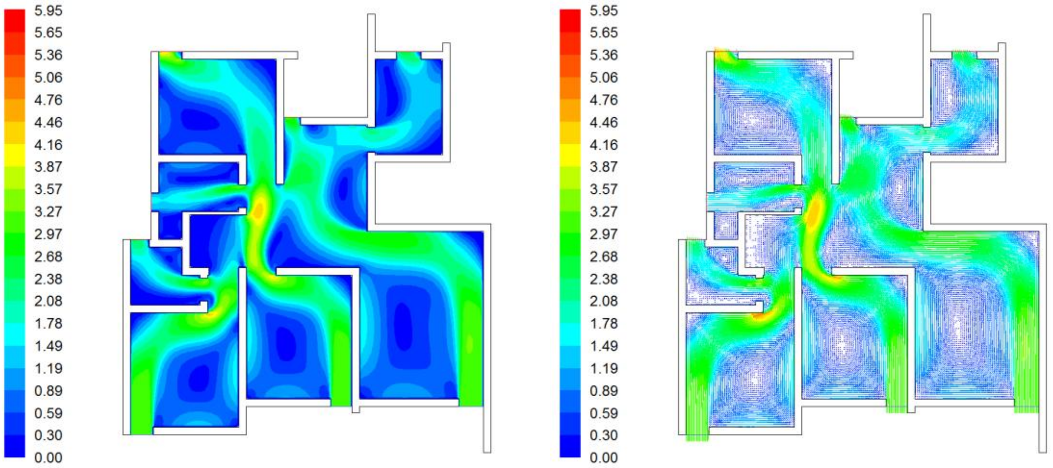

Figure 4.20 Wind velocity and turbulence field of CASE07 under indoor natural ventilation

Source: Author

(3)The simulation and analysis of the 1.5m height horizontal section of CASE08, as shown in figure 4.21:

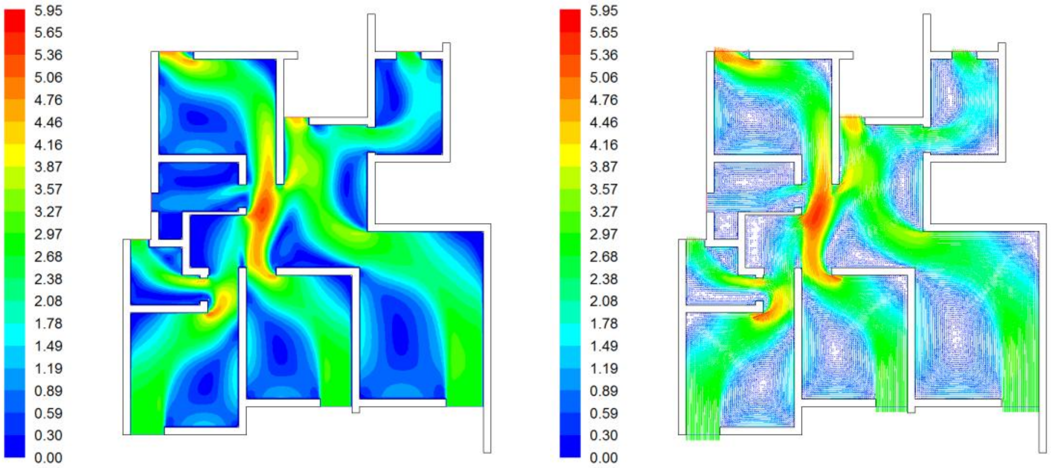

Figure 4.21 Wind velocity and turbulence field of CASE08 under indoor natural ventilation

Source: Author

According to Figure 21, with the width increase of outer doors and windows, when the opening width of outer doors and windows is 30% of room opening, the indoor supply air rate is increasingly large. And the average window velocity is also increased with it. On accounting of the farther relative position between doors and windows and internal doors of rooms, the airflow path flowing through the indoor is longer. And indoor wind velocity field distribution and wind turbulence distribution are relatively even. Under the circumstance, indoor wind environment of CASE08 is similar to CASE05, because in the first category of changes, width of doors and windows is consistent with the practical width of the buildings involved. By integrating with the data in Table 4.2 and Table 4.5, it indicates that the door and window size of CASE08 is slightly less than the original case and it is almost the same, revealing that the indoor ventilation environment under the opening width of this working condition can be considered as the indoor wind field simulation situation as changing the door and window position under the circumstance of maintaining and unchanging the original door and window opening width for buildings involved.

(4)The simulation and analysis of the 1.5m height horizontal section of CASE09, as shown in figure 4.22:

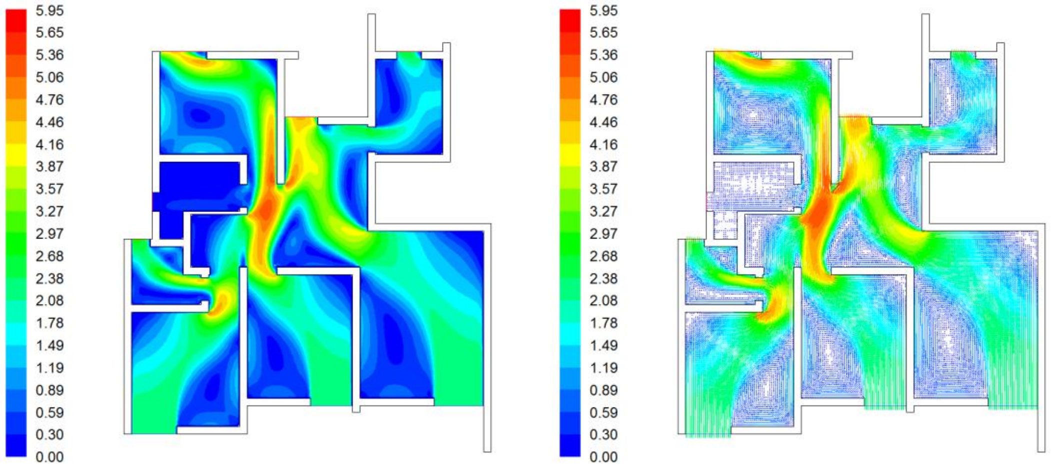

Figure 4.22 Wind velocity and turbulence field of CASE09 under indoor natural ventilation

Source: Author

As shown in Figure 4.22, when the opening width of outer doors and windows is 40% of room opening, the wind velocity field distribution in the simulated type doesn't have a large difference from CASE08. For balcony ventilation in public dining rooms and living rooms, the air inlet and outlet area is greater than the outer window area of bedrooms, resulting in the strong "cross-ventilation". However, the indoor wind turbulence distribution is also slightly better than CASE08, so the main living space velocity distribution in bedrooms and living rooms is relatively even and slow.

(5)The simulation and analysis of the 1.5m height horizontal section of CASE10, as shown in figure 4.23:

It can be seen from Figure 4.23 that the distribution of indoor wind velocity field and wind turbulence field of CASE09 are basically the same when the width of the outside door and window opening is 50% of the room width. From this, we can conclude that: within a certain range, as the width of the outer door and window openings becomes larger, the distribution of indoor wind velocity field gradually becomes more uniform and the distribution range of the wind turbulence field becomes larger and more uniform; with the small width of the door and window openings, although the relative increase of wind speed is beneficial to the summer surface heat dissipation of residents, the uneven distribution of the flow field can not create a suitable indoor natural ventilation environment.

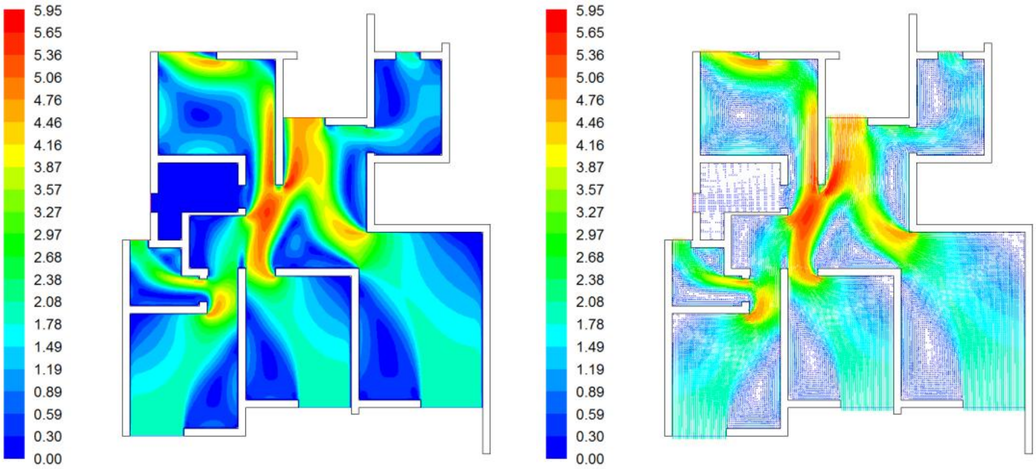

Figure 4.23 Wind velocity and turbulence field of CASE10 under indoor natural ventilation

Source: Author

To sum up, if the outer door and window width has the larger proportion in the corresponding room opening, the indoor natural ventilation effect will be better. However, when the outer door and window width reaches more than 30% of opening width, the influences of doors and windows on indoor wind turbulence distribution and ventilation status are not obviously any more. For this reason, when the proportion of outer door and window width in opening width is 30%-40%, indoor natural ventilation is the best.

4.4.3 Analysis of the Third Type of Simulation Results

(1)The simulation and analysis of the 1.5m height horizontal section of CASE11, as shown in figure 4.24:

According to the wind field slice map at 1.5m of indoor natural ventilation in CASE11, it shows that when the included angle between outdoor wind direction and south elevation of the CASE01 building is 15°, indoor supply air rate is very small and wind velocity is too low. Northward rooms almost have no ventilation quantity, because by comparing with the fast outdoor wind velocity between the small air inlet and wind direction angle, it is difficult to guide outdoor wind into indoor. At the moment, the air inlet is large, but airflow coverage flowing through the indoor is too small. The entire indoor space is similar to a closed cavity. Too low indoor ventilation environment or even zero wind velocity of indoor ventilation environment is extremely unfavorable for residents, thus this working condition can’t give the suitable indoor natural ventilation environment to residents.

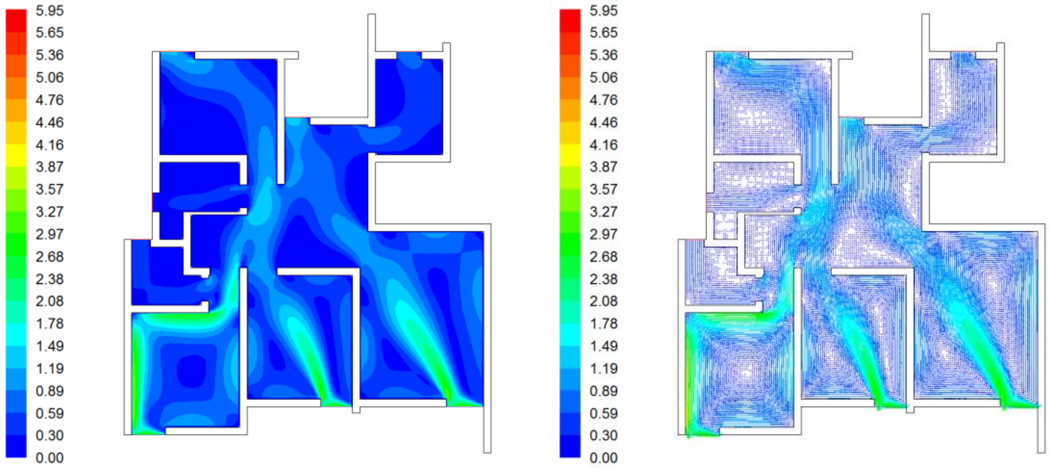

Figure 4.24 Wind velocity and turbulence field of CASE11 under indoor natural ventilation

Source: Author

(2)The simulation and analysis of the 1.5m height horizontal section of CASE12, as shown in figure 4.25:

Based on the wind field slice map at 1.5m of indoor natural ventilation in CASE12, it is noted that when the included angle between the outdoor wind direction and south elevation of CASE01 building is 30°, since the “cross-ventilation” effect caused by the indoor door and window position is too obvious, majorities of airflows flowing from the southward air inlet window may directly and quickly flow through the main indoor space, such as bedrooms, lobbies and dining rooms. Similarly, it also can be observed from the wind turbulence that wind velocity distribution is extremely uneven. There are three obvious north-south “cross-ventilation” airflows in the southing suite slantly running through the living space. Moreover, there is almost no ventilation effect in the primary life space. Generally speaking, indoor wind field supply air rate of CASE12 is slightly increasing by comparing with CASE11, but local ventilation quantity is too concentrated and has the faster flow velocity. Under such circumstances, the natural ventilation in summer will lead to the unsuitable indoor ventilation environment and this goes against providing the favorable indoor thermal comfortable environment.

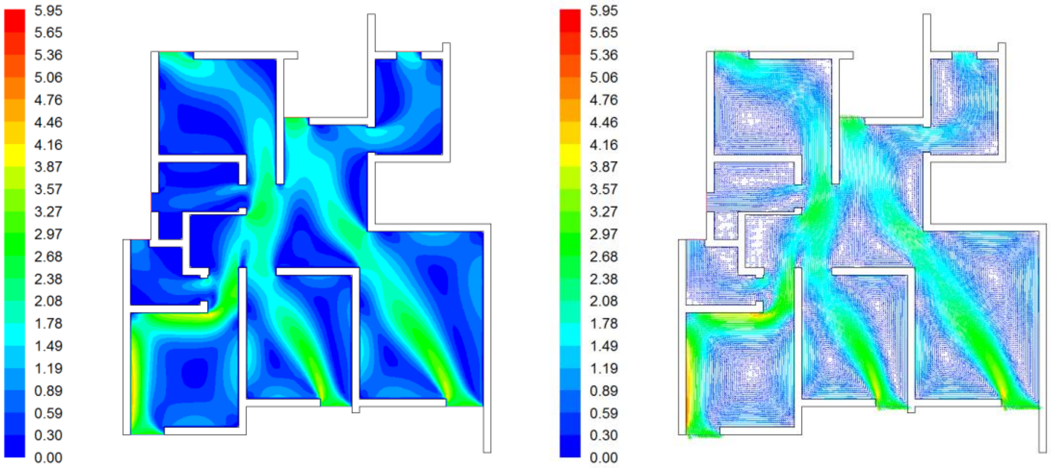

Figure 4.25 Wind velocity and turbulence field of CASE12 under indoor natural ventilation

Source: Author

(3)The simulation and analysis of the 1.5m height horizontal section of CASE13, as shown in figure 4.26:

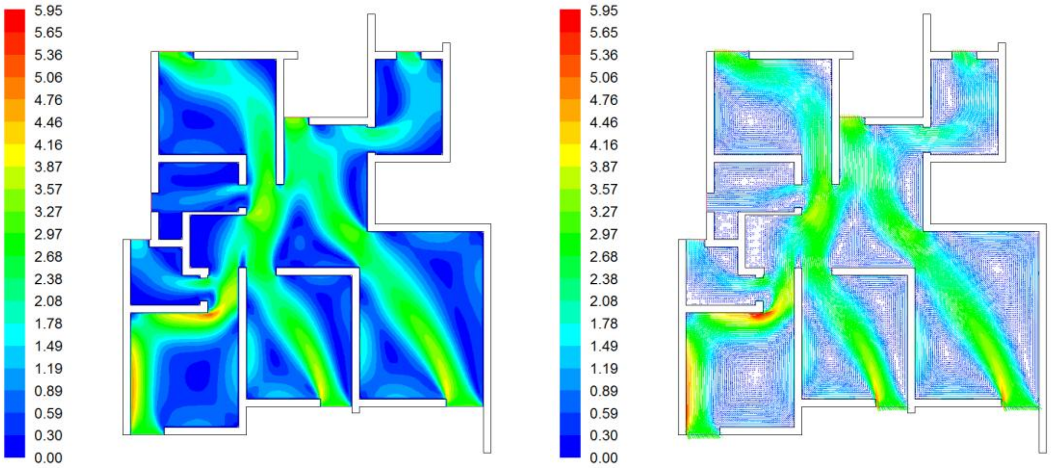

Figure 4.26 Wind velocity and turbulence field of CASE13 under indoor natural ventilation

Source: Author

By referring to the wind field slice map at 1.5m of indoor natural ventilation in CASE13, it reveals that when the included angle between outdoor wind direction and south elevation of CASE01 building is 45°, the indoor natural ventilation is relatively similar to CASE12. Though the angle between the outdoor wind direction and southward air inlet window is enlarged, supply air rate is increased, airflow coverage flowing through the indoor is increased, and wind velocity slows down. Nevertheless, on the basis of combining with the wind turbulence, the indoor still has lower partial space ventilation quantity. What's more, the airflow is still too concentrated, so this working condition still can't offer the suitable indoor natural ventilation environment to households.

(4)The simulation and analysis of the 1.5m height horizontal section of CASE14, as shown in figure 4.27:

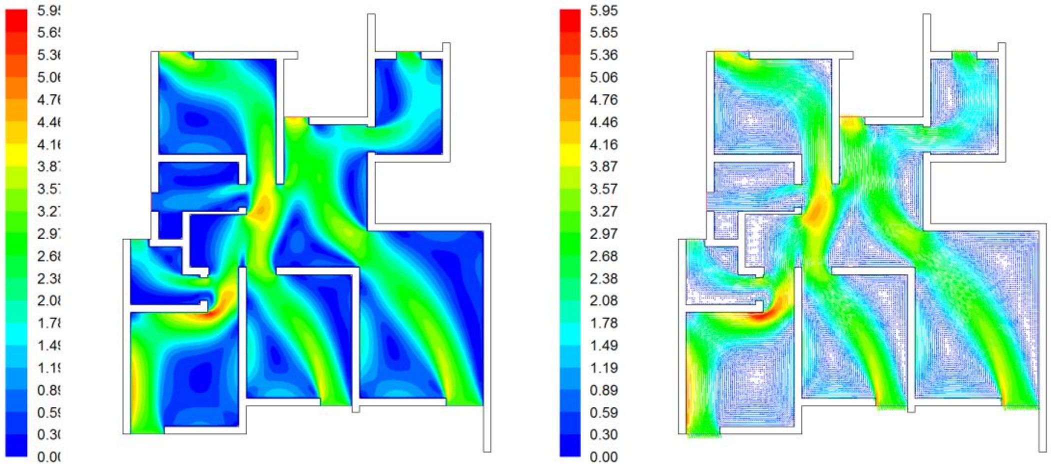

Figure 4.27 Wind velocity and turbulence field of CASE14 under indoor natural ventilation

Source: Author

Based on the wind field slice map at 1.5m of indoor natural ventilation in CASE14, it shows that when the included angle between the outdoor wind direction and south elevation of CASE01 building is 60°, the indoor natural ventilation is greatly improved by comparing to CASE12. Indoor ventilation quantity distribution is evener. According to the wind turbulence analysis, it can be found that it is similar to working condition in CASE13. Two southward rooms have two diverse turbulences, so this working condition can't greatly provide the suitable indoor natural ventilation environment for households.

(5)The simulation and analysis of the 1.5m height horizontal section of CASE15, as shown in figure 4.28:

Based on the wind field slice map at 1.5m of indoor natural ventilation in CASE15, it can be observed that when the included angle between the outdoor wind direction and south elevation of CASE01 building is 75°, the indoor natural ventilation under this working condition is similar to CASE08. Due to the large included angle between outdoor wind direction and air inlet window, there is more supply air rate in the indoor space. Moreover, by comparing with top four working conditions, airflow coverage flowing through the indoor space is expanded. And slow wind velocity distribution is evener, thus in the third category of simulation, this working condition's indoor natural ventilation environment is better.

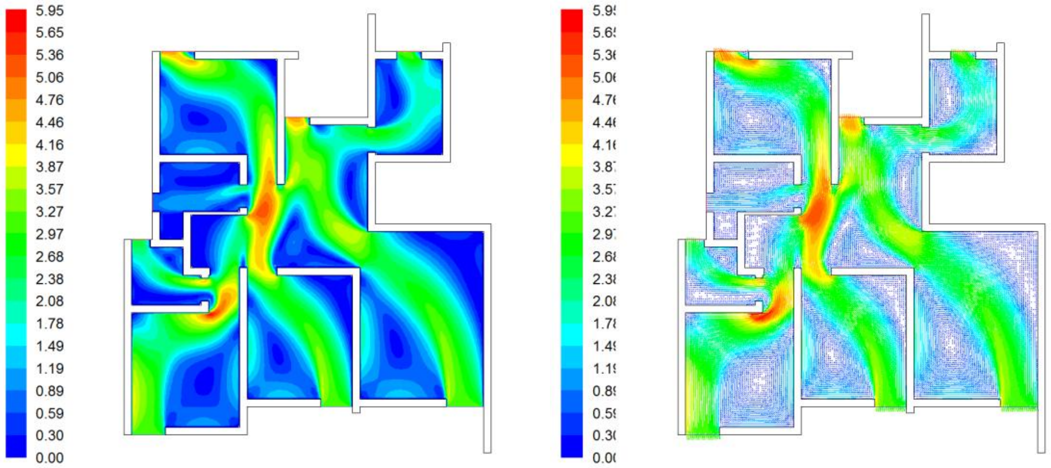

Figure 4.28 Wind velocity and turbulence field of CASE15 under indoor natural ventilation

Source: Author

(6)The simulation and analysis of the 1.5m height horizontal section of CASE16, as shown in figure 4.29:

As can be seen from the horizontal section of the naturally ventilated wind field in Figure 4.29, the angle between the outdoor wind direction and the south facade of Building Case01 is 90°, which the wind direction is a positive south. Because of the same relative position of the façade doors and windows and the width of the façade doors and windows, the indoor ventilation of this condition is identical to that of the CASE08. Similarly, because of the large angle between the outdoor wind direction and the south-facing air-intake window, the air volume in the room is large at this moment. And in this type of simulation, the airflow in this condition flows through the indoor coverage much the same as the CASE15, and the wind speed is moderated and the wind turbulence field is more uniform. Therefore, in the third type of simulation, this condition of the indoor natural ventilation environment is equally good.

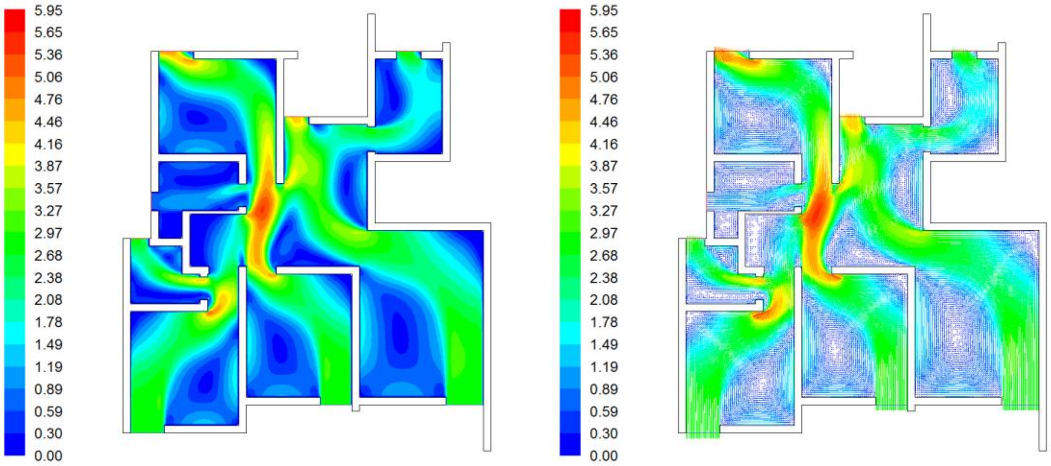

Figure 4.29 Wind velocity and turbulence field of CASE16 under indoor natural ventilation

Source: Author

To sum up, in summer, as the angle between outdoor natural wind direction and the main entrance window of the case building gradually becomes larger, the comprehensive effect of indoor natural ventilation will get better and better. Combined with the comprehensive analysis of CASE015 and CASE16, we can see that the indoor natural ventilation is superior when the angle between the outdoor natural wind direction and the air inlet window of the case building — the south facade of the building is between 75 ° and 90 °.

4.4.4 Analysis of the Fourth Type of Simulation Results

(1)The simulation and analysis of the 1.5m height horizontal section of CASE17, as shown in figure 4.30:

Section 4.2 shows that the outdoor simulation wind speed of CASE17 is 2.7m/s, combined with its horizontal section of the naturally ventilated wind field in Figure 4.30 can be seen, the main indoor space have adequate air flow and the distribution of indoor wind velocity field and wind turbulence field are more uniform. There is only one turbulence phenomenon in all of the main rooms, which will make the indoor ventilation better. The average wind speed over the entire space is moderate, and there is no phenomenon that the local wind speed is too concentrated and the flow velocity is too fast, like the "cross ventilation". In such conditions, natural ventilation in summer can provide occupants with a more suitable indoor thermal comfort environment.

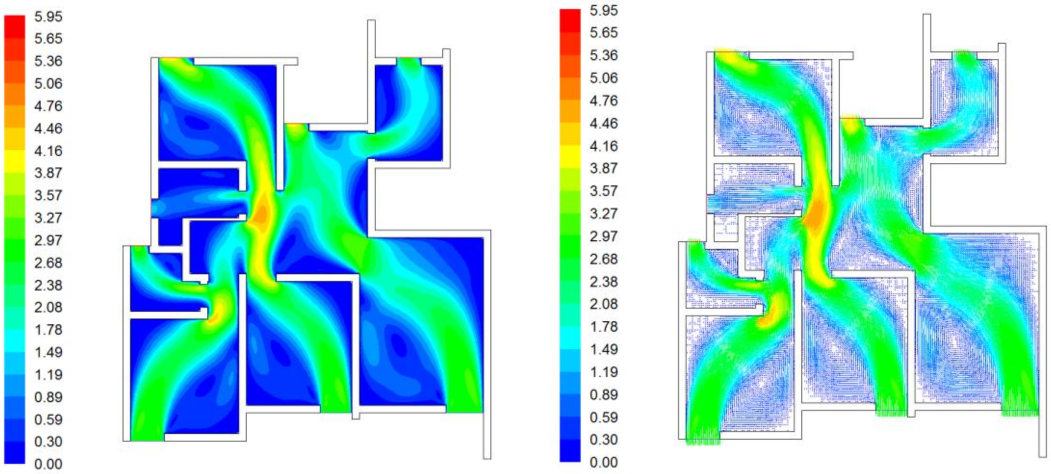

Figure 4.30 Wind velocity and turbulence field of CASE17 under indoor natural ventilation

Source: Author

(2)The simulation and analysis of the 1.5m height horizontal section of CASE18, as shown in figure 4.31:

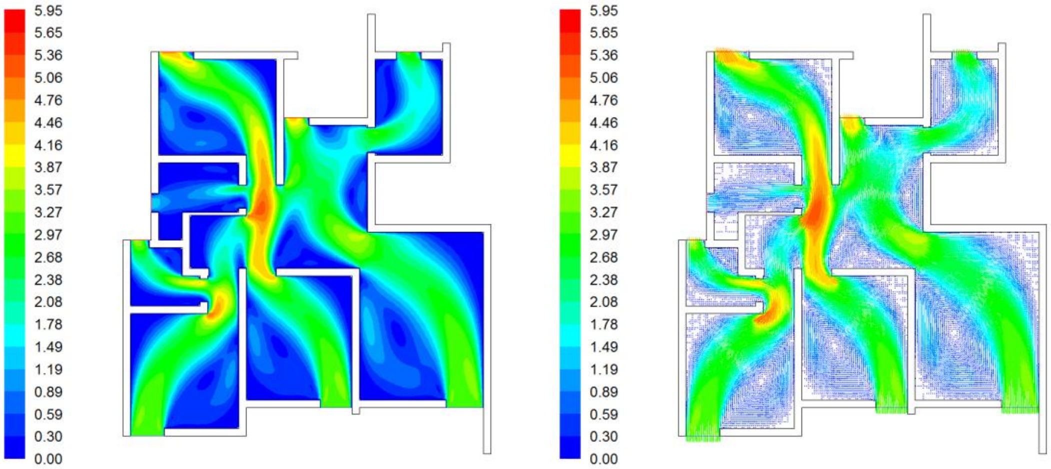

Figure 4.31 Wind velocity and turbulence field of CASE18 under indoor natural ventilation

Source: Author

By the same token CASE18 outdoor simulation wind speed 3.1m/s, at this time its simulation parameters is similar with CASE08. As can be seen from the horizontal section of the naturally ventilated wind field in Figure 4.31, compared with the CASE17 its indoor air volume is increasing, the average wind speed also will be slightly increased. Indoor wind turbulence field in each of the main rooms are also distributed in only one direction of the flow field. Indoor air coverage is also increased and bathroom and kitchen ventilation has also improved. Therefore, under such outdoor wind speed conditions, the indoor natural ventilation environment can provide occupants with a more suitable indoor thermal comfort environment.

(3)The simulation and analysis of the 1.5m height horizontal section of CASE19, as shown in figure 4.32:

The outdoor simulation wind speed of CASE19 is 3.4m/s. Combined with its horizontal section of the naturally ventilated wind field in Figure 4.32 can be seen that the indoor air intake is similar with CASE18, but the average wind speed has increased. The indoor main room also has only one kind of turbulent field phenomenon, and the distribution area of the air flow also increases. The overall average flow velocity is relatively slow. However, on the west side of the dining room, the wind speed of the two bedroom doors opposite to each other was slightly faster and the airflow distribution was relatively concentrated. Although compared with the CASE18, its indoor natural ventilation is slightly discomfort. But from a general perspective, it is still possible to create a more suitable indoor environment for occupants.

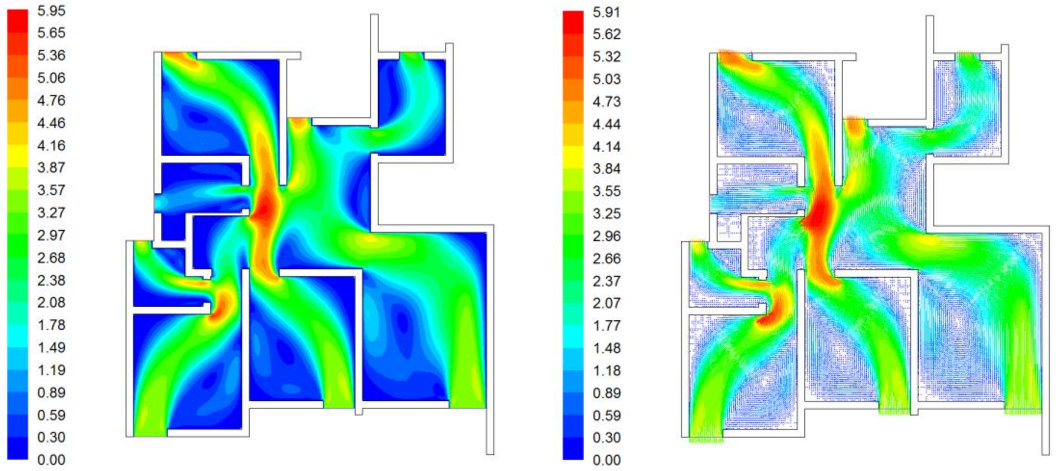

Figure 4.32 Wind velocity and turbulence field of CASE19 under indoor natural ventilation

Source: Author

(4)The simulation and analysis of the 1.5m height horizontal section of CASE20, as shown in figure 4.33:

The outdoor simulation wind speed of CASE20 is 3.6m/s. Combined with its horizontal section of the naturally ventilated wind field in Figure 4.33 can be seen, with the outdoor wind speed continues to increase, the average indoor wind speed is also significantly larger. As the wind speed at the south entrance becomes larger and the air volume increases, there is a phenomenon of "cross ventilation" between the two bedrooms in the interior and the wind speed at the outlet on the north side also increases significantly. Although the distribution of wind turbulence in the main indoor space is good, too fast an airflow speed will cause an unfavorable experience for occupants. So overall, the indoor natural ventilation in this condition is not as good as CASE19.

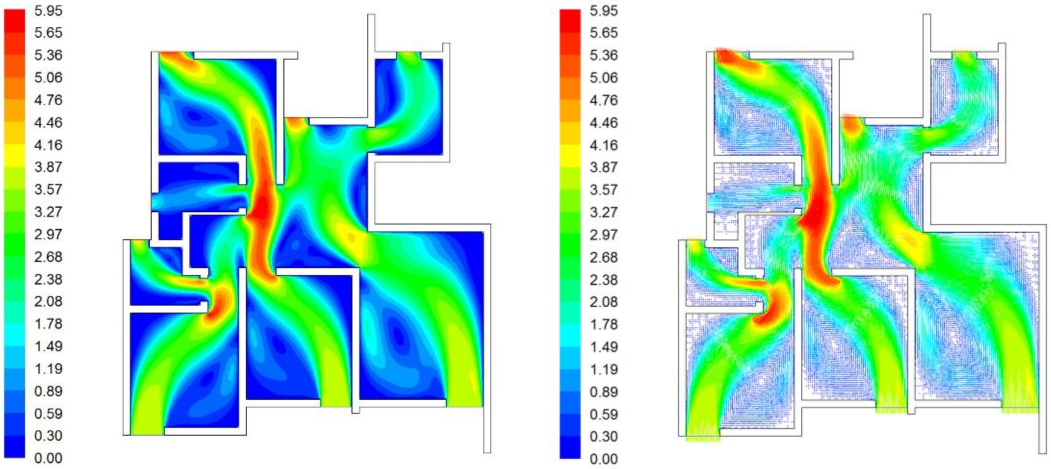

Figure 4.33 Wind velocity and turbulence field of CASE20 under indoor natural ventilation

Source: Author

(5)The simulation and analysis of the 1.5m height horizontal section of CASE21, as shown in figure 4.34:

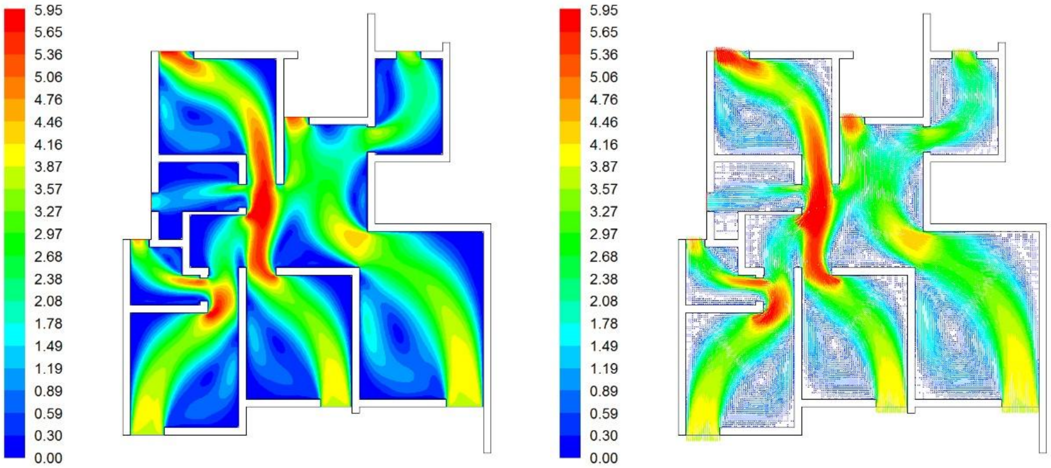

Figure 4.34 Wind velocity and turbulence field of CASE21 under indoor natural ventilation

Source: Author

The outdoor simulation wind speed of CASE21 is 3.8m/s. Combined with its horizontal section of the naturally ventilated wind field in Figure 4.34 can be seen, the average indoor air velocity has been greatly enhanced and the indoor appeared obvious "cross ventilation" phenomenon. The wind speed near the vents on both sides of the north and south is very high, and this fast airflow tends to connect with each other. Therefore, under such conditions, the indoor natural ventilation environment has dropped compared with CASE20.

(6)The simulation and analysis of the 1.5m height horizontal section of CASE22, as shown in figure 4.35:

The outdoor simulation wind speed of CASE22 is 4.0m/s. Combined with its horizontal section of the naturally ventilated wind field in Figure 4.35 can be seen, this time the overall indoor air flow simulation speed are generally large. And compared with the CASE21, this flow between the vents on both sides of the north and south is faster and eventually connected. The natural ventilation of the occupants at this wind speed is less appropriate.

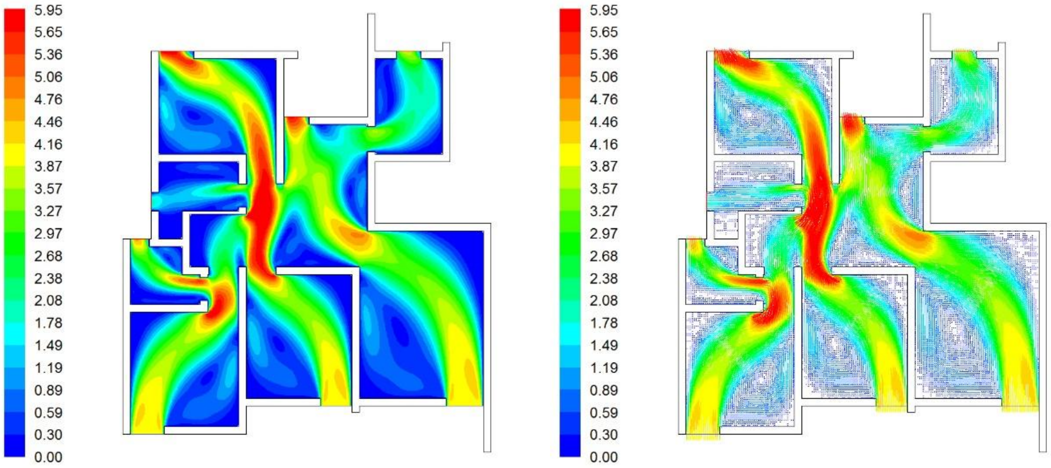

Figure 4.35 Wind velocity and turbulence field of CASE22 under indoor natural ventilation

Source: Author

In summary, we can see that with the height of the floor where the occupants are located, the corresponding outdoor wind speed will also become larger. Combining the simulation data and Table 4.9, it can be seen that when the number of floors is around 1-7, natural ventilation can provide occupants with a comfortable indoor environment. Then when the number of floors is gradually rising, outdoor wind speed becomes larger. At about 10th floor, the effect of natural ventilation will begin to be inadequate and will continue to decrease as the floor rises.

4.5 Chapter Summary

This chapter conducts the numerical simulation on indoor natural ventilation for Case01 building. By comparing the relative position of exterior door and window with indoor door, the ratio of opening width of exterior door and window (window-wall ratio), and the outdoor wind direction and wind speed, the influence of these variables on indoor natural ventilation is compared and analyzed, and the main conclusions are drawn as follows:

(1)The relative position between outer doors and windows and internal doors of the corresponding room has the great influences on indoor natural ventilation effect of residential buildings. Moreover, the larger relative position is, the better ventilation effect will be.

(2)The proportion of the opening width of the exterior door and window with the width of the corresponding room also has an influence on natural ventilation effect of residential buildings. According to the simulation results of the Case01 building, it can be seen that the indoor natural ventilation works best when the ratio of the opening width to the width of the corresponding room is 30% -40%. In other words, when the proportion of actual outer door and window width in the corresponding room opening width is 60%-80%, this proportion is based on the horizontal pull window of outer doors and window. Besides, with the increase of outer door and window width, the viewing horizon range obtained households also will be improved.

(3)When using natural ventilation in residential buildings, the air flow in the room is best organized when the angle between the building orientation and the main outdoor wind direction in summer is between 75 ° and 90 °.

(4)When the outdoor wind speed changes, indoor natural ventilation environment will be different. Under the premise of the outdoor wind speed of 10m from the ground of 3.1m/s, the indoor natural ventilation environment is more comfortable when the wind speed is slightly reduced, ie, the number of floors is about 1-7. However, as the simulated outdoor wind speed continues to increase, the effect of natural ventilation will begin to be inadequate at around the 10th floor. And as the floors continue to rise, indoor air quality, which relies solely on natural ventilation, will continue to decline.

In view of corresponding changes in carbon emission of buildings by using different methods to enhance indoor natural ventilation effect, chapter five will further study the changes of the outer door and window position and size and their influences on carbon emission alternation of buildings.

Chapter 5 | The Physical Impact on Building Carbon Emissions of The Change of Residential Exterior Doors and Windows

5.1 Defining the Scope of Calculation

Generally speaking, physical properties of buildings are restrained by thermal performance of external building envelope structure and relevant regulations of building design. The physical performance influences of residential buildings in this study refer to physical property changes of outer doors and windows, resulting in objective changes of building material consumption in the case buildings or influences of energy consumption changes in yearly daily operation of buildings by changing the residential window-wall ratio in the service stage. However, the energy consumption simulation calculation about building equipment system operation in PKPM energy consumption software won't consider the daily habits of residents or outside subjective factor changes. In order to conform to the reality as calculating carbon emission changes, this study obtains the energy consumption simulation correction factors in chapter three and applies it in the subsequent calculation by making a comparison on the relationship between measured data and simulated energy consumption.

In general, as estimating carbon emission of residual buildings, carbon emission changes in each stage from material production to final recycle and disassembly should be calculated in accordance with the theoretical system of building full life circle (FLC). According to *Carbon Emission Measurement Standard (CECS374-2014)* in China, the main carbon emission unit of residential building FLC is present in Table 5.1:

Table 5.1 Statistical table of main carbon emission units in residential buildings

Life Cycle Stage	Major Carbon Emission Units
Production Stage Of Building Materials	1. The use of main building materials and components; 2. The use of building envelope materials and components; 3. The use of building filling materials, components and equipment.
Building Construction Stage	1. The transportation of building materials, components and equipment; 2. The operation of construction machinery and equipment; 3. The office of construction site.
Building Operation And Maintenance Stage	1. The operation of building equipment system;

	2. The maintenance and replacement of building materials, components and equipment; 3. The replacement of building materials, components, equipment transport.
Building Dismantling Stage	1. The operation of dismantling machine; **2. The transportation of wastes.**
Building Recycling Stage	1. The recyclable materials and components of the main structure of the building; **2. The recyclable materials and components of building envelope;** 3. The recyclable materials and components recycling of building filling materials.

Source: Author

Since the above-mentioned table covers each stage of residential building FLC and almost gets involved in all carbon emission units, and complexity of data collection and wide working range exceed the range field of this study, this study will focus on screening out the carbon emission unit that is greatly related to physical changes of outer doors and windows to do in-depth study after referring to the research achievements of scholars, for the sake of focusing on key influence factors, while maintaining scientificity. By comparing with the carbon emission difference before and after physical changes of outer doors and windows in each unit, this study greatly states the influences of changing outer doors and windows on building carbon emission changes. This study selects carbon emission change unit in five stages, including (1) utilization of materials, construction elements and components for building envelope structure; (2) transportation of building materials, construction elements, components and equipment; (3) operation of building equipment system; (4) transportation of waste; (5) recycling of materials and components in building envelope structure(see the bold parts in Table 5.1).

Outer doors and windows change indoor natural ventilation and also change window-wall ratio of buildings. In order to maintain indoor temperature, energy consumption in yearly operation stage of relevant building equipment system will be changed with it. In addition, changes of window-wall ratio will also change material quantity of external building envelope structure. Moreover, the size of window-wall ratio will be slightly changed relative to the former. This is the reason why the above-mentioned five carbon emission units are closely related to physical changes of outer doors and windows. This study summarizes the carbon emission influences caused by five carbon emission unit changes as follows: (1) changes of outer doors and windows cause the carbon emission changes in building equipment system operation; (2) Changes of outer doors and windows cause the carbon emission changes in external building envelope structure and component materials of outer doors and windows. The correlation of carbon emission variation is expressed as the Formula 5.1:

$$\triangle E_{PHY} = \triangle E_{ESO} + \triangle E_{MPT} \quad (5.1)$$

$\triangle E_{PHY}$ is the physical effects of residential building carbon emissions caused by the changes of outer door and window($kgCO_2/ m^2$);

$\triangle E_{ESO}$ is the changes in actual carbon emissions of the operation of equipment systems during the operation and maintenance phase of residential buildings caused by the changes of outer door and window($kgCO_2/ m^2$);

$\triangle E_{MPT}$ is the changes in the carbon emission of materials related to exterior insulation of residential buildings caused by the changes of outer door and window($kgCO_2/ m^2$).

The following will take the Case01 as the benchmark of calculation object. According to the better change method of indoor natural ventilation design method stimulated in chapter four and acquisition of the better landscape range, the farthest relative position between outer doors and windows with the corresponding rooms and 40% opening width of outer doors and windows in the corresponding rooms are selected for carbon emission simulation and comparison.

5.2 Change of Carbon Emission Caused by the Changes of Outer Door and Window to Operation of Building Equipment System

Under the precondition of ensuring complete relevant data information for building energy consumption calculation, this section will select change measures of outer doors and windows on internal natural ventilation as the simulation guide. The study will only change the position and size of the external door and window on the Case01, and use PKPM software for simulation analysis to calculate the actual power consumption per square miter of the equipment system based on the changed of Case01 in the normal operation period according to Formula 5.2:

$$\triangle AD = \triangle AP \times C \tag{5.2}$$

△AD is the change of actual annual electricity consumption per square meter of the building after the change compared with the original during the operational phase(kWh);

△AP is the change of simulated annual electricity consumption per square meter of the building after the change compared with the original during the operational phase(kWh);

C is the correction factor of the simulated data relative to the empirical data obtained from Chapter 3, which is 0.059.

5.2.1 Data Simulation and Power Consumption Analysis

As mentioned above, the software simulation aims to gain the carbon emission difference with the corresponding original energy consumption after changing outer doors and windows in the case building. As a result, under the precondition of variation control, this experiment applies PKPM software to simulate Case01 building. Based on yearly power consumption data of building equipment system after enlarging width of doors and windows and original power consumption simulation results of Case01 building in Table 3.7, various indexes before and after changing yearly energy consumption in the cse building are listed as follows (Table 5.2):

Table 5.2 Index changes of simulated energy consumption in case building

Total Floors: 7 Building Total Height: 20.30m Building Area: 3167.25m²

Case01	Raw Data	Data after changing the width of the door and window
The South Side of Window-Wall Ratio	0.35	0.47
The South Side of Window Area(m^2)	317.52	427.51
The Change Of Window Area(m^2)	0	109.99
The North Side of Window-Wall Ratio	0.28	0.34
The North Side of Window Area(m^2)	250.90	304.51
The Change of Window Area(m^2)	0	53.61
Annual Simulated Power Consumption of Buildings(kWh/m^2)	53.46	58.24
Yearly simulated power consumption variation of unit area(kWh/m^2)	0	4.78
Yearly simulated power consumption variation of the entire building(kWh)	0	15139.46

Source: Author

According to the results in Table 5.2, it can be observed that relative to the building power consumption of the original building, the yearly simulated power consumption increased by covered area per square meter after enlarging width of doors and windows is 4.78kWh/m^2. According to 3167.25m^2 of the simulated case building, the yearly simulated power consumption increased by enlarging width of doors and windows is 15139.46kWh. The cause for such a change is that the thermal insulation properties of outer doors and windows are lower than the thermal performance of outer wall. The increase and decrease of them will slightly reduce thermal insulation of the entire external envelope structure for the changed building, thus the yearly energy consumption of the building is slightly increased. It can be observed from Figure 3.7 in chapter three that there is the large difference between the simulated data and measured data of the original building, because PKPM software simulation doesn't consider daily behavioral influences of residents on actual heating and refrigeration equipment. Similarly, it can be observed that the yearly power consumption variation after enlarging width of doors and windows calculated by simulation software is insufficiently accurate. After considering the correction factor of the simulation data obtained from Formula 3.1, the actual power consumption after changing the Case01 building based on Formula 5.2 is present in Table 5.3:

Table 5.3 Index changes of measured energy consumption in case building

Total Floors: 7 Building Total Height: 20.30m Building Area: 3167.25m^2

Case01	Raw Data	Data after changing the width of the door and window
Annual simulated energy consumption variation of unit area(kWh/m^2)	0	4.78
Annual simulated energy consumption variation of the entire building(kWh)	0	15139.46
Correction Factor	0.059	0.059
Annual energy consumption variation of actual unit area(kWh/m^2)	0	0.28
Annual actual energy consumption variation of the entire building(kWh)	0	886.83

Source: Author

It can be observed from Table 5.3 that for enlarging outer doors and windows, the annual actual energy consumption increased by the Case01 building per square meter is 0.28kWh/m^2. The annual actual power consumption increased by the entire building is 886.83kWh.

5.2.2 Calculation of Changes in Carbon Emissions from Building Equipment Systems

After obtaining the variation difference of annual actual power consumption of the building after changing the outer doors and windows, according to the benchmark emission factor of power grids in China regions 2015 issued by Tackle Climate Change Department in National Development and Reform Commission (NDRC) in 2016, the power consumption variation of the improved building is converted to the corresponding carbon emission value as the Formula 5.3:

$$\triangle E_{ESO} = \triangle AD \times EF_{ELECTRICITY} \tag{5.3}$$

$\triangle E_{ESO}$ is the changed carbon emission of the heating and cooling($kgCO_2/m^2$);

$\triangle AD$ is the changed annual electricity load per square meter(kWh);

$EF_{ELECTRICITY}$ is the emission factor of the electricity(tCO_2/MWh).

In China, power grid boundary is uniformly divided into regional power grids of North China, Northeast, East China, Central China, Northwest China and South China. The benchmark emission factor of power grids in each region is totally different. The division of the above-mentioned six areas is illustrated in Table 5.4:

Table 5.4 The grid zone of China

Grid Zone	Covered Cities
North China	Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia Autonomous Region
Northeast China	Liaoning, Jilin, Heilongjiang
East China	**Shanghai**, Jiangsu, Zhejiang, Anhui, Fujian
Central China	Chongqing, Henan, Hubei, Hunan, Jiangxi, Sichuan
Northwest China	Shaanxi, Gansu, Qinghai, Ningxia, Tibet Autonomous Region, Xinjiang Autonomous Region
South China	Guangdong, Guangxi Autonomous Region, Yunnan, Guizhou, Hainan

Source: *http://cdm.ccchina.gov.cn/*

Tackle Climate Change Department in NDRC studies and confirms the benchmark emission factor of China regions. The emission factor of each region is shown in Table 5.5. And in this dissertation we choose the East China zone, which is where shanghai is located.

Table 5.5 Emission factor values of regional power grid in China

Grid Zone	$EF_{grid,OM,y}(tCO_2/MWh)$	$EF_{grid,BM,y}(tCO_2/MWh)$
North China	1.0416	0.4780
Northeast China	1.1291	0.4315
East China	0.8112	0.5945
Central China	0.9515	0.3500
Northwest China	0.9457	0.3162
South China	0.8959	0.3648

Notes: (1) OM is the weighted average of margin emission factor for electric quantity in 2011-2013; BM is the margin emission factor of capacity until 2013; (2) This result is calculated on the published summarized data of the power plant.

Source: *http://cdm.ccchina.gov.cn/*

Where OM is the margin emission factor of electric quantity and BM is the margin emission factor of capacity. The calculation method of the current electric power emission factor is the weighted average of OM and BM which the weight is 50% respectively. In this study, the weighted average of them should be used as the electric power emission factor of power grids. The case building in this study is located in Shanghai, which belongs to East China power grid. According to two electric power emission factors of OM and BM in East China power grid, it can be observed that the weighted value is $0.70285tCO_2/MWh$. According to the above-mentioned Table 5.3 and Formula 5.3, it can be observed the carbon emission influences of changing outer doors and windows caused by annual actual operation of the residential building in the operation maintenance stage, as shown in Table 5.6:

Table 5.6 Change of carbon emission caused by the changes of outer door and window to the actual energy consumption of building equipment system

Total Floors: 7 Building Total Height: 20.30m Building Area: $3167.25m^2$

	Raw Data	Data after changing the width of the door and window
The South Side of Window-Wall Ratio	0.35	0.47
The Change Of Window Area(m^2)	0	109.99
The North Side of Window-Wall Ratio	0.28	0.34
The Change of Window Area(m^2)	0	53.61
Correction Factor	0.059	0.059
Annual Simulated Power Consumption of Buildings(kWh/m^2)	53.46	58.24
Annual Simulation Power Consumption Changes of Per Square Meter(kWh/m^2)	0	4.78

Annual Actual Power Consumption Changes of Per Square Meter(kWh/m^2)	0	0.28
Emission Factor(tCO_2/MWh)	0.70285	0.70285
Annual Actual Carbon Emissions Changes of Per Square Meter($kgCO_2/m^2$)	0	0.20
Annual Actual Power Consumption Changes of the Whole Building(kWh)	0	886.83
Annual Actual Carbon Emissions Changes of the Whole Building($kgCO_2$)	0	633.45

Source: Author

Therefore, for the original Case01, the increase of external doors and windows on the building energy consumption caused by changes in the amount of carbon emissions per square meter according to the Formula 5.3 can be drawn as:

$$\triangle E_{ESO} = 0.28 \times 0.70285 = 0.20(kgCO_2/\ m^2)$$

5.3 Change of Carbon Emission Caused by the Changes of Outer Door and Window to Production and Transportation of Building Envelope Material

In this study, changes on the external building envelope structure material consumption through the physical changes of outer doors and windows are reflected in two aspects:

(1) Changes of outer wall material consumption caused by outer door and window position and size changes;

(2) Changes of outer window size caused by outer door and window size changes.

According to the simulated result of the farthest relative position between outer doors and windows with the corresponding rooms in Case01 building and 40% of outer door and window width in the opening width of corresponding rooms, it can be observed that the north-south window-wall ratio is enlarged, so the increase of outer doors and windows will reduce the exterior wall coating consumption. This change is the earning of the design method for building carbon emission. Furthermore, the window-wall ratio increase enlarges the outer window size, resulting in increasing door and window material consumption. This is the design method to increase carbon emission of the case building.

5.3.1 Changes in the Amount of Material Used in the Building Envelope

Due to physical qualitative change influences of outer doors and windows, Case01 Building gains the carbon emission earning in the construction stage caused by reducing building material consumption. As above mentioned, this building is a seven-floor residential building. Since the top is designed as the untouchable roof, external wall structure of the case building includes two types. However, the physical property changes of outer doors and windows only get involved in 1-6 floors of the case building, so the construction drawing of outer wall in the common floors is shown in Figure 5.1. It can be observed from the figure that the wall structure is ranked from outside to inside as follows: cement mortar (20.0mm), polystyrene particle jelly coating (50.0mm), ALC aerated concrete block 240 (240.0mm) and cement mortar (20.0mm).

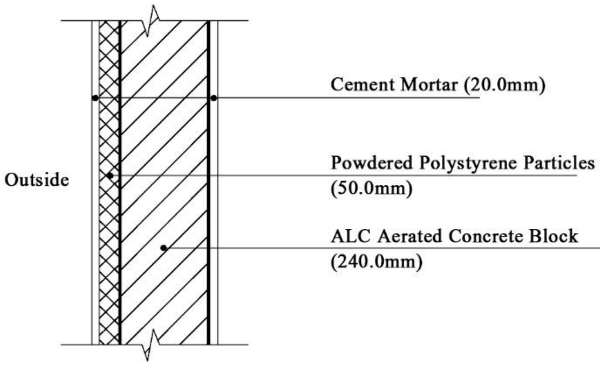

Figure 5.1 Exterior wall structure diagram of the ordinary layer

Source: Author

Similarly, changes of outer windows in the case building changed by physical properties of outer doors and windows also get involved in the 1-6 floors of this building. Moreover, the variation of total area in outer windows is consistent with the variation of outer wall area in the standard layer. As mentioned above, carbon emission unit involved in each stage of the building has the complicated categories, so after focusing on screening carbon emission unit statistics (Table 5.1) of FLC in the residential building, carbon emission change measurement of building envelope structure materials, components and construction elements only just calculates the carbon emission variation brought by changing material consumption absolute of relevant building materials after enlarging doors and windows relative to the original building. As a result, for change measurement of carbon emission in outer windows, this study only calculates the carbon emission variation of material consumption change absolute in the corresponding doors and windows caused by net area change in outer doors and windows.

It can be observed from the construction drawing that the outer door and window materials used by this building are consistent and even: thermal insulation metal aluminum profile multi-cavity sealing frame. The heat transfer coefficient of the frame is Kf=5.0W/(m^2·K). The percentage of frame area in total area of outer doors and windows is 20%. The heat transfer coefficient of Low-E glass (6 transparency+12A+6 transparency) is Kf=3.2W/(m^2·K). Considering the external envelope structure material and component area variation caused by changing physical properties of outer doors and windows in the Case01 Building, this study conducts the corresponding statistical calculation through the simulation software PKPM. The detailed data change is present in Table 5.6, thus the total area variation is 163.6m^2.

To sum up, the carbon emission variation generated by production and transportation in external building envelope structure materials is expressed as the Formula 5.4:

$$\triangle E_{MPT} = (\triangle E_1 + \triangle E_2) \times \frac{S}{FA} \tag{5.4}$$

$\triangle E_{MPT}$ is the amount of change in carbon emissions over the life cycle of residential building-related envelope materials(kgCO_2/ m^2);

$\triangle E_1$ is the amount of carbon emission per square meter of ordinary outer wall;

$\triangle E_2$ is the amount of carbon emissions per square meter of external doors and windows;

S is the amount of change in the area of the outer door and window(m^2);

FA is the total building area.

The specific increased carbon emission value is determined by carbon emission of each material in its FLC, requiring for finding out a quantized approach, so as to do horizontal comparison between this study and other carbon emission unit. It can be observed from chapter two that the database Athena LCA Software in this study will be used as the acquisition approach of benchmark emission of external building envelope structure.

5.3.2 The Introduction to the Carbon Emission Database——ATHENA

Life Cycle Assessment (LCA) is used to analyze products' environmental influences and potential environmental influences in the entire life cycle (it refers to influences of resource utilization and emission on the environment). Such an environmental evaluation method has been developed as early as the 1960s. As the special products built by men, environmental influences of buildings can be divided into two parts: firstly, buildings cause indirect environmental problems in their service stage by coals, hydraulic power and electric power. Secondly, building materials result in energy consumption in production, construction stage and final recycling stage.

Figure 5.2 The database evaluation area diagram of ATHENA

Source: ATHENA database

Athena is the environmental impact analysis database invented by Canadian ATHENATM sustainable material study. It is based on LCA to do corresponding energy influence evaluation on the entire buildings and components. The evaluation data are originated from the American full life circle list database (NREL) and the database independently developed by Canadian Athena College. The evaluation range of the database is wide and comprehensive. In addition to the operation energy consumption in the service stage, the database not only gets involved in carbon emission data of building materials, but also contains carbon emission data in energy utilization, transportation, construction and demolition, as shown in Figure 5.2. The quantitative calculation contains a total of 8 contents:[16]

(1)Energy Consumption: It is used for recording the total energy consumption in material exploitation, production, processing, transportation, construction, and final treatment stages;

(2)Raw material utilization: It is used for recording the raw material usage required by material exploitation, processing, transportation, construction, and final treatment process;

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[16] Wendi Zhang, Haibei Xiong, Chao Zhang et al. *"Environmental Impact Assessment of Buildings with Different Materials Based on LCA [J]."* Journal of Jiamusi University (Natural Science Edition), 2014, (01): 29-32.

(3)Greenhouse effect: Based on CO_2, greenhouse gas output of materials is calculated;

(4)Acid rain: It refers to acid compound output with the reference measurement of H+ equivalent;

(5)Influences on human respiratory health: It is used for recording PM2.5 in life cycle of materials;

(6)Water pollution: It refers to N total quantity by diffusing microorganisms in water body;

(7)Ozone loss: With the measurement of CFCs, it is used to measuring chemical substances of chlorofluorocarbon;

(8)Photochemical smoke effect: With the measurement of oxynitride (NOx), it measures the harmful mixed smoke caused by photochemical reaction in the atmosphere.

Furthermore, considering the influences brought by different regional environments, when Athena LCA Software is used for calculation, it is necessary to select the corresponding specific cities or climatic regions to stand for the position attributes of the building. By comparing with the climatic position selected in this study, Atlanta that has the high similarity in Shanghai is used for data statistics and calculation.

5.3.3 Estimating the Change of Carbon Emissions of Building Envelope Material

This study selects the ecological calculation tool of the residential building components—EcoCalculator for Residential Assemblies in Athena LCA Software for calculation. In essence, it is a structured Excel spreadsheet. Different building components (e.g. outer wall, stand column, beam and floor) correspond to the respective worksheet. Only to find out the components of the corresponding part between the table and the case building can we calculate the carbon emission variation in the FLC. The operation interface is shown in Figure 5.3.

Figure 5.3 The user interface of EcoCalculator

Source: ATHENA database

Figure 5.4 The total life-cycle carbon emissions per square foot of case wall

Source: ATHENA database

The carbon emission of wall components corresponding to the case building in its FLC is based on the database page, as shown in Figure 5.4. According to the model information, it can be observed that the concrete block wall of two-side plastering with XPS thermal insulation material is closest to No.3 wall building in database (Concrete Block 2, Coat Stucco Over Porous Surface, R5 XPS Continuous Insulation), thus the GWP value of the case wall is 7.07kgCO_2/ft^2. The carbon emission variation of the unit area can be calculated in line with the Formula 5.5:

$$\triangle E_1 = \triangle E_{GWP} \times C_T \tag{5.5}$$

$\triangle E_1$ is the amount of carbon emission per square meter of ordinary outer wall;

$\triangle E_{GWP}$ is the carbon emission variation of the corresponding outer wall in EcoCalculator(kgCO_2/ ft^2);

C_T is the conversion ratio from square foot to square meter which is about 10.76.

On the basis of the Formula 5.5, the carbon emission variation of unit area's outer wall in the standard layer in its FLC is shown as follows:

$$\triangle E_1 = 7.07 \times 10.76 = 76.07(\mathrm{kgCO_2}/\,\mathrm{m}^2)$$

Figure 5.5 The total life-cycle carbon emissions per square foot of exterior windows and doors

Source: ATHENA database

Similarly, the carbon emission of outer door and window components corresponding to the case building in the FLC is illustrated in Figure 5.5, thus the carbon emission variation of the unit area in outer doors and windows of the standard layer can be calculated as the Formula 5.6:

$$\triangle E_2 = \triangle E_{D\&W} \times C_T \tag{5.6}$$

$\triangle E_2$ is the amount of carbon emission per square meter of outdoor windows and doors;

$\triangle E_{D\&W}$ is the amount of changes in carbon emissions in the EcoCalculator table for exterior doors and windows($\mathrm{kgCO_2}/\,\mathrm{ft}^2$);

C_T is the conversion ratio from square foot to square meter which is about 10.76.

Therefore, according to formula 5.6, we can see that the amount of change of carbon emission of the exterior doors and windows per square meter of ordinary floor in the whole life cycle is:

$$\triangle E_2 = 67.63 \times 10.76 = 727.70(\mathrm{kgCO_2}/\,\mathrm{m}^2)$$

By combining with the simulation conclusion on outer windows in chapter four and calculation situation of outer doors and windows selected in this chapter, the integrated data are systemized as shown in Table 5.7:

Table 5.7 Change of Carbon Emission Caused by the Changes of Outer Door and Window to Production and Transportation of Building Envelope Material

Total Floors: 7   Building Total Height: 20.30m   Building Area: $3167.25\mathrm{m}^2$

Case01	Raw Data	Data after changing the width of the door and window
Total Area Change of Outer Wall(m^2)	0	-163.6
Total Area Change of Outer Door and Window(m^2)	0	+163.6
The Amount of Carbon Emission Per Square Meter of Ordinary Outer Wall($kgCO_2/m^2$)	0	-76.07
The Amount of Carbon Emission Per Square Meter of Outdoor Windows and Doors($kgCO_2/m^2$)	0	+727.70
Change of Carbon Emission of Building Envelope Material($kgCO_2/m^2$)	0	+33.66
Carbon Emission Changes Throughout the Whole Life Cycle of the Building Envelope Materials($kgCO_2/m^2$)	0	+106606.67

Source: Author

According to the Formula 5.4, total carbon emission variation of the building's relevant external envelope structure material in its FLC caused by enlarging the outer doors and windows in unit area is shown as:

$$\triangle E_{MPT} = (-76.07 + 727.70) \times \frac{163.6}{3167.25} = 33.66(\ kgCO_2/m^2)$$

5.4 Physical Effects Analysis of the Change of Exterior Door and Window on Building Carbon Emissions

From the Formula 5.1, by adding influences in two aspects stated in section 5.2 and section 5.3 of this chapter, the physical influences on the building's carbon emission obtained from Table 5.6 and Table 5.7 by enlarging outer doors and windows are shown in Table 5.8:

Table 5.8 Physical influence of the change of outer door and window on building carbon emissions

Total Floors: 7   Building Total Height: 20.30m   Building Area: 3167.25m^2

Case01	Raw Data	Data after changing the width of the door and window
Total Area of External Wall Door Window(m^2)	0	163.6
Change of Carbon Emission of Building Equipment System($kgCO_2/m^2$)	0	0.20

Change of Carbon Emission of Building Envelope Material(kgCO_2/ m^2)	0	33.66
The Physical Impact on Building Carbon Emissions of the Change of Residential Exterior Doors and Windows(kgCO_2/ m^2)	0	33.86

Source: Author

After enlarging the outer doors and window width, the physical influences on carbon emission by changing outer doors and windows in unit area of Case01 Building are shown as follows:

$$\triangle E_{PHY} = \triangle E_{ESO} + \triangle E_{MPT} = 33.86(kgCO_2/ m^2)$$

To sum up, this chapter only selects the case where the relative position of the outer door and window with the corresponding room is the farthest, and the width thereof accounts for 40% of the corresponding room to calculate the carbon emission. Under this condition, the window-wall ratio of Case01 increased from the original 0.22 to 0.27. And according to the relevant data, it can be calculated that the increase of door and window width has increased the annual carbon emissions of the building. At the same time, according to the relevant literature, Enshen Long put forward that no matter the size of the building form factor, the annual air-conditioning energy consumption increases with the increased of window-wall ratio, in his article *"The Influence of Window-Wall Ratio on the Hot and Cold Energy Consumption and Energy Efficiency of Residential Buildings"*; in the article *"The Impact of Window-Wall Ratio on Building Energy Consumption"*, Maihua Liu put forward that the influence of window-wall ratio on building energy consumption is greater, and the energy consumption of building is directly proportional to the ratio of window-wall ratio and in the article, *"Influence of Window-Wall Ratio on Building Energy Consumption in Hot Summer and Cold Winter Area"*, Chengwen Yan's research result shows that "the heat load of buildings increases with the increased of window-wall ratio". Combined with the data in Table 4.3 to Table 4.7 in Section 4.2 of Chapter 4, this study uses PKPM software to calculate the energy consumption of case data with different window-wall ratios and summarizes the results as shown in Table 5.9:

Table 5.9 The relationship between window-wall ratio and energy consumption

	CASE06	CASE07	CASE08	Original	CASE09	CASE10
Width	10%	20%	30%	Original	40%	50%
Window-Wall Ratio	0.12	0.17	0.22	0.22	0.27	0.32

Energy Consumption	49.48	51.40	53.37	53.46	58.24	61.78

Source: Author

It can be seen from Table 5.9 that the energy consumption of equipment system in Case01 is directly proportional to the ratio of the window-wall ratio. When the width of the exterior door and window of Case 01 is 10% and 20% of the width of the corresponding room, the window-wall ratio will be less than 0.22 in the original case. And because the impact of carbon emissions from the material of outside doors and windows is much larger than it from the building envelope materials. Therefore, after comprehensive consideration, we can see that in the case of the above two types of width ratio of external doors and windows, the carbon emissions change compared to the original case will be reduced. For the case that the width of the outer door and window occupies 30% of the width of the corresponding room, the total area of the outer door and window can be quite close to that of the original case according to the Table 4.5, so the window-wall ratio of them are all about 0.22. So its annual carbon emissions from building equipment systems is almost the same as the original case. For the case that the width of the outer door and window is 50% of the width of the corresponding room, the window-wall ratio is greater than 0.27. So the amount of carbon emission change will be greater than that from the building in accordance with the width of the outer door and window occupies 40% of the width of the corresponding room. In other words, if the original building is taken as a reference, simply increasing the width of doors and windows will indeed increase the carbon emission, while reducing the width of doors and windows will reduce the carbon emissions.

Through the study analysis, it can be observed that there are many factors affecting carbon emission. For increase of carbon emission by enlarging outer door and window width and window-wall ratio, some effective measures can be taken for compensation. In addition, this study will continue in Chapter 6 to explore the potential of household behavior to reduce carbon emissions to residential buildings. Taking Case01 as an example, the study well estimate the potential for the behavior of occupant carbon emission reduction under the indoor natural ventilation where the relative position of the outer door and window to the corresponding room interior door is the farthest and the outer door and window width is 40% of the width of the corresponding room.

5.5 Chapter Summary

This chapter focused on studying the physical influences of changing outer doors and windows on building carbon emission. In FLC of buildings, according to *Carbon Emission Measurement Standards* (CECS374-2014), this chapter selected the carbon emission units that were the most relevant of physical changes of outer doors and windows in the case building for calculation, including utilization of external envelope structure materials, components and construction elements, transportation of building materials, components, construction elements and equipment, operation of building design system, transportation of waste, and recycling of external building envelope structure materials and components. This chapter systemized these units as physical changes of outer doors and windows, respectively studied and calculated the carbon emission variation brought by equipment system operation in the case building, and carbon emission changes brought by FLC of external building envelope structure.

As measuring carbon emission variation on building equipment system operation by changing outer doors and windows, this study utilized the common energy consumption simulation software PKPM in design engineering practice to analyze and calculate the case building, combined with the target building power consumption and specific questionnaire to correct residents' daily behavioral influences on the simulation results, and finally got the influences of changing outer doors and windows on annual actual energy consumption of the case building. Next, according to the latest benchmark emission factor of power grids in Chinese regions published by Tackle Climate Change Department in NDRC, the carbon emission variation on equipment system operation of the case building by changing physical properties of outer doors and windows including people's behavioral influence factors was calculated after combining with the annual actual power consumption variation of Case01 Building.

As studying the carbon emission variation brought by outer doors and windows on external building envelope structure in FLC, this chapter firstly used the external building envelope structure's material consumption change caused by outer doors and windows for comparison. Moreover, by referring to the design conclusion obtained in chapter four, the carbon emission variation of reducing outer wall materials in the building involved in its FLC is defined as the carbon earning—the carbon emission reduction, while the carbon emission variation of increasing outer door and window materials in its FLC is defined as carbon increment. Next, by referring to EcoCalculator for Residential Assemblies building material carbon emission database subordinate to

Athena software, this chapter calculated the carbon emission variation on the external building envelope structure in its FLC by enlarging outer doors and windows.

Based on the Formula 5.1, the influences in the above-mentioned two aspects were added to draw a conclusion that under the farthest relative position between outer doors and windows and internal doors of corresponding rooms and 40% of outer door and window width in opening width of corresponding rooms, total physical variation of outer door and window variation on carbon emission of the case building was 33.86($kgCO_2/m^2$). By making a comparison between this working condition and the original building, after enlarging the outer door and window—window-wall ratio, the annual carbon emission could be slightly increased. This conforms to the research conclusion on window-wall ratio and building energy consumption influences obtained by other scholars. Through the integrated analysis, it can be observed that physical influences on building carbon emission by changing outer doors and windows belong to a variation. In other words, building carbon emission will be increased by enlarging outer door and window width, while carbon emission will be slightly reduced by reducing outer door and window width.

The physical changes of outer doors and windows are closely related to physical changes and thermal performance of building carbon emission and also can change carbon emission of residential buildings. In order to make the study have practicability and practical reference value, the next chapter will conduct the in-depth study on household behaviors' emission reduction potential and possibility, attempt to find out the relation between indoor natural ventilation and household behaviors' emission reduction, carry out analysis and study under the support of relevant theoretical results, and try to explore multi-aspect carbon emission reduction potential owned by indoor natural ventilation as much as possible. The physical influence results of building carbon emission estimated in this chapter will be used for comprehensively analyzing changes of outer doors and windows in below, so as to give the estimation of household behaviors' emission reduction potential under the indoor thermal comfort experience.

Chapter 6 | Carbon Emission Reduction Potential of Resident Behavior to Indoor Natural Ventilation in Residential Buildings

It can be observed from the above-mentioned chapters that as conducting energy consumption simulation for the buildings involved, there is a difference between measured energy consumption and simulated energy consumption. In addition to limitation of simulation software and errors caused by different energy consumption in building equipment, household behaviors and habits in heating and cooling energy consumption equipment will affect simulation results to a large extent, proving that household behaviors have the great potential in carbon emission reduction of residential buildings and it is deserved to study.

6.1 Research on Residents' Behavior

6.1.1 Residents Thermal Comfortable Demand Characteristics and Criteria

In the article *"Shenzhen natural summer residential ventilation cooling experimental study"*, Xiaowen Ma said that usually when the outdoor temperature is about 30°C and relative humidity less than 85% it is appropriate to use natural ventilation to cool down. Huifang Liu in the *"indoor thermal comfort air-conditioning system measurement and control of energy-saving research"* concluded that when the indoor temperature at 25°C ~ 29°C, if the indoor wind speed in the 0.6 ~ 0.8m / s range, it will also to meet the thermal comfort of occupants required. Based on the questionnaire survey of a large number of residents located in the district of hot summer and cold winter thermal zone, Lina Yang made an analysis in the article *“multi-solution phenomenon and potential of building natural ventilation”*. The average outdoor temperature of residents using air conditioners is 30.8 degrees Celsius. In a paper entitled *"Summer Thermal Comfort and Adaptability of Houses in Hot Summer and Cold Winter Areas"*, Wei YANG obtained the thermal neutral temperatures of residents in naturally ventilated buildings through objective questionnaire surveys and the use of Probit model electronic simulation, the thermal environment in which it feels lukewarm is 28.3°C, the expected temperature is 27.9°C, and the upper limit of the acceptable summer temperature is 31.6°C. In the article of *“indoor thermal* *environment and human thermal comfort of naturally ventilated buildings in hot summer and cold winter area"*, Liu Jing concluded that the heat neutral temperature of residents is also 28.3°C by using the thermal adaptability model and the actual investigation results. And Danfeng He in *"building openings and the direction of the impact on the natural ventilation of residential buildings"*, a article by combining the literature, sorted out the relationship between indoor air flow velocity and human comfort, as shown in Table 6.1:

Table 6.1 Relationship between indoor wind speed and human comfort

Wind Speed(m/s)	Impact on Human Activity
0~0.25	Imperceptible
0.25~0.5	Cheerful, Does not affect the work
0.5~1.0	Generally Happy, Sometimes beware of paper being blown away
1.0~1.5	Slight windy feeling
＞1.5	A clear sense of wind, If maintaining good working efficiency and health conditions, need to improve ventilation and control of ventilation path

Source: Author

According to *the Building Ventilation Effect Test and Evaluation Standards* JGJ/T309-2013 industrial standards implemented by China on February 1, 2014, it proposes a requirement for indoor natural ventilation of buildings: the air velocity in personnel activity area of natural ventilation should be between 0.3m/s-0.8m/s.

6.1.2 Study on Related Criteria of Thermal Comfort in Indoor Environment

According to the chapter two, it can be observed that one of standards judging indoor natural ventilation effects is the thermal comfort of indoor environment. ASHRAE theory indicates the definition of thermal comfort environment as the satisfied thermal environment of the mankind in the psychological state. Moreover, it is defined in ISO7730 as follows: people's subjective satisfaction judgment on surrounding thermal environment. The thermal comfort of human is defined in ASHRAE standards as follows: thermal comfort is the satisfied conscious state on the thermal environment. It can be observed from these definitions that in the judgment on environmental thermal comfort, the key influence factor is the thermal feeling of people. The subject of thermal comfort is human, fully indicating that good or bad indoor natural ventilation effect will generate a great influence on household behaviors. Meanwhile, it also shows that household behaviors have the huge emission reduction potential in the improvement design of indoor natural ventilation. The standard of evaluating thermal comfort of indoor environment is based on the human thermal comfort model—PMV thermal comfort model obtained by Danish Professor Fanger and his colleges in the experimental study. This model is the relatively comprehensive index to evaluate thermal environment. Professor Fanger divided PMV value into 7 grades from -3—+3 scores. The representative significance of each grade is present in Table 6.2:

Table 6.2 Thermal sense scale

PMV Value	+3	+2	+1	0	-1	-2	-3
Thermal Comfort	Hot	Warm	Slightly Warm	Comfortable	Slightly Cool	Cool	Cold

Source: Author

After the PMV thermal comfort model was proposed, the PMV thermal comfort model might be not accurate as predicting the actual thermal feeling through the scholars' studies and practical applications, especially for the field investigation. The thermal neutral temperature confirmed by the thermal comfort model still makes some people unsatisfied. For example, when Schiller investigated the office workers in San Francisco, he found that the neutral temperature predicted by the PMV model was higher 2.4°C than the practice;[17] Oseland did an investigation on British office buildings, finding that neutral temperature measured by PMV thermal comfort standard was higher 3.6°C than the measured maximum;[18] after analyzing 18 actual studies, Brager and de Dear found that the neutral temperature predicted by the standard was 2.1 °C above normal in some cases and 3.4 °C below some cases[19] etc.

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17 Schiller GE. *"A Comparison of Measured and Predicted Comfort in Office Buildings [J]."* ASHRAE Transactions, 1990, 96(1): 609-622.

18 Oseland NA. *"Thermal Comfort in Naturally Ventilated Versus Airconditioned Offices [C]."* Proceedings of the 7th International Conference on Indoor Air Quality and Climate, 1996, 1: 215-220.

19 Brager GS, de Dear RJ. *"Thermal Adaptation in the Built Environment: A Literature Review [J]."* Energy and Buildings, 1998, 27(1): 83-96.

Figure 6.1 Adaptive thermal comfort standard for naturally ventilated buildings

Source: Thermal comfort in naturally ventilated buildings: revisions to ASH RAE Standard 55

In view of more and more field investigations, it shows that the PMV index proposed by Fanger has a great difference by comparing with the actual thermal comfort investigation results under the non-air-conditioning environment. By aiming at the disabled PMV model under the natural ventilation environment, de Dear and Brager came up with the "adaptation model".[20] Besides, according to 90% and 80% of acceptable comfort, the range of the indoor comfortable temperature is defined, as shown in Figure 6.1. Based on the air-conditioning residential investigation, it can be found that under the natural ventilation situation, the acceptable outdoor environmental temperature of households can reach 30°C.

Through the above-mentioned narration, it is noted that since there is a difference in physiological and psychological feelings between people, the PMV index not only accurately stand for feelings of all people. For this reason, Fanger also put forward the predicted percent dissatisfied (PPD) index to stand for people's unsatisfied percent for thermal comfort environment and gave the relation between PMV and PPD by using the probability analysis.[21]

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[20] de Dear R, Richard J, Brager G S. *"Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASH RAE Standard 55."* Energy and Buildings, 2002, 34(6): 549-561.

21 Yingxin Zhu. "*Building Environmental Science [M].*" Beijing: China Building Industry Press, 2005.

$$\mathrm{PPD} = 100 - 95\exp[-(0.03353\mathrm{PMV}^4 + 0.2179\mathrm{PMV}^2)] \qquad (6.1)$$

The PMV-PPD relation curve chart is present in Figure 6.2. It can be observed from the figure that when PMV is equal to zero, namely when the environment is kept in thermal comfort, the corresponding PPD is equal to 5%, indicating that 5% of people are still unsatisfied with the surrounding environment.

Figure 6.2 PMV-PPD relationship curve

Source: *The influence and the effect evaluation of the position and the size of windows on the natural ventilation in residential buildings*

By combining with the Formula 6.1 -- thermal comfort equation and Figure 6.2, it can be observed that it rationally describes the relation between the environmental thermal comfort and human behavior factors. Moreover, this PMV-PPD thermal comfort evaluation index has been used by ISO07730, showing that -0.5—+0.5 of PMV is the recommended range. In other words, 10% of people are allowed to show dissatisfaction for environmental thermal comfort. In addition, the comfort zone applied by ASHRAE55-1992 at least enables 80%of people to feel satisfied, namely PMV value is between -0.8 and +0.8.

6.1.3 Reflections on PMV Thermal Comfort Standard

By studying the PMV standard and summarizing relevant literatures, it can be observed that PMV standard is used to predict the thermal comfort evaluation feeling of the masses and it is not realistic to satisfy all people. Moreover, it is hard to accurately measure thermal feeling and thermal comfort, so it is necessary to know about the respondents' subjective response on the environment and consider the physiological and psychological differences between people through the questionnaire. Unfortunately, such a measured investigation method also has limitation, implying that people have all kinds of experience habits on the indoor environment thermal comfort improved by the natural ventilation in residential buildings. Also, it shows that household behaviors' emission reduction potential is huge. According to relevant literatures, there is the strong correlation between human neutral temperature and outdoor environment temperature in Shanghai.[22] Humphreys indicated that in natural ventilation buildings, outdoor temperature is an important parameter predicting thermal comfort, because it not only embodies the clothing status of people, but also indirectly shows other factors affecting thermal comfort, including human behaviors and mental adaptation.[23] Meanwhile, it is also noted that as studying the indoor natural ventilation and improving the suitable indoor thermal comfort environmental conditions, outdoor temperature is also an important reference factor.

6.2 Questionnaire on Carbon Emission Potential of Indoor Natural Ventilation and Household Behavior

For purpose of further exploring the influences of indoor natural ventilation on indoor thermal comfort and residents' thermal comfort behaviors in the hot summer and cold winter zone, this chapter is further concentrated on the research focus on the basis of previous studies on household behavior demands and applies a questionnaire to gain the relationship between household behaviors and indoor natural ventilation emission reduction potential in the hot summer and cold winter zone. Moreover, after comprehensively analyzing and comparing with the questionnaire results, this chapter extracts and selects the key factors to obtain the relevant data of residents' thermal comfort behaviors and gain the temperature boundary range of residents' thermal

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[22] Xiaojiang Ye, Zhiwei Lian, Yuangao Wen et al. *"Study on Adaptive Thermal Comfort in Shanghai [J]."* Building Heat Ventilation and Air Conditioning, 2007, 26 (5): 86-88.

[23] Humphreys MA. *"Field Studies and Climate Chamber Experiments in Thermal Comfort Research [J]."* Thermal Comfort: Past Present and Future, 1994: 52-72.

comfort in summer stipulated by the existing thermal comfort standard *GB18049-2000-T Middle Thermal Environment PMV and PPD Index Measurement and Thermal Comfort Conditions*, and its relationship with the outdoor environment temperature under the actual behavioral experience. Moreover, according to the above-mentioned study, it can be observed that outdoor temperature has the great reference value on measuring the human neutral temperature (suitable indoor thermal comfort temperature for residents).

6.2.1 Questionnaire Design and Sample Population Selection

This questionnaire gets involved in respondents' basic information, basic residential situation and residents' thermal comfort behavior habits, and subjective feelings on ventilation means and methods for residents in residences (see Appendix B for details). By understanding the respondents' basic information, it is convenient for recording and analyzing residents' energy consumption equipment behaviors and energy-saving habits.

The questionnaire applies the combination of online granting and offline granting. In the investigation stage, this questionnaire selects respondents in the area involved. The sample range basically covers majorities of provinces and areas in the Chinese hot summer and cold winter zone, as well as visitors in each age stage and stratum, hoping to find out the relationship between indoor natural ventilation and household behaviors' emission reduction potential based on the large-scale investigation data, as well as boundary data of door environment temperature under the suitable actual indoor ventilation environment experience, so as to provide data reference for measuring the behavior habits of residents based on the indoor natural ventilation improvement and estimating the corresponding household behaviors' emission reduction potential.

6.2.2 Statistics and Analysis of Questionnaire Results

6.2.2.1 An Overview of the Basic Information of the Sample Population

The research range refers to the suitable thermal comfort of residents in the hot summer and cold winter zone. First of all, the samples of the questionnaire are selected in line with the thermotechnical partition to exclude the ineffective samples. This questionnaire records thermotechnical proportion and domestic appliance configuration. The statistical results are present in Figure 6.3 and Figure 6.4:

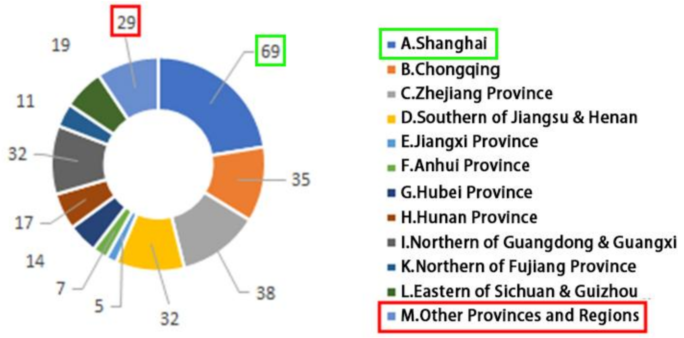


Figure 6.3 The distribution of respondents

Source: Author

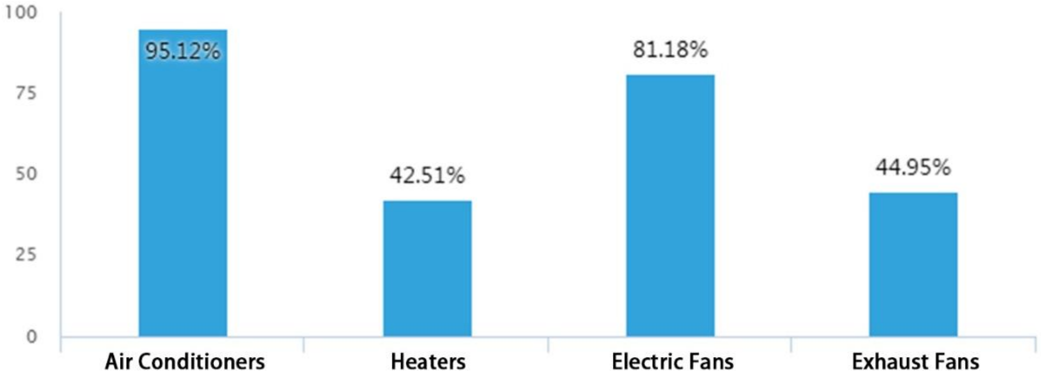


Figure 6.4 The electrical configuration of respondents

Source: Author

There are a total of 308 investigation samples. According to the different geological positioning in the hot summer and cold winter zone, these samples are divided into 13 areas. It can be found from the figure that 29 samples are excluded from the hot summer and cold winter zone, accounting for 9.42% of total samples, showing that there are 279 effective questionnaires that can be used for the subsequent statistical analysis. In the effective questionnaires, there are 265 air-conditioned households, 226 households with electric fans, 119 households with heaters and 125 households with exhaust fans, accounting for 95.12%, 81.18%, 42.51% and 44.95%, respectively. Through the effective screening on sample information, it can be observed that the configuration rate of air-conditioning in the hot summer and cold winter zone is very high, revealing that the energy conservation of air-conditioning is contributed to implementing the low-carbon emission reduction for Chinese residential buildings.

After understanding the basic sample information, independent variables and dependent variables of investigation data are classified and conducted cross-over analysis, so as to study respondents' behavioral habits about natural ventilation and behavioral emission reduction potential.

6.2.2.2 Indoor Natural Ventilation Habits of the Sample Family

The cross-over analysis based on the respondent family composition and behavior habits is present in Figure 6.5 and Figure 6.6. It can be observed from Figure 6.5 that regardless of the family composition, except for sleep in indoor activity process, residents tend to the life conditions of indoor natural ventilation. Compared with old people, young people prefer to live with relaxation to gain natural ventilation, while old people prefer to work under the natural ventilation conditions. By observing the Figure 6.6, it can be observed that regardless of the family composition, the operating frequency of electric fans is low. It can be guessed from the section 2.3 in this study, no matter for work or leisure time, residents tend to natural wind or simulate natural wind (air-conditioning), instead of mechanical wind generated by electric fans. In the family without children, people tend to cool air-conditioning ventilation, especially for young people. In the family without children, it obviously shows that even if indoor life environment is hot, majorities of residents will select natural ventilation, showing that indoor natural ventilation is better than air-conditioning for residents' good health. Meantime, it can be judged that if some design methods are used to improve the life environment of indoor natural ventilation, residents have the huge tendency to select the natural ventilation, proving that improvement of indoor natural ventilation will have a great positive influence on household behaviors.

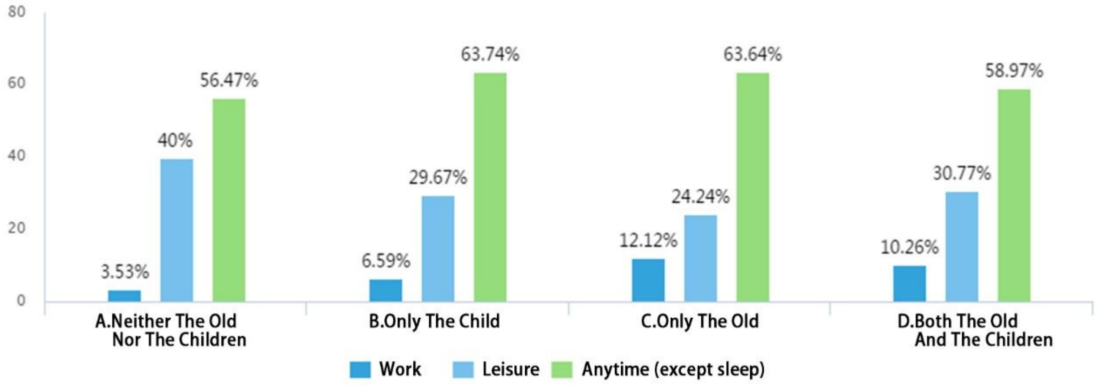


Figure 6.5 Sample Family Composition and Its Natural Ventilation Acceptability Habits

Source: Author

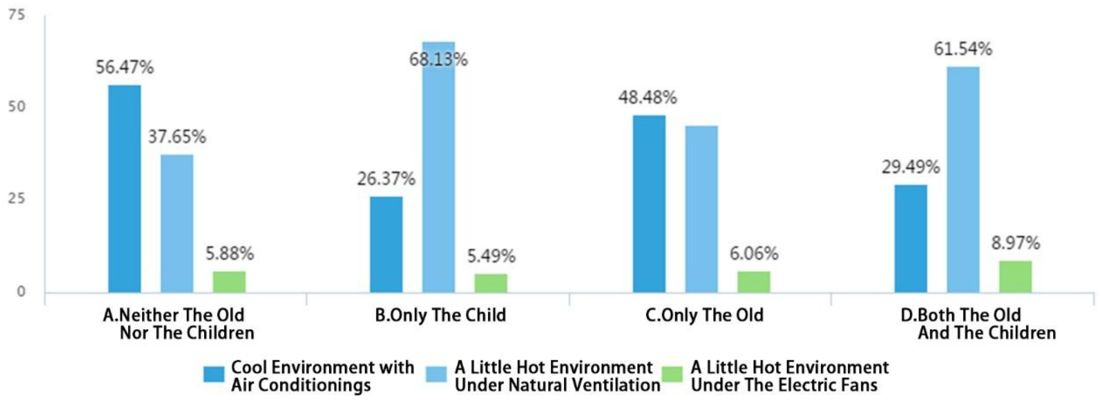


Figure 6.6 Sample Family Composition and Its Natural Ventilation Environment Behavior

Source: Author

6.2.2.3 The Relationship between Indoor Natural Ventilation and Residents' Daily Life

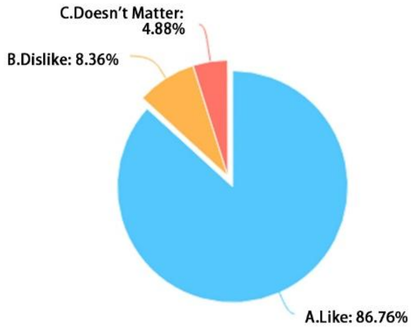


Figure 6.7 Residents' tendency to wind in the hot days

Source: Author

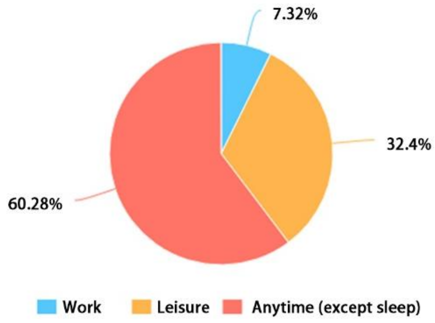


Figure 6.8 Selection of living conditions under natural ventilation

Source: Author

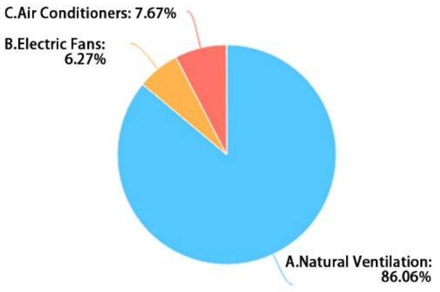


Figure 6.9 Residents' preferential ventilation mode in the hot days

Source: Author

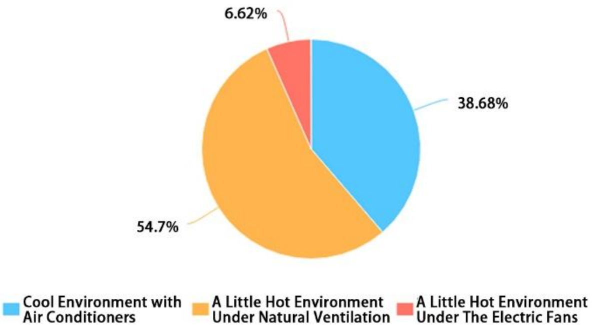


Figure 6.10 Residents' wind tendency under the different thermal environment

Source: Author

It can be observed from Figure 6.7 that residents in the hot summer and cold winter zone greatly desire for natural wind. 86.76% of residents tend to natural ventilation cooling when it is hot in rooms. Moreover, by observing Figure 6.8, it is noted that natural ventilation has the great potential to build the favorable relaxation and work for residents. It can be observed from Figure 6.9 that when it is hot, majorities of residents (86.06%) will select the indoor cooling giving priority to natural ventilation. According to Figure 6.10, for the ventilations election under the different thermal environment, 54.7% of residents select hot environment with natural wind, 38.68% of residents select cooling air-conditioning environment, and only 6.62% of residents select hot environment with electric fans. It can be found from the above-mentioned statistical results that respondents prefer to the natural wind and have the great intention to select natural ventilation to regulate thermal comfort tendency in the thermal environment, indicating that the favorable indoor natural ventilation environment of residential buildings will cause a great influence on household behaviors.

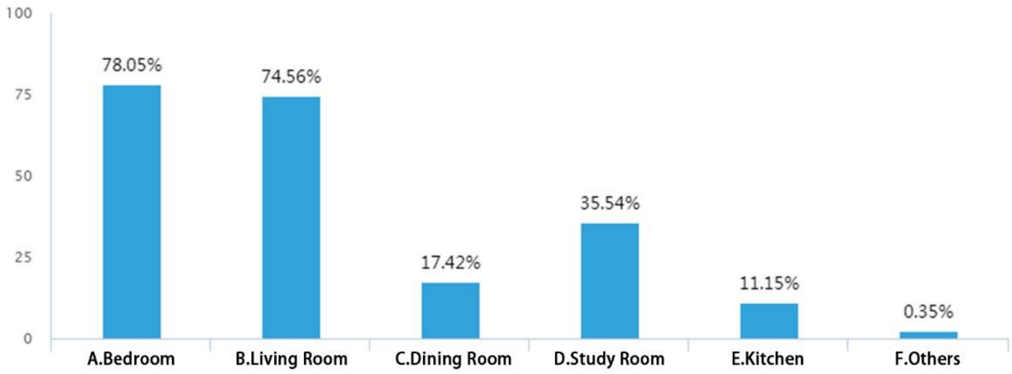


Figure 6.11 Statistics on the occupancy rate of daily indoor activities of residents

Source: Author

Based on the investigation data statistics in the Figure 6.11, the staying space of residents' daily activities at home gives priority to bedrooms and living rooms, accounting for 78.05% and 74.56%, respectively. By combining with the indoor ventilation evaluation results for three buildings involved in chapter three, it is judged that as considering the improvement design of natural ventilation in the residential buildings, the spatial importance ranking is shown as: living rooms=bedrooms>studies>restaurants>kitchens> toilets and other auxiliary rooms.

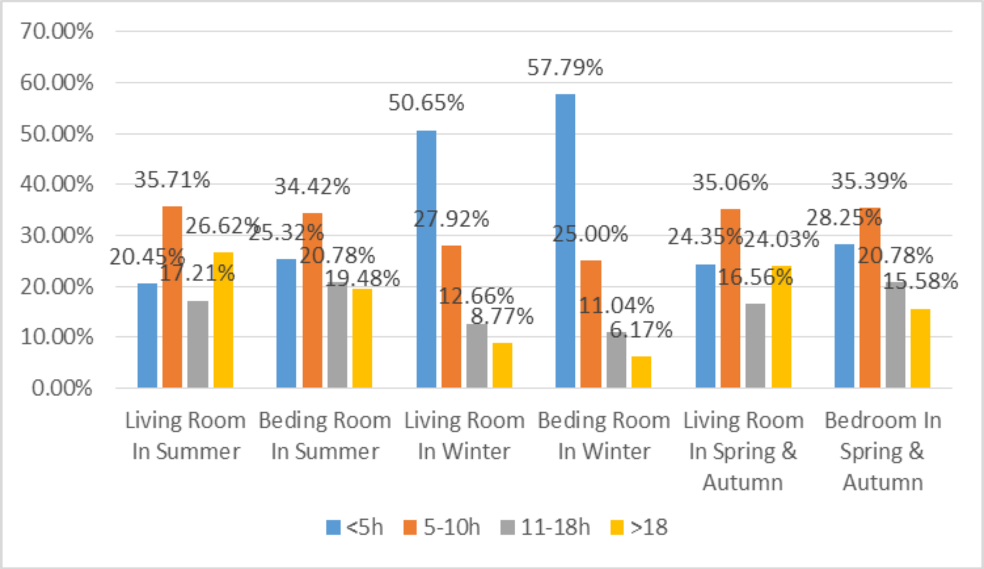


Figure 6.12 The windowing time distribution of living rooms and bedrooms in different seasons

Source: Author

Table 6.3 The windowing time statistics of living rooms and bedrooms in different seasons

		Max.	Min.	Average	Standard Deviation
Summer	Living Room	24	2	11.75	8.06
	Bedroom	24	0	10.68	7.67
Winter	Living Room	24	0	6.55	6.64
	Bedroom	24	0	5.66	6.12
Spring & Autumn	Living Room	24	0	11.19	8.01
	Bedroom	24	0	9.78	7.35

Source: Author

The windowing time situations of living rooms and master bedrooms for respondents in different reasons are present in Table 6.3 and Figure 6.12. Through the integrated analysis, it can be observed that windowing time of living rooms is slightly greater than bedrooms, while residents' windowing time in summer is greater than the transition seasons and winter. The windowing rate data statistics of living rooms and master bedrooms in different seasons is present in Figure 6.13, finding that the color column of large windowing rate in summer and transition seasons is obviously higher than the winter. It can be observed from the above-mentioned data that respondents in the hot summer and cold winter zone pay more attention to the indoor natural ventilation. Also, favorable indoor natural ventilation environment in summer is more important and has a great influence on residents' behaviors.

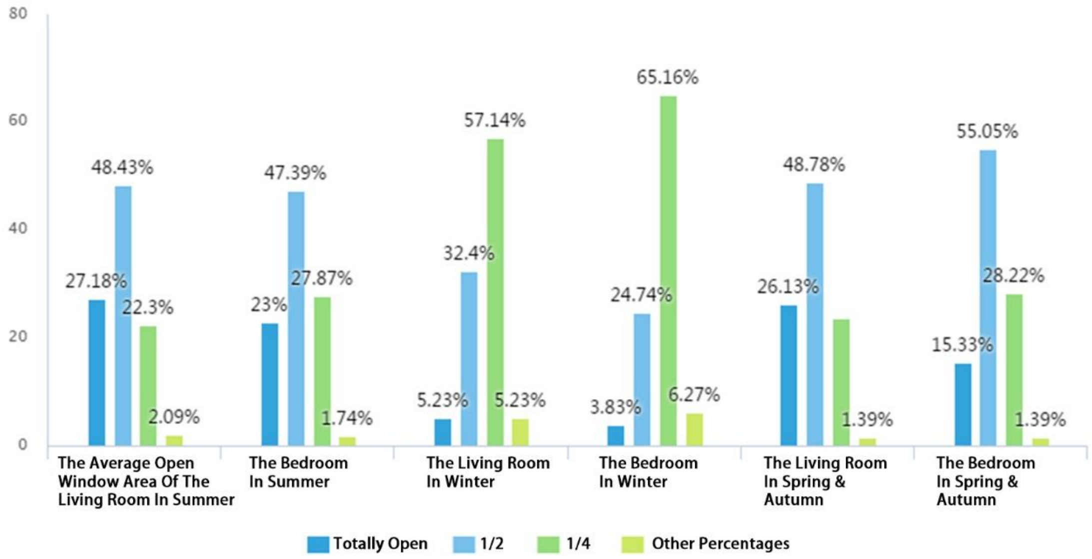


Figure 6.13 The windowing rate distribution data of living rooms and bedrooms in different seasons

Source: Author

6.2.2.4 Outdoor Temperature Range Suitable for Natural Ventilation Based on the Results of the Questionnaire

For this questionnaire, one is the outdoor temperature limit of refrigeration and heating electrical equipment. The limit reveals that residents in the hot summer and cold winter zone find out the suitable natural ventilation outdoor temperature range. The outdoor temperature value of relevant equipment used by respondents is summarized in Table 6.4. Moreover, the outdoor temperature weighted average of respondents by using air-conditioning is 30.61°C.

Table 6.4 Outdoor temperature statistics for the use of HVAC equipment(°C)

		Max.	Min.	Weighted Average
Summer	Outdoor Temperature of Using Air Conditioning	36	23	30.61
	Outdoor Temperature of Using Electric Fan	35	24	28.89
Winter	Outdoor Temperature of Using Air Conditioning	15	-4	4.71
	Outdoor Temperature of Using Heaters	15	-5	5.67

Source: Author

It can be observed from Figure 6.14 that in summer of the hot summer and cold winter zone, only 10.91% of air-conditioned residents will start to use air-conditioning in the temperature interval of “≤26°C”, which is kept in the standard thermal comfort temperature range of summer residents defined in Chinese *GB18049-2000-T Middle Thermal Environment PMV and PPD Index Measurement and Thermal Comfort Conditions*. In other words, when outdoor temperature doesn’t exceed 26°C, 10.91% of respondents feel uncomfortable indoor thermal comfort environment, so it is necessary to use air-conditioning to regulate. It can be observed from section 6.1 in this chapter that outdoor temperature is also a very important reference standard to predict indoor thermal comfort of residents, showing that in the temperature interval range of “≤26°C”, residents’ thermal comfort satisfaction of respondents in the air-conditioning rooms can be 89.09%, which is close to 90%.

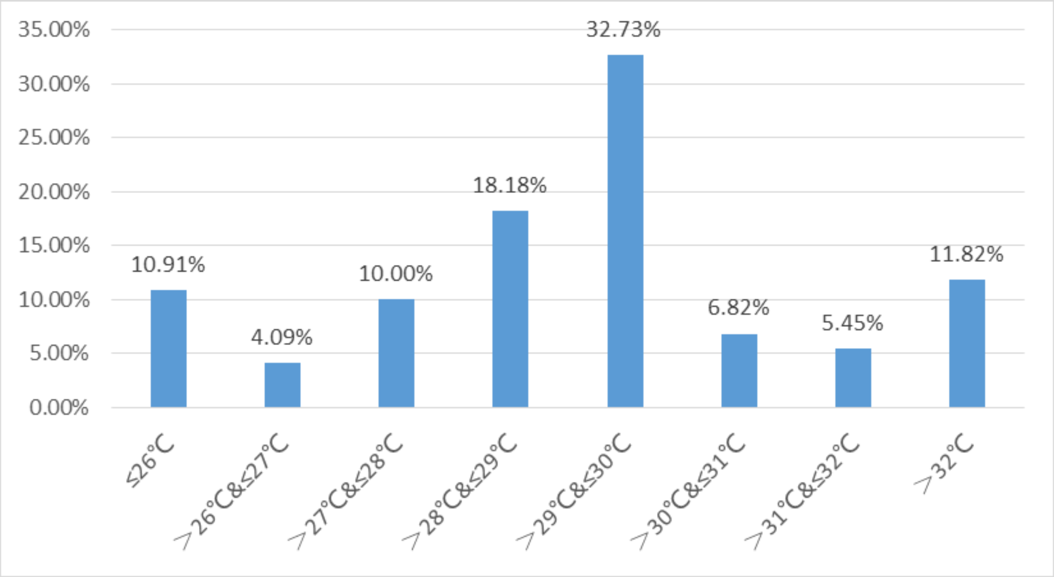


Figure 6.14 Outdoor temperature distribution of using air conditioners in summer

Source: Author

Similarly, it can be observed from section 6.1 in the chapter, PMV-PPD thermal comfort evaluation index applied in ISO07730 shows that 10% of people are allowed to dissatisfy the environmental thermal comfort in the suitable thermal comfort environment, namely the satisfaction is 90%, which is similarly equal to the satisfaction obtained by outdoor temperature data by using air-conditioning in summer after referring to investigation results. This can prove the accuracy of summarizing indoor natural ventilation’s thermal comfort standard in residential buildings in section one in this chapter. Based on it, it also combines with the outdoor temperature interval data result of air-conditioning percent for respondents in Figure 6.14, it can approximately estimate the indoor thermal comfort satisfaction of respondents, as shown in Table 6.5. Considering the investigation time and workload, this study does a research about outdoor temperature of using air-conditioning in summer, so the temperature interval precision uses a degree centigrade as a span unit.

Table 6.5 Indoor thermal comfort satisfaction of sample population based on survey data

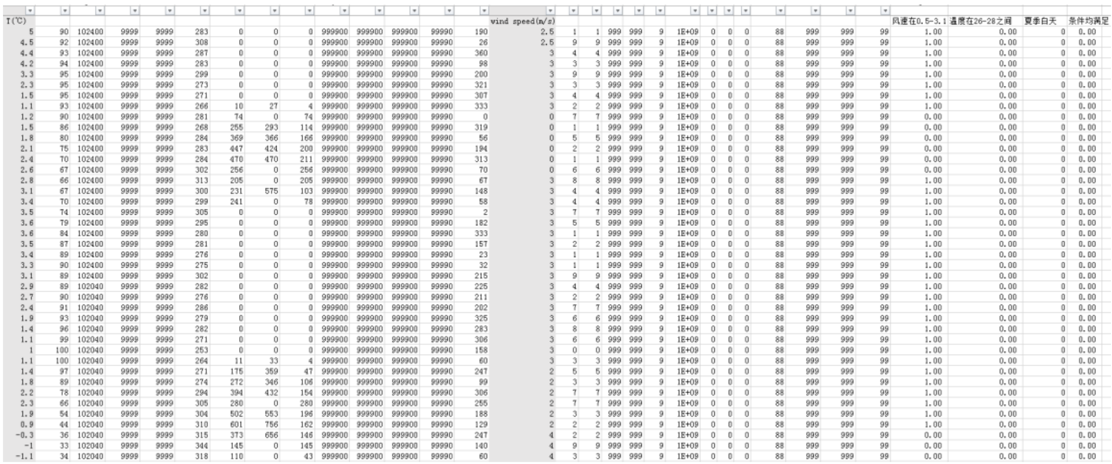
	Satisfaction
≤26°C	89.09%
>26°C & ≤27°C	85.00%
>27°C & ≤28°C	75.00%
>28°C & ≤29°C	56.82%
>29°C & ≤30°C	24.09%
>30°C & ≤31°C	17.27%
>31°C & ≤32°C	11.82%
>32°C	0.00%

Source: Author

By referring to the residents' thermal comfort demands in chapter two, the boundary control limit(e.g. temperature and wind velocity)of the thermal comfort should be a suitable boundary interval range, instead of a temperature spot or a wind velocity limit. Considering the relevant characteristic study on residents' thermal comfort demand theory in section one in this chapter, according to PMV-PPD comfort model, the defined thermal comfort zone at least should satisfy 80% of people. Based on the precision limitation of the investigation and data results in Table 6.5, this study will take the corresponding temperature interval with 75% of satisfaction in Table 6.5 through the integrated study as the upper limit of suitable natural ventilation's outdoor temperature range interval in the hot summer and cold winter zone, showing that it is correspondingly used for estimating the household behaviors' reduction emission potential in the hot summer and cold winter zone. The suitable indoor thermal comfort boundary interval in summer can be expanded to 26-28°C.

6.3 Estimation of Carbon Emission Reduction Potential of Household Behavior under Natural Ventilation

This research process still uses the Case01 Buildings as the measurement benchmark and selects the data relating to household behaviors' emission reduction potential in the hot summer and cold winter zone analyzed by the practical questionnaire, so as to estimate the household behaviors' emission reduction potential in the corresponding hot summer and cold winter zone under the circumstance. Based on it, this study explores the relationship between physical influences of changing outer doors and windows on Case01 Building and household behaviors' emission reduction potential, so as to analyze the importance of household behaviors' emission reduction potential in indoor natural ventilation low-carbon design of residential buildings.



T(℃)														wind speed(m/s)														风速在0.5-3.1	温度在26-28之间	夏季白天	条件均满足
5	90	102400	9999	9999	283	0	0	0	999900	999900	999900	99990	190	2.5	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
4.5	92	102400	9999	9999	308	0	0	0	999900	999900	999900	99990	26	2.5	9	9	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
4.4	93	102400	9999	9999	287	0	0	0	999900	999900	999900	99990	360	3	4	4	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
4.2	94	102400	9999	9999	283	0	0	0	999900	999900	999900	99990	98	3	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.3	95	102400	9999	9999	299	0	0	0	999900	999900	999900	99990	200	3	9	9	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.3	95	102400	9999	9999	273	0	0	0	999900	999900	999900	99990	321	3	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.5	95	102400	9999	9999	271	0	0	0	999900	999900	999900	99990	307	3	4	4	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.1	93	102400	9999	9999	266	10	27	4	999900	999900	999900	99990	333	3	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.2	90	102400	9999	9999	281	74	0	74	999900	999900	999900	99990	0	0	7	7	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
1.5	86	102400	9999	9999	268	255	293	114	999900	999900	999900	99990	319	0	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
1.8	80	102400	9999	9999	284	369	366	166	999900	999900	999900	99990	56	0	5	5	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
2.1	75	102400	9999	9999	283	447	424	200	999900	999900	999900	99990	194	0	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
2.4	70	102400	9999	9999	284	470	470	211	999900	999900	999900	99990	313	0	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
2.6	67	102400	9999	9999	302	256	0	256	999900	999900	999900	99990	70	0	6	6	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
2.8	66	102400	9999	9999	313	205	0	205	999900	999900	999900	99990	67	3	8	8	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.1	67	102400	9999	9999	300	231	575	103	999900	999900	999900	99990	148	3	4	4	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.4	70	102400	9999	9999	299	241	0	78	999900	999900	999900	99990	58	3	4	4	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.5	74	102400	9999	9999	305	0	0	0	999900	999900	999900	99990	2	3	7	7	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.6	79	102400	9999	9999	295	0	0	0	999900	999900	999900	99990	182	3	5	5	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.6	84	102400	9999	9999	280	0	0	0	999900	999900	999900	99990	333	3	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.5	87	102400	9999	9999	281	0	0	0	999900	999900	999900	99990	157	3	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.4	89	102400	9999	9999	276	0	0	0	999900	999900	999900	99990	23	3	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.3	90	102400	9999	9999	275	0	0	0	999900	999900	999900	99990	32	3	1	1	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
3.1	89	102400	9999	9999	302	0	0	0	999900	999900	999900	99990	215	3	9	9	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.9	89	102040	9999	9999	282	0	0	0	999900	999900	999900	99990	225	3	4	4	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.7	90	102040	9999	9999	276	0	0	0	999900	999900	999900	99990	211	3	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.4	91	102040	9999	9999	286	0	0	0	999900	999900	999900	99990	202	3	7	7	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.9	93	102040	9999	9999	279	0	0	0	999900	999900	999900	99990	325	3	6	6	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.4	96	102040	9999	9999	282	0	0	0	999900	999900	999900	99990	283	3	8	8	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.1	99	102040	9999	9999	271	0	0	0	999900	999900	999900	99990	306	3	6	6	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1	100	102040	9999	9999	253	0	0	0	999900	999900	999900	99990	158	3	0	0	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.1	100	102040	9999	9999	264	11	33	4	999900	999900	999900	99990	60	3	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.4	97	102040	9999	9999	271	175	359	47	999900	999900	999900	99990	247	2	5	5	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.8	89	102040	9999	9999	274	272	346	106	999900	999900	999900	99990	99	2	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.2	78	102040	9999	9999	294	394	432	154	999900	999900	999900	99990	306	2	7	7	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
2.3	66	102040	9999	9999	305	280	0	280	999900	999900	999900	99990	255	2	7	7	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
1.9	54	102040	9999	9999	304	502	553	196	999900	999900	999900	99990	188	2	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
0.9	44	102040	9999	9999	310	601	756	162	999900	999900	999900	99990	129	2	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	1.00	0.00	0	0.00
-0.3	36	102040	9999	9999	315	373	656	146	999900	999900	999900	99990	247	4	2	2	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
-1	33	102040	9999	9999	344	145	0	145	999900	999900	999900	99990	140	4	9	9	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00
-1.1	34	102040	9999	9999	318	110	0	43	999900	999900	999900	99990	60	4	3	3	999	999	9	1E+09	0	0	0	88	999	999	99	0.00	0.00	0	0.00

Figure 6.15 The display of meteorological data in Shanghai area under the Excel software

Source: Author

According to relevant studies, it can be found that the number of air-conditioning installed by each household in residential buildings is 2.72set/household.[24] Considering that this section aims to explore household behaviors' emission reduction potential, this study selects 1P average output power of common air-conditioning to calculate the air-conditioning energy consumption as 735W. The Excel software treatment is present in Figure 6.15. Based on Meteorological Data in Shanghai obtained

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[24] Shun Zheng, Xiang Zhou, Jingsi Zhang et al. *"Investigation and Analysis of Residential Air Conditioning Energy Consumption in Shanghai in summer [J]."* HKV, 2016, (03): 38-41.

by the building energy consumption simulation software EnergyPlus in Department of Energy, when the wind velocity at daytime in summer in Shanghai is 0.5-3.1m/s and outdoor temperature is greater than 26°C and less than or equal to 28°C, the total hours are recorded in Figure 6.16.

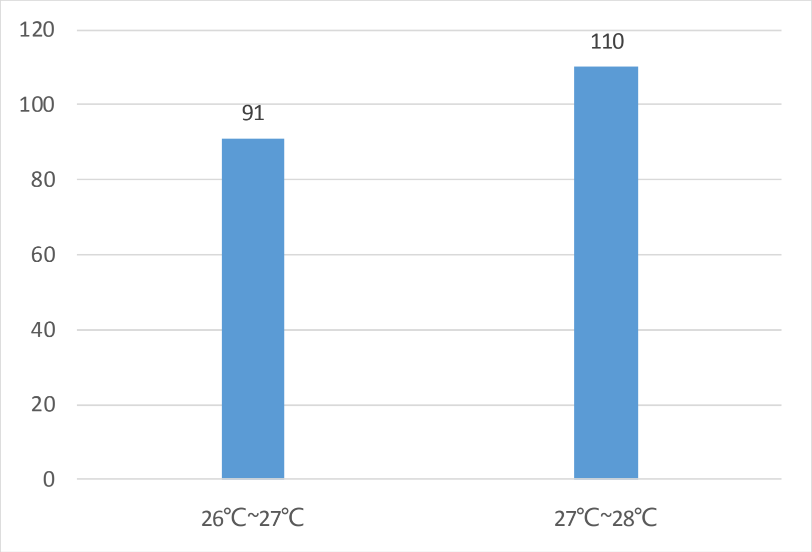

Figure 6.16 Total number of temperature intervals in accordance with the conditions

Source: Author

It can be observed from the above-mentioned section, the upper limit of suitable thermal comfort boundary interval in summer for respondents to be estimated is expanded to 28°C. By combining with its difference area comparing to the 26°C of suitable indoor thermal comfort boundary in summer stipulated in the current standards, as well as the corresponding respondent satisfaction, it shows that the air-conditioning energy consumption usage amount of respondents is used to estimate the household behaviors' emission reduction potential. Based on the basic information of Case01 Building in section 3.1, this building involved has 24 households. The overall floorage is 3167.25m^2. By integrating with the respondent satisfaction in the hot summer and cold winter zone selected in the last section and total houses in the difference area of the temperature interval, the corresponding household behaviors' emission reduction potential is estimated in line with the Formula 6.1:

$$E_P = C_A \times H_A \times W \times C_P \times EF_{ELECTRICITY} \times \frac{U}{FA} \tag{6.1}$$

E_P is the estimated carbon reduction potential of household behavior (kgCO$_2$/m^2);

C_A is the average installed air-conditioning per household in Shanghai;

H_A is the accumulated total hour in the different temperature intervals as 201 hours;

W is the average air conditioning power;

C_P is the thermal comfort satisfaction of sample population in hot summer and cold winter area, which is 75%;

$EF_{ELECTRICITY}$ is the regional grid baseline emission factor for Case01(tCO_2 / MWh);

U is the total number of households in Case01;

FA is the overall floorage of the Case01.

Therefore, according to the formula 6.1, it can be estimated that the potential of carbon emission reduction of households in the hot summer and cold winter area corresponding to the 01 case is:

$E_P = 2.72 \times 201 \times 735/1000 \times 75\% \times 0.70285 \times 24/3167.25 = 1.61 (kgCO_2/m^2)$

6.4 Chapter Summary

First of all, this chapter studied relevant theoretical literatures on household behavior demands in the hot summer and cold winter zone and drew a conclusion that based on the practical application of the thermal comfort index, it is not realistic that the same indoor environment building make all residents satisfy the thermal neutral environment, but it only can satisfy demands for most of people. Moreover, in the natural ventilation buildings, outdoor temperature is the important parameter to predict the indoor thermal comfort.

Secondly, this chapter focused on discussing the relevant households' daily behavior habits relating to natural ventilation. Based on the investigation and assisted by literatures, this paper recorded and analyzed existing buildings and equipment service behavior habits, finding that energy consumption and carbon emission of residential buildings in the hot summer and cold winter zone are not only determined by building equipment system energy consumption and relevant building material carbon emission mentioned in previous chapters, but also are greatly affected by indoor natural ventilation environment. Through the investigation, the famous member composition of different households will affect the applicability of indoor natural ventilation and behavioral habits. If the design method can improve the life environment of indoor natural ventilation, households have the large tendency to the natural ventilation, so as to generate the positive influences on equipment energy consumption in the residential use stage. This questionnaire also drew a conclusion that as considering the improvement design of indoor natural ventilation in residential buildings, the importance ranking of the residential space should be ranked as: living rooms=bedrooms>studies>restaurants> kitchens>toilets and other auxiliary rooms. Moreover, by combining with the existing thermal comfort theory, based on the suitable natural ventilation outdoor temperature range of the questionnaire results and combination of outdoor temperature distribution probability as using air-conditioning in summer, this chapter summarized the thermal comfort satisfaction of respondents and provided the corresponding data reference for estimating the household behaviors' emission reduction potential.

In the end, based on investigation results and existing theoretical achievements, household behaviors' emission reduction potential of the corresponding indoor natural ventilation in the Case01 Building was conducted simulated estimation. By analyzing the meteorological data in Shanghai, the air-conditioning data installed by Shanghai households and benchmark emission factor of regional power grid in chapter five, this chapter selected relevant data of household behaviors' emission reduction potential in the hot summer and cold winter zone obtained by the practical questionnaire as the reference. According to Formula 6.1, the household behaviors' emission reduction potential in the corresponding hot summer and cold winter zone was calculated as 1.61($kgCO_2/m^2$) under the benchmark of Case01 Building. As a matter of factor, it could be judged from the parameter calculation in the estimation process that the household behaviors' emission reduction potential couldn't accurately stand for residents' emission reductions of Case01 Building, but it could be used as the relational reference data between physical influences of changing outer doors and windows on Case01 Building and household behaviors' emission reduction potential. In the end, this chapter analyzed the importance of household behaviors' emission reduction potential in the natural ventilation low-carbon design of residential buildings.

Chapter 7 | Summary and Prospect

7.1 Conclusions

Beginning with simulation, demonstration and questionnaire, this study explores the effects of outer door and window design methods on improving indoor natural ventilation of residential buildings through quantitative analysis from the perspective of carbon emission and combines with practical investigation to improve residents' behavioral influences and residential environment, while enhancing residents' residential experience. The study makes a comparison between carbon emission expenditure of equipment system and building consumption variation as changing outer doors and windows of residential buildings, and preliminarily discusses the carbon emission possibility of residential buildings' indoor natural ventilation design in the hot summer and cold winter zone in accordance with the relation with household behaviors' emission reduction potential relating to residential indoor natural ventilation estimated by questionnaire survey data.

By systemizing the whole thesis, this study can draw the following conclusions, which can be summarized as the residential indoor natural ventilation design method in the hot summer and cold winter zone under the carbon emission reduction perspective:

(1)Outer door and window position: The relative position between outer doors and windows and internal rooms of corresponding rooms has a great influence on residential indoor natural ventilation effects. Moreover, if the relative position is farther, the ventilation effects are better. In the design process of residential buildings, each room should interlace outer doors and windows and internal doors and try to set it as the "cross ventilation" layout that is good for rooms. The inertia effect of airflow is used to change the direction for natural ventilation flow in the rooms, so as to ensure more rooms will gain direct airflow. In this way, indoor wind turbulence will be evener to avoid from too concentrated local ventilation quantity caused by uneven wind velocity.

(2)Windowing width proportion: In certain range, operable windowing width change will affect indoor window turbulence distribution and window velocity. It can be observed from the simulation that by taking No.1 Building as an example, when the outer doors and windows are horizontal sliding windows and operable minimum ratio is 50% of windows, with the expansion of operable window in outer doors and windows, wind turbulence distribution range of indoor natural ventilation is enlarged with it. Moreover, distribution is evener. When outer door and window width accounts for 30%-40% of the opening window, indoor natural ventilation effect is the best. In other others, when outer door and window width of the buildings involved is 60%-80% of the opening width in the corresponding rooms, indoor ventilation effect is the best. On the contrary, with the decrease of outer door and window width, wind velocity is enlarged, turbulence distribution range is relatively decreased and it is uneven.

(3)Building direction: When residential buildings apply the indoor natural ventilation, good or bad indoor ventilation is related to the included angle between building direction and summer wind. Through the simulation, it can be noted that when the included angle between building direction and summer wind is 75°-90°, wind velocity field and wind turbulence distribution of indoor natural ventilation are the best and the most uniform.

(4)Different outdoor wind speed: When the outdoor wind speed changes, indoor natural ventilation environment will also be different. Under the premise of the outdoor wind speed of 10m from the ground of 3.1m/s, the indoor natural ventilation environment is more comfortable when the wind speed is slightly reduced. However, as the simulated outdoor wind speed continues to increase, the effect of natural ventilation will begin to be inadequate. And as the floors continue to rise, indoor air quality, which relies solely on natural ventilation, will continue to decline.

Furthermore, this study also explores household behaviors and indoor natural ventilation emission reduction potential of residential buildings in summer. By summarizing relevant literatures and analyzing practical investigations, it is noted that indoor natural ventilation has the great emission reduction potential in household behaviors' emission reduction. The favorable indoor ventilation effect in summer can improve indoor thermal comfort environment, so as to reduce utilization of air-conditioning to some extent and reduce carbon emission of residential buildings. This study is based on the Case01 Building and combines with existing relevant theoretical achievements and practical questionnaires to do integrated analysis. By regarding relevant data of household behaviors' emission reduction potential in the hot summer and cold winter zone as the reference, this study estimates the potential behavioral emission reduction ability in the hot summer and cold winter zone. The more intuitive numeral results are compared to obtain the relation between indoor natural ventilation low-carbon design of residential buildings and household behaviors' emission reduction potential, as shown in Figure 7.1:

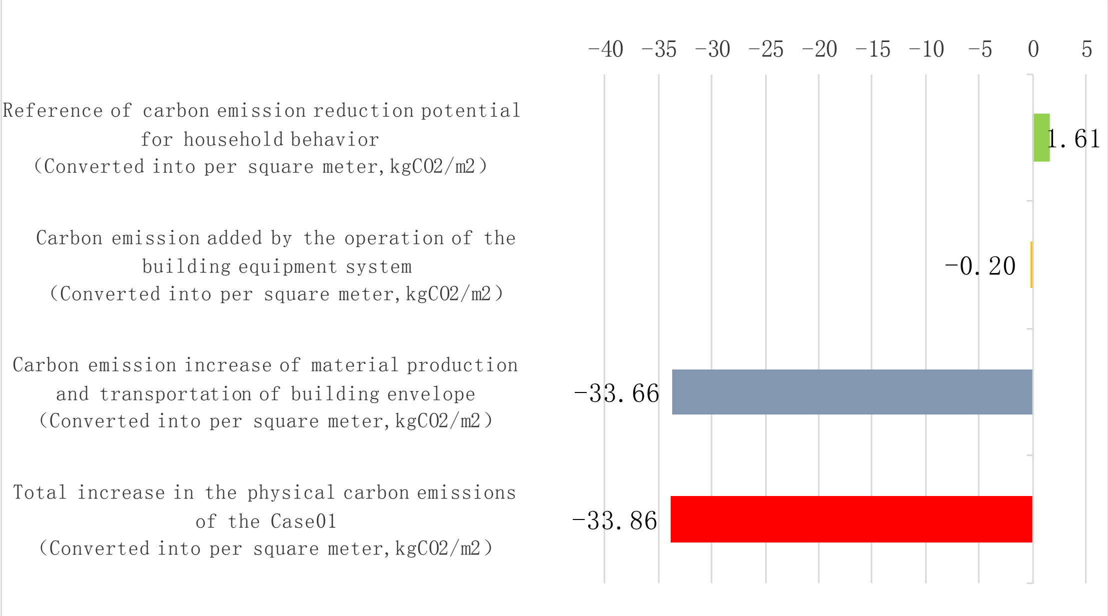

Figure 7.1 Energy consumption and conceptual relation schema of each carbon emission unit

Source: Author

It can be observed from Figure 7.1 that if time of measuring carbon emission variation is one year, external building envelope structure material and carbon emission increase in FLC have the greatest influences on the carbon emission variation of buildings involved. This is the main source of carbon emission variation in the buildings involved. By contrast, energy consumption increased by building equipment increase is about 1/100 of carbon emission increase in external building envelope structure, while household behaviors' emission reduction potential is about 1/20. However, after combining with the weighted FLC of buildings, the proportion of each carbon emission unit is greatly changed. The operation energy consumption of building equipment and household behaviors' emission reduction potential will be changed with time, while carbon emission variation of external building envelope structure won't be changed with service time of buildings, thus the time-weighted carbon emission influence is illustrated in Figure 7.2. It can be observed from the figure that from the 25th year of the building operation, household behaviors' emission reduction potential gradually exceeds the total physical carbon emission increase of buildings to dominate the carbon emission proportion in buildings involved.

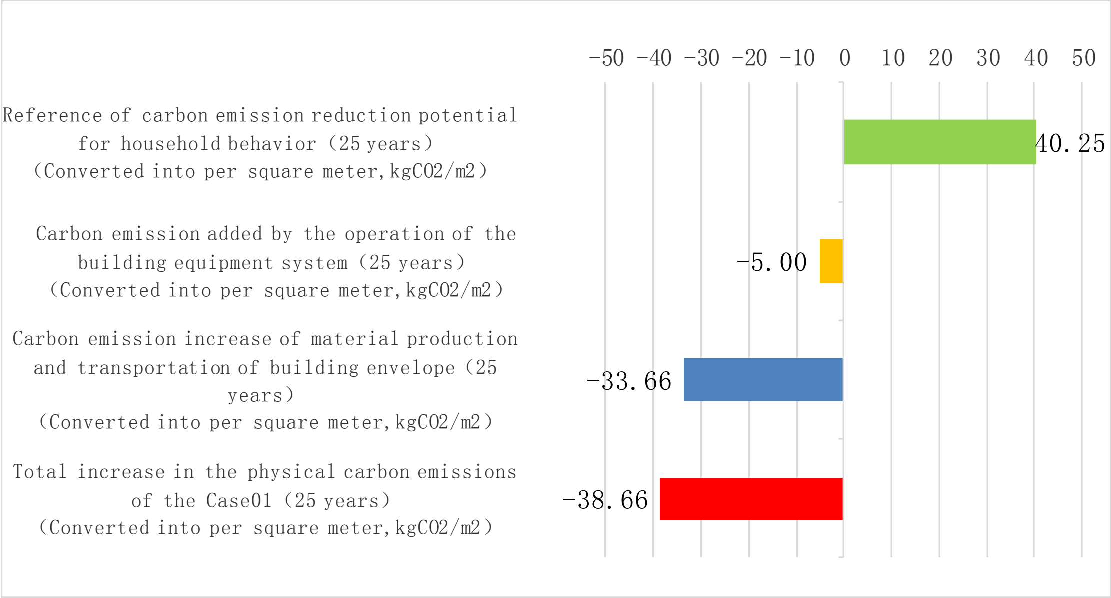

Figure 7.2 Conceptual relation schema of each carbon emission unit after time weighting

Source: Author

To sum up, the rational indoor natural ventilation design of residential buildings in the hot-summer and cold-winter zone has the potential to reduce residential carbon emission in multiple aspects, so it is deserved for us to study and explore.

7.2 Prospect and Deficiency

Through the analytical study, the indoor natural ventilation design of residential buildings can depend on building equipment system in low degree to maintain residential service operation, while improving and enhancing residents' living life quality, so as to realize carbon emission to some extent. This study is expected to enlighten architectural insiders in the era of transforming from energy conservation to emission reduction, while enriching the research system and relevant contents in building design industry from the perspective of carbon emission, especially for people who engage in residential building design, and also value the people-oriented design philosophy at the beginning of design, hoping to promote the sustainable health development in the residential building industry.

In addition to get some delightful research achievements, the author also clearly realizes there are some research limitation to some extent. However, it has a long way to do the following study for this topic and it still has shortcomings to be studied and improved:

First of all, this study applies the combined method of empirical data and simulation for discussion, thus it inevitably will face up with problems brought by the research method. In terms of the empirical buildings, there is too much intervention in the research process. Moreover, the number of empirical buildings and investigation data is limited. As exploring the relation between demonstration and simulated software, it can’t accurately control and analyze relevant variables. With regards to energy consumption simulation, energy consumption software has the large limitation. This study tries to reduce errors in the energy consumption process by exploring its relation with empirical data, but it still has some differences in theory and practice of energy consumption simulation for time and level limitation. For CFD simulation, due to shortcomings in knowledge level, there is still thoughtless process in the indoor natural ventilation situation. This is also one of factors for errors.

Furthermore, this study focuses on studying the indoor natural ventilation design method, but hasn’t deeply studied relevant carbon emission influences of different building materials. Based on the carbon emission data calculated in chapter five, it can be observed that carbon emission of external building envelope materials in the FLC has the considerable proportion in early design investment period and its influences can’t be neglected, either. Besides, it can be found from the carbon emission data of residential buildings provided by the carbon emission database that the carbon emission difference of different materials in the production materialization and demolition stage is amazing, thus building materials also have the great carbon emission potential. The carbon emission differentiation study with it is the range that hasn’t be involved in this paper. Moreover, it will be further expanded in the future study.

At last, as studying improvement of residential indoor environment by using the indoor natural ventilation design method, there is the physical carbon emission influences. Also, this study comprehensively analyzes relevant theoretical achievements and practical investigation data results of household behavior demands. Based on the simulated buildings, this study estimates the correspondent households’ potential behavioral emission reduction ability. Nevertheless, individual data source in the estimation process can’t be definitely verified. For example, under the precondition of the existing theoretical achievements, the investigated outdoor temperature distribution data of using air-conditioning by respondents in summer are used as reference to analyze practical indoor thermal comfort temperature and satisfaction of households in the hot-summer and cold-winter zone, but this study hasn't found out the accurate relation between them, thus the estimated household behaviors' emission reduction potential only can be considered as the reference to explore the relation with the physical carbon emission in buildings involved.

The research emphasis is the indoor natural ventilation design and carbon emission, which actually are complicated. If they are expected to be studied thoroughly, various influence factors should be comprehensively considered and studied. In terms of indoor ventilation effect, it is hard to use the single physical evaluation indexes including indoor temperature, wind velocity distribution or wind turbulence to measure the physical truth. With regards to residents' thermal comfort, the measurement standards are summarized through the subjective investigation on households, so this study hasn't compared it with the indoor window environment. Furthermore, this paper hasn't studied numerous emission units contained in building carbon emission. As a whole, owing to limitation in level, knowledge and energy, the involved range of this study may be the tip of the iceberg. It is still insufficient in depth and width, but this study just has conducted the preliminary exploration on the capable field. Though there are some achievements, it is small in number and weak in strength. Also, the study should be expanded and perfected in the wider and deeper level and perspective, thus this study will have the universality and practical significance.

Chapter 8 | Design of Tongji Yazhu Community

This dissertation would do a project design as a solid evidence. I would apply the conclusions which were got from the previous chapters to this project design, in order to show that indoor natural ventilation could be effective enough to the residents, then, it can real save carbon emission for the community.In terms of the climate and energy saving issue, I finally chose a site in Shanghai, China, which the residential community named “Tongji Yazhu Community”.

Figure 8.1 Tongji Yazhu Community

Source: http://sh.jiwu.com/tu/5883828.html

8.1 Site Analysis

Tongji Yazhu Community is located in the old town of Songjiang District, which inherits the old prosperity and memory. The surrounding infrastructure is well-supported. It is close to the line 9 subway station and Songjiang Stadium Station. There are more than a dozen bus lines and it is also close to the Shanghai-Hangzhou high-speed road, so the traffic is convenient. The project was created by the expert team of Tongji Real Estate to create a fine residence zone for Shanghai Old City. The community's architectural style is simple and elegant, with nearly 60% green coverage, and a maximum of 52 meters of large-scale culverts, creating an elegant residential environment for the sunshine viewing of households. The plot ratio of the community was 1.60, and the greening rate reached 35%. It covers an area of 60019 square meters and has a total construction area of 11,420 square meters and a total of 858 households.

The construction year of Tongji Yazhu Community was July 2011. During the design and construction of this residential area, reference was made to the current Chinese version of *JGJ134-2010 Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Regions*. According to the design standards, in addition to the body shape coefficient and the thermal performance of the external protection structure material of the building in the community, the window-wall ratio of the exterior windows (including the transparent part of the balcony doors) of the building should not exceed the limits specified in Table 8.1.

Table 8.1 The Window-wall ratio limits for the different orientations

Orientation	Window-wall ratio
North	0.40
East & West	0.35
South	0.45
One room per apartment (partly facing)	0.60

Source: JGJ134-2010 Design Standard

The article will select two high-rise residential buildings from the Tongji Yazhu Community as an example, and combine the results obtained in the previous chapter on optimizing the design of indoor natural ventilation of residential buildings in hot summer and cold winter regions, to carry out relevant optimization designs to them. Referring to the relevant data in Chapter six to estimate the carbon emission reduction potential of the residents, the study will explore the changes in the carbon emissions of the two buildings when the window-wall ratio changes or even exceeds the limit compared with the limits specified in the regulations.

8.2 Design Process

8.2.1 Selecting a Group of Buildings as an Engine of the Entire Community

The two high-rise residential buildings selected for this study are located in the northern part of Tongji Yazhu Community, and are the tallest in this community (as shown in Figure 8.2). Taking this as an example, it is possible to better represent different indoor ventilation optimization design methods for suites of different heights.

Figure 8.2 The range of the site area

Source: Author

The basic building information is shown in Table 8.2:

Table 8.2 The basic information of building

Location	Shanghai(31.31°N，120.61°E)
Thermal Partitions	Hot summer and cold winter zone
Building Orientation	South
Structure Tyoe	Shear wall structure
Shape Coefficient	0.36
Building Area	11042.46 ㎡

Building Volume	32023.13m^3
Building Surface Area	11491.95 ㎡
Building Storey	18
Number Of Households	108
Storey Height	2.9m
Building Height	52.20m
Exterior Wall Construction (From Outside To Inside)	Cement Mortar (20.0mm) + Powder Polystyrene Particle Slurry (50.0mm) + ALC Aerated Concrete Block 240 (240.0mm) + Cement Mortar (20.0mm)
Exterior Window Structure	Insulated Metal Profile Low-E Multi-chamber Sealing Window(6+12A+6)
Window-Wall Ratio	East 0.07; South 044; West 0.07; North 0.32

Source: Author

8.2.2 Design Strategy

Figure 8.3 The standard floor plan

Source: TJAD

According to the conclusions obtained in Chapter four, this design wil only optimize the external doors and windows of the building and keep all other design elements unchanged. The standard floor plan of the simulated building is shown in Figure 8.3. It can be seen from the figure that the case building contains two independent vertical traffic cores, and each core is connected to three households. In the middle of the household, the north side is adjacent to the vertical traffic core and only the kitchen on the north side has a small high ventilation window. Therefore, this type of the apartment is basically considered to be impervious to the north-south ventilation. The units on both sides of the vertical traffic core are transparent to the north and south, which has a great potential for optimizing indoor natural ventilation.

(1) Optimum design of relative position of outer doors and windows:

It will design the maximum distance between the outer doors and windows of the main rooms with the corresponding inner door in the apartment.

(2) Optimum design of relative width of outer doors and windows:

However, architectural design is not limited to two-dimensional world, but a three-dimensional project. Therefore, when the size of the exterior doors and windows of the case building is changed accordingly, this study will also take into account the different outdoor wind speeds corresponding to different heights, and combine the height of the apartment of the case building with the simulation results in section 4.4.4 to divide the households of the case building into three parts according to their height: The first part is from 1 to 8 floor, the relative width of outer doors and windows is 50%; the second part is from 9 to 14 floor, the relative width of outer doors and windows is 40%; the third part is from 15 to 18 floor, the relative width of outer doors and windows is 30 %. In combination with Figure 4.12, the outdoor wind speed values for the above three simulations are 3.1m/s, 3.6m/s and 4.0m/s, respectively.

8.3 Design Results

8.3.1 The Design Works with the Analysis of CFD Simulation

(1) The analysis of optimization effects of natural ventilation in 1-8 floors:

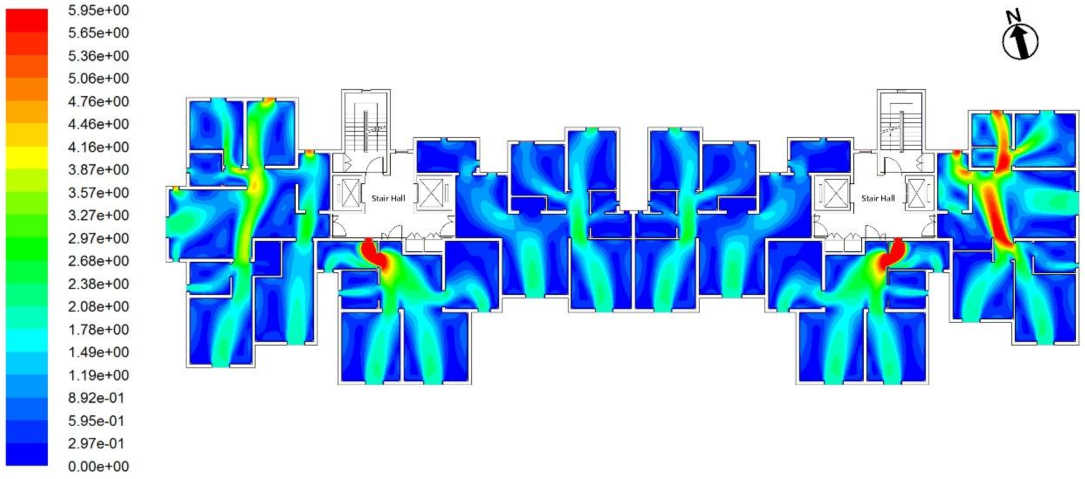

Figure 8.4 Simulation of the indoor ventilation of the 1-8 floors before optimization

Source: Author

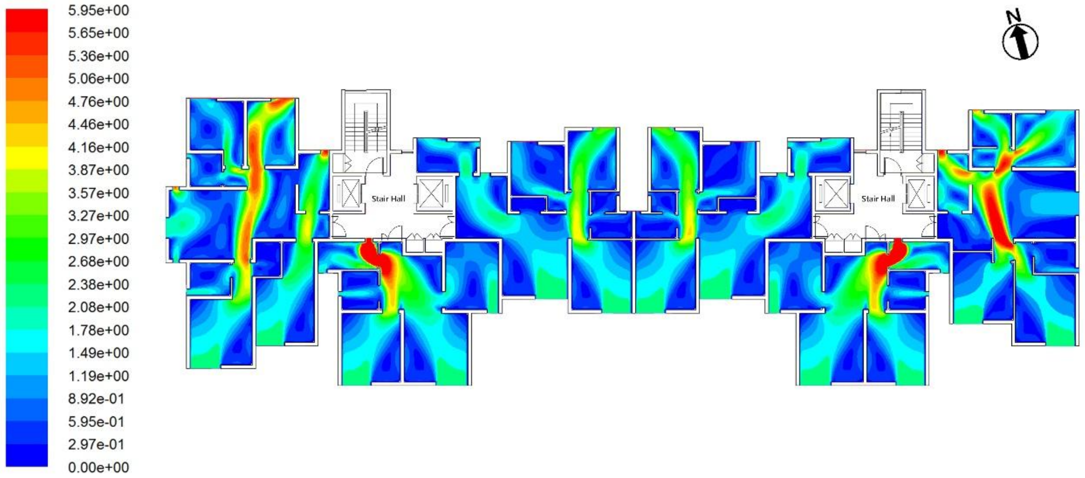

Figure 8.5 Simulation of the indoor ventilation of the 1-8 floors after optimization

Source: Author

Figure 8.4 represents the simulation of the indoor natural ventilation environment of the households located on floors from 1 to 8 of the case building before the optimization. It can be seen from the figure that the indoor ventilation of the two households located on the south side of the traffic core is the worst, and the average indoor wind speed is very low. There is only a small airflow at the location near the kitchen on the north side. Its overall ventilation is not good. The overall natural indoor ventilation of two completely axisymmetric households located between two traffic cores is also not optimistic enough. Natural winds flowing through the room have very slow wind speeds, and there is very little airflow coverage. In this state, the room on the north side has almost no natural ventilation effect. However, households located on the east and west sides of the traffic core have higher indoor wind speeds. The coverage of natural winds in the west one is relatively small, and the east one has a very distinct phenomenon of “cross ventilation” in the dinning room. On the other hand, in Figure 8.5, after the opening of the outer doors and windows of the case building was enlarged and optimized, the indoor natural ventilation simulation status is generally strengthened. It can be seen that the indoor ventilation intensity of the units located on the south side of the traffic cores has been significantly improved, and the airflow coverage has increased significantly. The southward room between the two occupants of the traffic core also received more adequate ventilation than before. While the most east household has obtained more ventilation, its indoor "cross ventilation" phenomenon has also slightly weakened.

(2) The analysis of optimization effects of natural ventilation in 9-14 floors:

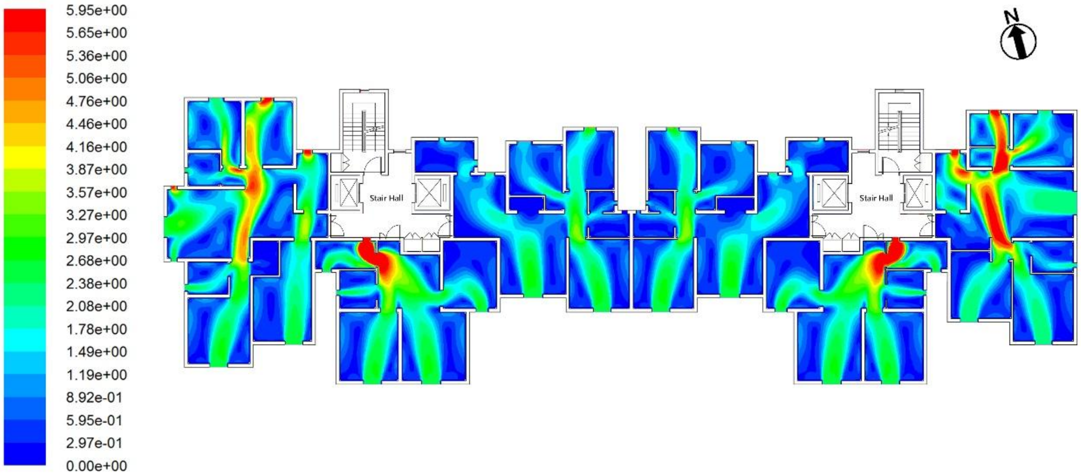

Figure 8.6 Simulation of the indoor ventilation of the 9-14 floors before optimization

Source: Author

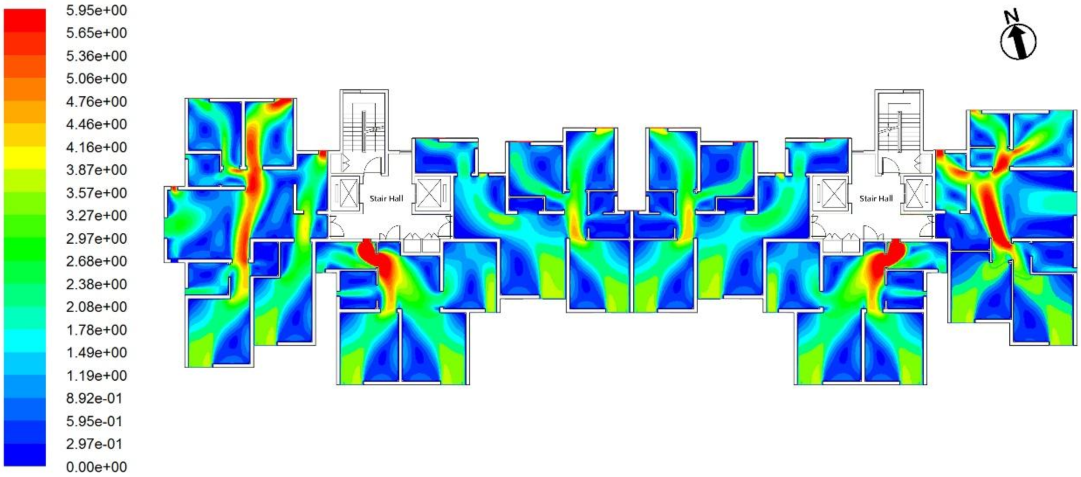

Figure 8.7 Simulation of the indoor ventilation of the 9-14 floors after optimization

Source: Author

Figure 8.6 represents the simulation of the indoor natural ventilation environment of the households located on floors from 9 to 14 of the case building before the optimization. It can be seen from the figure that the indoor ventilation of the two households located on the south side of the traffic core is also the worst. Although the average indoor wind speed slightly increased, the airflow coverage is still very small. The overall ventilation is not good. The overall natural indoor ventilation of the two households located between the two traffic cores is improved compared to Figure 8.4 but is not optimistic enough. The natural wind that flows through into the room has very slow wind speeds and very little airflow coverage. In this state, the rooms on the north side, especially on the northeast side, have almost no effect of natural ventilation. On the east and west sides of the households, although the overall indoor wind speed is relatively large, the natural wind flow of the west one is still more concentrated, and the restaurant of the east one also has a clear “cross ventilation” phenomenon. On the other hand, in Figure 8.7, after the opening of the outer door and window of the case building was also optimized and optimized, the indoor natural ventilation simulation status is generally improved. It can be seen that the indoor ventilation intensity of the units located on the south side of the traffic nucleus has been significantly improved, and the airflow coverage has increased significantly. The southward room between the two occupants of the traffic core also received more adequate ventilation than before. While the most east household has obtained more ventilation, its indoor “cross ventilation” phenomenon has become more pronounced.

(3) The analysis of optimization effects of natural ventilation in 15-18 floors:

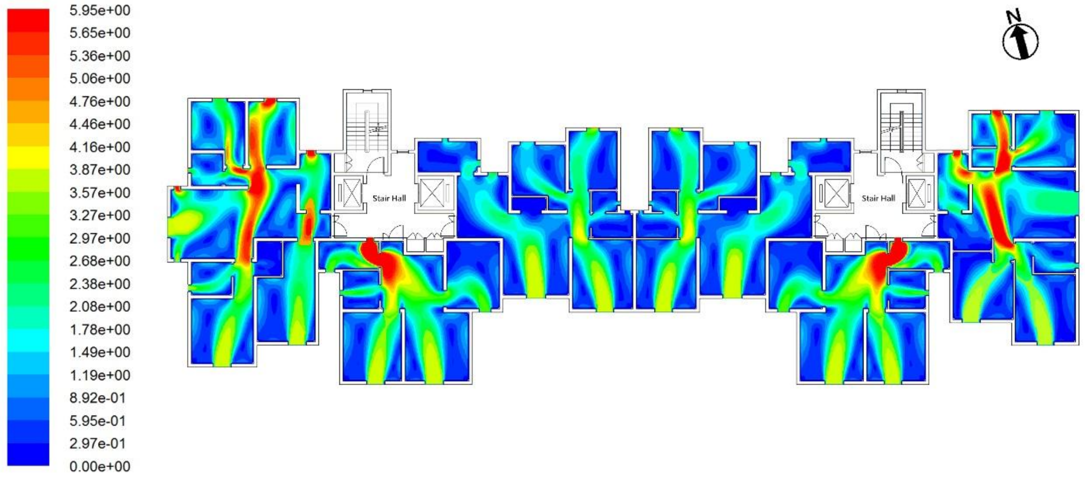

Figure 8.8 Simulation of the indoor ventilation of the 15-18 floors before optimization

Source: Author

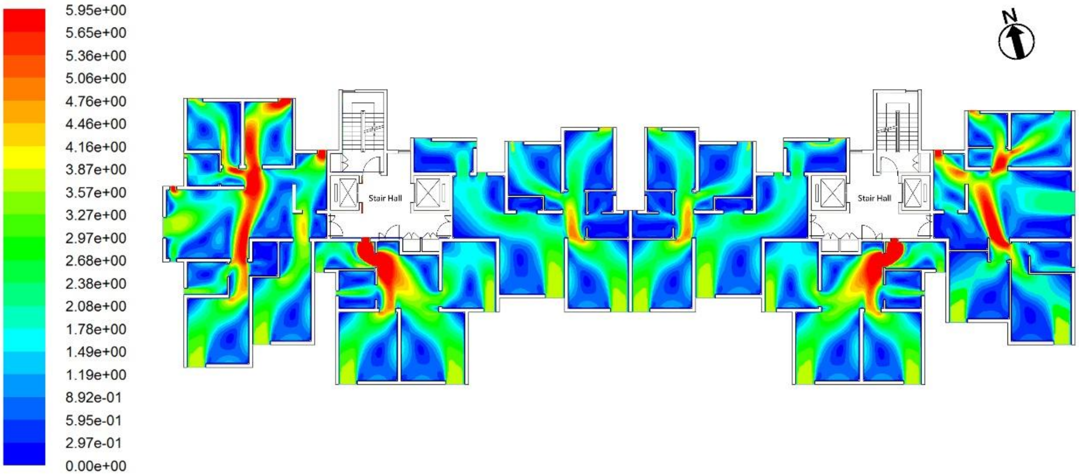

Figure 8.9 Simulation of the indoor ventilation of the 15-18 floors after optimization

Source: Author

Figure 8.8 represents the simulation of the indoor natural ventilation environment of the households located on floors from 15 to 18 of the case building before the optimization. As can be seen from the figure, at this time, because the households are at a high altitude from the ground, the wind speed is too high to all the households of their indoor natural ventilation. Because of the excessive flow rate, the air flow through the main room of the household is too concentrated and the ventilation coverage is generally insufficient. On the other hand, in Figure. 8.9, it was only optimized and adjusted the location of the outer doors and windows of the case building, but the width was almost unchanged from the original. It can be seen that after the optimization, the indoor natural ventilation wind speed of the units located on the south side of the traffic cores is slightly slowed down, and the airflow coverage is also significantly increased. Both of the natural wind speeds and the air distribution of two households between the traffic cores are more even. While the most east household has obtained more ventilation and airflow coverage, its indoor "cross ventilation" phenomenon has also clearly improved.

8.3.2 The Changes in the Facade of the Case Building

Figure 8.10 The south façade before and after optimization of the case building

Source: Author

Figure 8.11 The north façade before and after optimization of the case building

Source: Author

Figures 8.10 and 8.11 are the south elevation and the north elevation respectively before and after optimization of the case buildings. It can be seen from the figure that compared with the original facade, the optimized facade of the case building can be roughly divided into three parts from the bottom up. The position of the outer doors and windows of the main room has changed, and the size of the windows also varies with height. This allows the new façade to better allow occupants to use natural ventilation while also making the appearance of the case building change a little more. Getting rid of the original building facade is exactly the same from the bottom up. Table 8.3 is a summary of window-wall ratios before and after the optimization of case building. Combined with Table 8.1, the comprehensive analysis can be concluded that: The south and north window- wall ratio of the case building before the optimization are close to the specified regulatory limit, and the south and north window- wall ratio after the optimization exceed the limit; With the premise of improving the indoor natural ventilation level, the limits of the south and north window-wall ratio from the 1st to the 8th floors of the case building can be appropriately raised to 0.64 and 0.51; The limits of the south and north window-wall ratio from the 9th to the 14th floors of the case building can be appropriately raised to 0.53 and 0.44; The limits of the south and north window-wall ratio of from the 15th to the 18th floors of the case buildings (ie, 15 floors or more) can be the same as those specified in the specifications. Figure 8.12 is a site plan of the two case building in Tongji Yazhu Community.

Table 8.3 Window-wall ratio before and after the optimization of case building

	East	South	West	North	**Total**
Raw Data	0.07	0.44	0.07	0.32	0.23
New Data	0.07	0.55	0.07	0.46	0.29
1-8 floors	0.07	0.64	0.07	0.51	0.33
9-14 floors	0.07	0.53	0.07	0.44	0.28
15-18 floors	0.07	0.42	0.07	0.36	0.23

Source: Author

Figure 8.12 Site plan

Source: Author

8.4 Estimation of the Carbon Emission Reduction of the Project

8.4.1 Change of Carbon Emission Caused by the Operation of Building Equipment System

Table 8.4 Index changes of simulated energy consumption in case building

Total Floors: 18 Building Total Height: 52.20m Building Area: 11042.46m²

Case Building	Raw Data	Data after changing the width of the door and window
The South Side of Window-Wall Ratio	0.44	0.55
The South Side of Window Area(m²)	1222.56	1520.81
The Change Of Window Area(m²)	0	298.25
The North Side of Window-Wall Ratio	0.32	0.46
The North Side of Window Area(m²)	867.78	1252.08
The Change of Window Area(m²)	0	384.30
Annual Simulated Power Consumption of Buildings(kWh/m²)	53.66	59.58
Yearly simulated power consumption variation of unit area(kWh/m²)	0	5.92
Correction Factor	0.059	0.059
Annual energy consumption variation of actual unit area(kWh/m²)	0	0.35
Emission Factor(tCO_2/MWh)	0.70285	0.70285
Annual Actual Carbon Emissions Changes of Per Square Meter($kgCO_2/m^2$)	0	0.25

Source: Author

Table 8.4 is the summary of the indexes of the case building after the optimization. Combined with Table 5.5 and Formulas 5.2 and 5.3 in the previous chapter, it can be seen that the carbon emission per square meter caused by the optimization of the energy consumption of the building equipment system of the case building by the optimization of the external door and window openings is:

$$\triangle E_{ESO} = 0.35 \times 0.70285 = 0.25(kgCO_2/ m^2)$$

8.4.2 Change of Carbon Emission Caused by the Production and Transportation of Building Envelope Material

Table 8.5 Change of carbon emission caused by the changes of outer door and window to production and transportation of building envelope material

Total Floors: 18 Building Total Height: 52.20m Building Area: 11042.46m^2

Case01	Raw Data	Data after changing the width of the door and window
Total Area Change of Outer Wall(m^2)	0	-682.55
Total Area Change of Outer Door and Window(m^2)	0	+682.55
The Amount of Carbon Emission Per Square Meter of Ordinary Outer Wall(kgCO$_2$/ m^2)	0	-76.07
The Amount of Carbon Emission Per Square Meter of Outdoor Windows and Doors(kgCO$_2$/ m^2)	0	+727.70
Change of Carbon Emission of Building Envelope Material(kgCO$_2$/ m^2)	0	+40.28

Source: Author

From the foregoing, it can be seen by referring to the EcoCalculator for Residential Assemblies database and the combination of Table 8.5 and Formulas 5.5 and 5.6:

(1) The variation of carbon emission per square meter of the outer wall of the ordinary story of case building over its life cycle is:

$$\triangle E_1 = 7.07 \times 10.76 = 76.07(\text{kgCO}_2/\text{ m}^2)$$

(2) It can be seen that the amount of change of carbon emission of the exterior doors and windows per square meter of ordinary floor in the whole life cycle is:

$$\triangle E_2 = 67.63 \times 10.76 = 727.70(\text{kgCO}_2/\text{ m}^2)$$

Based on Formula 5.4, it can be deduced that the increase of per square meter outer door and window of the total amount of carbon emission changes brought by the relevant building envelope materials during their entire life cycle is:

$$\triangle E_{MPT} = (-76.07+727.70) \text{ x } \frac{682.55}{11042.46} = 40.28\ (\text{kgCO}_2/\text{ m}^2)$$

8.4.3 Estimation of Carbon Emission Reduction Potential of Household Behavior under Natural Ventilation

For the estimation of the natural ventilation and emission reduction potential of the behavior of households in case building, this study draws on the relevant data obtained in Chapter 6 and refers to Formula 6.1. It can be estimated that the potential of carbon emission reduction of households in the hot summer and cold winter area corresponding to the case building after the optimization is:

$$E_P = 2.72 \times 201 \times 0.735 \times 75\% \times 0.70285 \times \frac{108}{11042.46} = 2.07\ (kgCO_2/m^2)$$

8.5 Chapter Summary

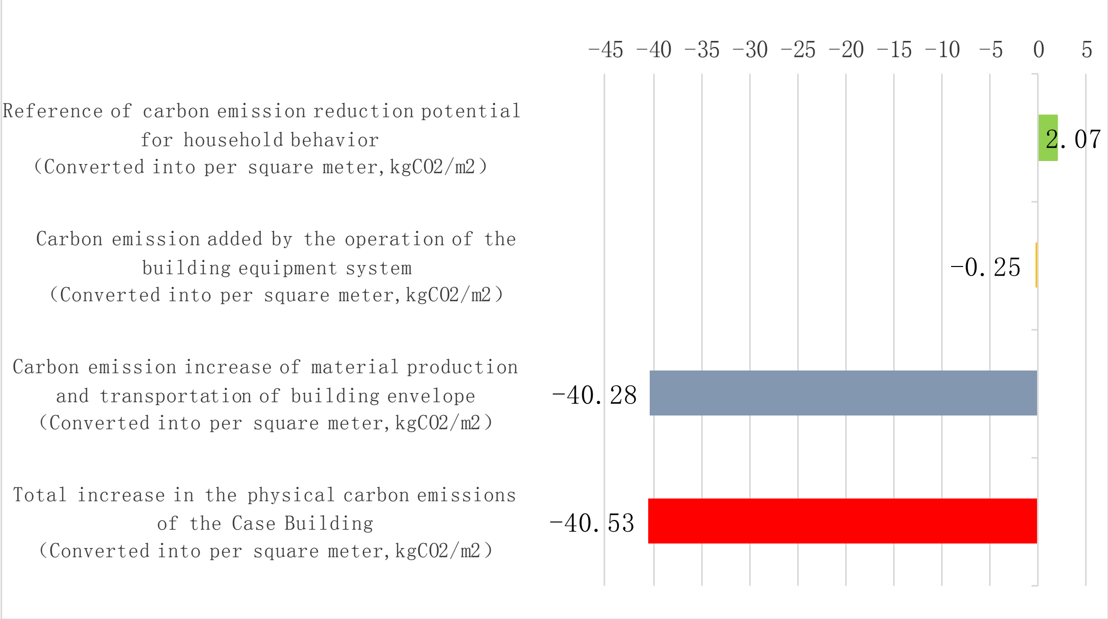

Figure 8.13 Energy consumption and conceptual relationships between carbon emission units

Source: Author

As can be seen from Figure 8.13, the most significant contributor to the change in carbon emissions from case buildings is also the increase in carbon emissions over the life-cycle of building envelope materials if the change in carbon emissions is estimated to be one year. This is the main source of change in case building’s carbon emissions. Compared with it, the energy consumption of construction equipment system is less then one percent of that while residents' potential for reducing carbon emissions is about one-twentieth of that. However, taking into account the weighted total life cycle time of buildings, the proportion of each carbon emission unit has greatly changed. As what we talked in the previous chapter, the energy consumption of construction equipment and the carbon emission reduction potential of residents' behavior all change over time. However, the change of carbon emissions from building envelope materials does not change with the time gose by. Therefore, the time-weighted carbon emission units are shown in Figure 8.14. It can be seen from the figure that since the 23th year of construction operation, the potential for carbon emission reduction by residents has surpassed the total increase of physical carbon emissions of buildings and has dominated the proportion of carbon emission in construction projects.

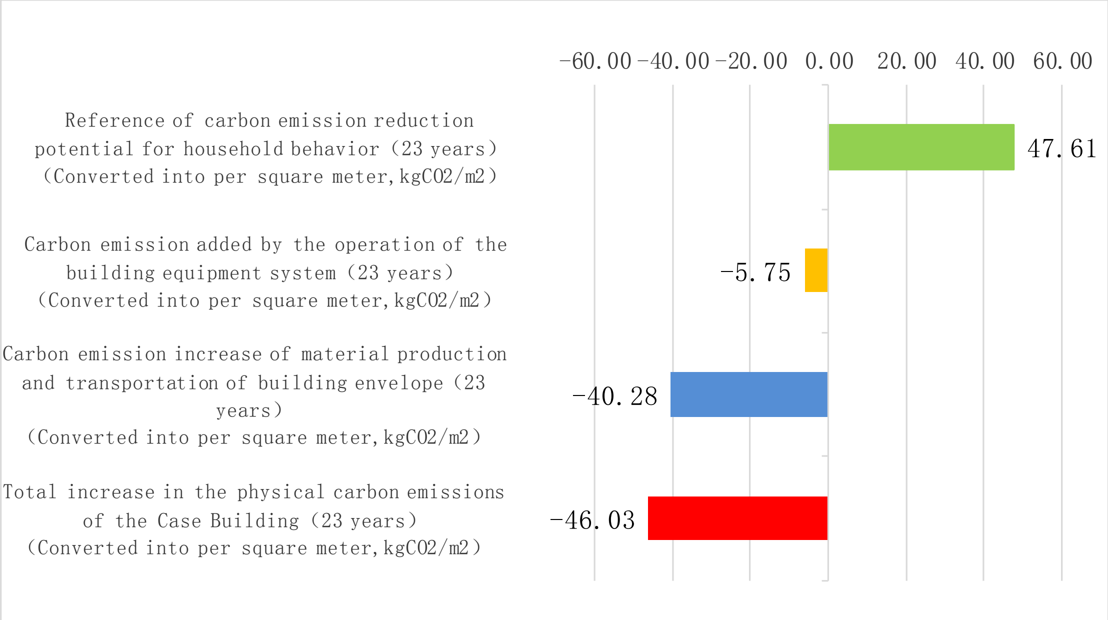

Figure 8.14 Concept relation diagram of each carbon emission unit after time weighted

Source: Author

In summary, after the optimization design and analysis of actual cases after this study, we can see that the reasonable natural indoor ventilation design of residential buildings in hot summer and cold winter areas does have the potential to reduce residential carbon emissions in many aspects, and it is worth our further research and exploration.

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Appendix A: Questionnaire of Empirical Housing Ventilation Evaluation

Q1. The floor of your home is:

A. The first floor B. Lower section C. Upper section D. Top floor

Q2. The position of your house on the floor is:

A. The west side B. Middle C. The east side

Q3. Residential comfort evaluation:

	5	4	3	2	1
Heat insulation (summer)					
Heat preservation (winter)					
Sound insulation					
Lighting					
Ventilation					

Q4. The best room for lighting is ________, the worst is _________.

A. Living room B. Dining room C. Bedroom

D. Study room E. Kitchen F. Bathroom

Q5. The best room for ventilation is ________, the worst is _________.

A. Living room B. Dining room C. Bedroom

D. Study room E. Kitchen F. Bathroom

Q6. What kind of appliances do you use for cooling or heating? (Multiple choice)

A. Air-conditioner B. Electric fan C. Floor heating

D. Heater E. Electric blanket F. Others (please fill) _________

Q7. In the summer, you usually set the temperature of the air conditioning as:

A. 16~18 °C B. 19~22 °C C. 23~26 °C D. 27~30 °C

Q8. In winter, you usually set the temperature of the air conditioning (floor heating / heater) as:

A. 16~18 °C B. 19~22 °C C. 23~26 °C D. 27~30 °C

Q9. Please choose to meet your lifestyle description (Multiple choice):

A. Close the air conditioner or heater before sleep.
B. Set off the air conditioner or heater at a time before sleep.
C. Turn off the air conditioner or heater when you go out temporarily.
D. Priority through the window ventilation or close the doors and windows to adjust room temperature.
E. In the summer preferred outdoor shade.

Q10. Do you have an old man or a child in your family?

A. Both B. Only old people C. Only child D. None

Q11. Your educational background is:

A. High school or below B. Undergraduate C. Master D. Doctor

Q12. Your monthly income is:

A. ＜10,000 RMB B. 10,000~20,000 RMB
C. 20,000~50,000 RMB D. ＞50,000 RMB

****

The following is completed by the investigators:

Interviewee gender: A. Male B. Female

The age of the interviewees:

A. Under 18 years B. 18~30 years C. 30~45 years
D. 45~60 years E. Over 60 years

Appendix B: Indoor Natural Ventilation and Thermal Comfort of Residents in Hot Summer and Cold Winter Areas

A Basic Information:

Q1 Your current place of residence is:
A. Shanghai B. Chongqing C. Zhejiang D. The Southern of Jiangsu and Henan
E. Jiangxi F. Anhui G. Hubei H. Hunan
I. The Northern of Guangdong and Guangxi J. The Southern of Shaanxi and Gansu
K. The Northern of Fujian L. The Eastern of Sichuan and Guizhou M. Other Areas

Q2 Your gender is:
A. Male B. Female

Q3 Your age is:
A. Under 18 years old B. 18-30 years old C. 30-45 years old
D. 45-60 years old E. Over 60 years old

Q4 Your highest academic qualification is:
A. Elementary School B. Junior High School C. High School
D. Bachelor E. Master F. Doctor

Q5 You have lived in your current residence:
A. Within six months B. Half year to one year
C. One year to three years D. More than three years

Q6 Your current identity is:
A. Homeowner B. Tenant C. Other ____________

Q7 The number of households in your current home is __________:
A. 1 B. 2 C. 3 D. 4 E. 5 F. 6 G. More than 7

Q8 Your family composition is:

A. Neither the aged nor children B. Only children
C. Only the aged D. Both the aged and children

Q9 Are you a student or practitioner in the architecture profession?
A.Yes B. No

Q10 The total annual income for your family is:
A. 0-50K RMB B. 50-100K RMB C. 100-200K RMB D.More than 200K RMB

B Residential Basic Conditions and Residents' Thermal Comfort Habits

Q11 Your current home is located on ________ floor; the height of floor ____ meters; this building has a total of ________ floors.

Q12 Your home is facing: ____; What rooms do you have on the north and south sides of your home?
South side_________________ North side__________________.
A. Bedroom B. Living Room C. Restaurant
D. Study E. Kitchen F. Toilet G. Other ___________

Q13 Home appliance deployment (multiple selection and blanking)
(1)☐ Air Conditioning:
Using it when the outdoor temperature in summer is higher than ____°C.
The usage period is generally☐Morning ☐Noon ☐Afternoon ☐Evening
____ hours per day, remarks: _________.
Using it when the outdoor temperature in winter is lower than ____°C.
The usage period is generally☐Morning ☐Noon ☐Afternoon ☐Evening
____ hours per day, remarks: _________.
The air-conditioning ventilation/dehumidification model uses ____ days of the year and ____ hours of daily use.

(2)☐ Heater:
Using it when the outdoor temperature in winter is lower than ____°C.
The usage period is generally☐Morning ☐Noon ☐Afternoon ☐Evening

_____ hours per day, remarks: __________.

(3)☐ Fan:

Using it when the outdoor temperature in summer is higher than _____°C.

_____ days of use throughout the year and _____ hours of daily usage, remarks: __________.

(4)☐ Exhaust Fan:

_____ days of use throughout the year and _____ hours of daily usage, remarks: __________.

C The Subjective Feelings of Ventilation

Q14 Which rooms do you mainly stay in when you at home_____________;

A. Bedroom B. Living Room C. Restaurant

D. Study E. Kitchen G. Other ____________

Q15 Freshness of outdoor air: ☐ Good ☐ Normal ☐ Bad;

Outdoor Noise: ☐ Good ☐ Normal ☐ Bad;

Are you satisfied with your own ventilation? ☐ Good ☐ Normal ☐ Bad.

Q16 Do you like ventilation when the weather is hot:

A. Like B. Do not like C. It does not matter

Q17 When do you like to have natural wind:

A. Work B. Leisure C. At any time (except sleep)

Q18 Favorite ventilation:

A. Natural wind B. Fan blower C. Air conditioning blow

Q19 Which of the following circumstances do you prefer:

A. A cool-air-conditioned environment

B. It's a bit hot but natural wind, and it's generally acceptable

C. It's a bit hot but has the fan, and it's generally acceptable

Q20 The conditions of window opening:

(1)Summer:

If you don’t have air conditioning, the living room will open ____ hours per day.

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

The bedrooms will open ____ hours per day,

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

(2)Winter:

If you don’t have air conditioning, the living room will open ____ hours per day.

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

The bedrooms will open ____ hours per day,

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

(3)Spring and autumn:

The living room will open ____ hours per day.

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

The bedrooms will open ____ hours per day,

Percentage of average window opening area: ☐Full open ☐1/2 ☐1/4 or __%

Q21 Air conditioning ventilation problems (optional):

A. The air is not fresh;

B. The cold wind is not comfortable;

C. It is not a natural environment;

D. The environment is dull;

E. In and out of the air-conditioned housing environment will have a hot and cold impact;

F It is easy to get sick.

Q22 Fan ventilation problems (optional):

A. Ventilation is monotonous;

B. Long-term ventilation is uncomfortable for people;

C. It is not a natural wind that only blows on one side of the body;

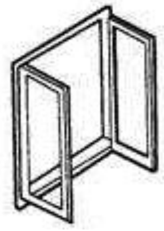
D. Cooling is not obvious;

E. It is easy to get sick.

Q23 What types of windows are used in your home (multiple choices):

Living room _______ Bedroom _______

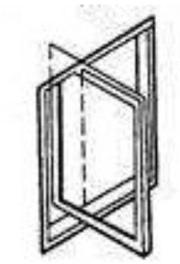
A. Casement window



B. Horizontal sliding window

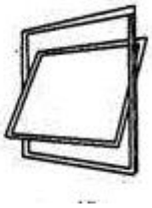
C. Vertical sliding window

D. Vertically pivoted window



E Top-hung window

F. Center-pivoted window



G. Hopper window