Contents lists available at Viser

Journal of South Architecture

http://www.viserdata.com/journal/jsa

Comparison of Domestic and Foreign Research on Natural Ventilation of Buildings Based on Bibliometric Analysis

XU Jiangying[1], CHEN Hong[2], XIONG Yuya[3]

Author Affiliations 1 Doctoral Student; 2 Professor, Corresponding Author, E-mail:chhwh@hust.edu.cn; 3 Doctoral Student; 1&2&3School of Architecture and Urban Planning, Huazhong University of Science and Technology

ABSTRACT: The outbreak of COVID-19 has made people pay more attention to the health performance of buildings. Natural ventilation plays an important role in improving the indoor air quality related to health. To reveal the research situation of research on the natural ventilation of buildings at home and abroad, we take the Web of science and CNKI's periodical literature about the natural ventilation research on buildings as the object of our research. Furthermore, we adopt the method of bibliometric analysis, and use the visualization function of the CiteSpace and VOSviewer tools. We systematically summarize the overall characteristics and evolution process of the research field. The analysis found that there are differences in research hotspots and trends in the field of building natural ventilation at home and abroad. The foreign research on the natural ventilation of buildings began earlier, and is richer and more detailed. Human health issues are the main concept throughout, with emphasis on air quality and human behaviour. In contrast, the related research in China began to be carried out late, and the overall research has shown the characteristics of decentralization, focusing on building energy conservation. Experiments and numerical simulations are the common research methods. The latest research attempts to introduce intelligent computer optimization technology to assist the natural ventilation of buildings in the design stage. Finally, summarizing the existing research results and put proposed research projects can provide the necessary basis and inspiration for research on building natural ventilation in China and contribute to the improvement of indoor air quality and the protection of the ecological environment.

KEY WORDS: natural ventilation; bibliometrics; CiteSpace; VOSviewer; research hotspots; research trends

Introduction

In 2020, a sudden COVID-19 pandemic swept the world, causing immeasurable losses to human society and exacerbating the global health crisis. The indoor environment where we live and work is the most common place for infectious diseases to spread. Existing studies have shown that effective natural ventilation in indoor environments can prevent the spread of infectious diseases [1], is beneficial to health, and the human body is more comfortable in a naturally ventilated environment than in an air-conditioned environment [2]. In addition, natural ventilation is the main passive strategy to reduce energy consumption by air conditioning systems. Therefore, while ensuring people's health and comfort, natural ventilation of buildings can effectively reduce building energy consumption and environmental pollution [3], which is of great significance to "Healthy China 2030"[1] and "China 2030 Carbon Peak"[2].

[**The format of citation in this article**]
XU Jiangying, CHEN Hong, XIONG Yuya. Comparison of Domestic and Foreign Research on Natural Ventilation of Buildings Based on Bibliometric Analysis [J]. Journal of South Architecture, 2024(4): 37-52.

• **Fund Projects**: National Natural Science Foundation of China (51778251): Research on the Correlation between the Spatial Form of Waterfront Blocks and the "Quantity" and "Effect" of River Wind Penetration - A Case Study of Cities in the Middle and Lower Reaches of the Yangtze River.
Document Identification Code A **DOI** 10.33142/jsa.v1i4.14758 **Article number** 1000-0232(2024)04-037-16

In the past three decades, domestic and foreign scholars have carried out a series of studies on naturalventilation of buildings and published a large number of papers, which makes it difficult to grasp the research focus and status of natural ventilation of buildings. At present, most of the review articles on natural ventilation of buildings by domestic scholars are from a single perspective, such as technology [4], effect [5] and application [6]. At the same time, the existing research is mostly sorted by time, but the overall context comparison of domestic and foreign research is rarely included. Based on this, this paper uses bibliometric methods to conduct a visual analysis of the literature on natural ventilation of buildings at home and abroad, and sorts out and summarizes some classic literature to provide reference for in-depth research on natural ventilation of buildings in the future.

1 Research methods and data sources

1.1 Research methods

This paper uses CiteSpace and VOSviewer as bibliometric tools. Both software can analyze the clustering and evolution of literature keywords, but each has its own characteristics. VOSviewer can present research hotspots through beautiful and clear color blocks; CiteSpace is better at keyword mutation analysis which displays research context and evolution process, convenient for mining recent research frontiers of disciplines.

1.2 Data sources

The Chinese and English literature sources are CNKI and Web of Science respectively, and the search time is from January 1, 1990 to December 31, 2020. In order to comprehensively collect relevant literature, literature retrieval is carried out in the followingsteps [7]. 1) Direct search: Professional terms "natural ventilation, single-side/side/direct ventilation, cross/convection/two-way ventilation, wind through-the-hallway wind" and "building" in Chinese, and "natural ventilation, single-side ventilation, cross ventilation" and "building" were used in combination for advanced subject search. 2) Retrospective search: In the literature retrieved in the previous step, similar related keywords, including "residence, office, large space, gymnasium" in Chinese and "residen* , office* , university* ", etc., were used for retrospective search. 3) Circular search: The search in the first two steps was circulated to include highly relevant literature. A total of 3,049 Chinese pieces were obtained using CNKI "all journals" as the source, and a total of 4,068 foreign literatures were obtained using the core set of Web of Science "all journals" as the source. Among them, 569 Chinese and 466 foreign pieces were from "important journals" in the field of architectural science [3].

2 General overview of domestic and foreign research

The overall analysis includes two aspects: annual publication volume and representative journals in the field of architectural science. The annual publication volume is analyzed based on the search results of "all journals" to fully reflect the publication trend; the representative journals are analyzed based on the search results of "important journals" with certain authority to further show the research background and overall pattern.

2.1 Annual publication volume

The number of documents reflects the changes in the degree of attention paid to academic research in this field. Comparing the annual publication volume of Chinese and English documents, different development trends are shown at home and abroad. The publication volume distribution index fitting analysis was performed on 3,049 Chinese documents and 4,068 English documents from 1990 to 2020, and the fitting degree (R^2) of the two curves reached 0.8523 and 0.8382 respectively. It can be considered that the number of Chinese documents on natural ventilation of buildings in this period showed a power-type growth, and the number of English documents showed an exponential growth (Figure 1).

Related research first appeared in 1990, and the overall publication volume was relatively small in the early stage. The number of papers published on naturalventilation of buildings abroad has increased rapidly since 1996, especially from 2010 to 2019. The number of papers published in China has shown great volatility, with 2003 as an important turning point. The outbreak of SARS in that year made people realize the importance of natural ventilation of buildings to health. Before that, there were few related studies, but related studies increased in that year,

and the number of papers published reached its peak in 2016. In recent years, as the SARS craze faded, the number of papers published has declined slightly. As an important factor that directly affects people's health, the outbreak of COVID-19 in 2020 may promote a new growth trend in the number of related papers after 2020.

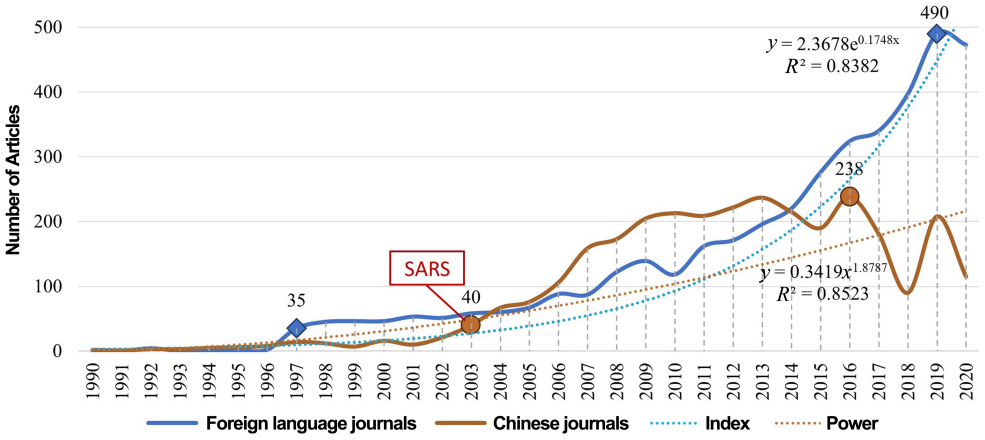

Figure 1 Annual publication of journal papers on naturalventilation of buildings

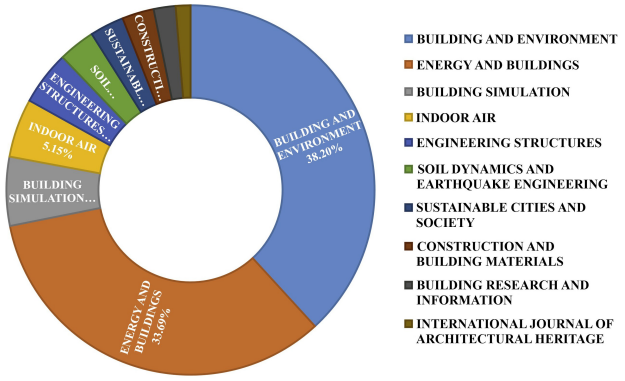

Figure 2 Representative journals of foreign research on natural ventilation of buildings

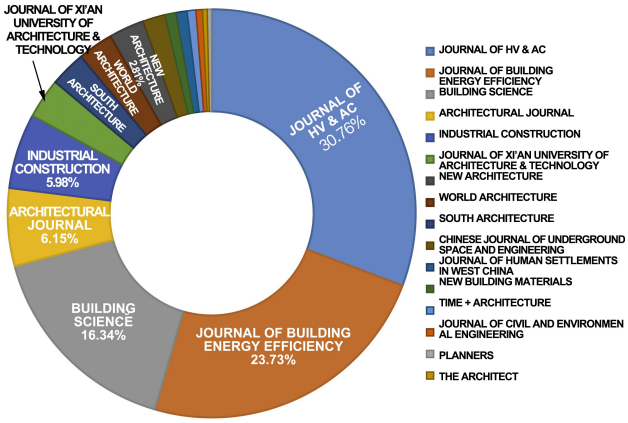

Figure 3 Representative journals of domestic research on natural ventilation of buildings

2.2 Representative journals

The retrieved journals were sorted to obtain a sunburst chart of representative journals on naturalventilation of buildings. In terms of the number of journal articles published, foreign research results on natural ventilation of buildings are mainly published in journals such as Building and Environment, Energy and Building, Building Simulation, and Indoor Air (Figure 2), with 178, 157, 28, and 24 articles respectively, accounting for 83% in total. The impact factors of these four journals are 4.971, 4.867, 2.472, and 4.739, respectively, all of which are heavyweight SCI journals in the field of architecture. Domestic papers are mainly published in journals such as Journal of HV & AC, Journal of Building Energy Efficiency, Building Science, Architectural Journal, and Industrial Construction (Figure 3), with 175, 135, 93, 35, and 34 articles respectively, accounting for 83% in total. The impact factors of these five journals are 0.955, 0.659, 1.093, 1.745, and 0.828, respectively, all of which are important journals in the field of architecture.

3 Research progress at home and abroad

3.1 Research progress abroad

3.1.1 Research hotspots

Using VOSviewer, a co-occurrence analysis of keywords in foreign literature on natural ventilation of buildings (Figure 4) and a statistical analysis of the keywords in the 4,068 foreignarticles retrieved were conducted, dividing the 581 frequently used keywords into five clusters. The higher the frequency of occurrence of the keyword

within the cluster, the larger the sphere in the co-occurrence analysis diagram, which also indicates that the keyword is the hot research topic of the cluster. However, since the same concept is expressed by multiple words (such as energy and energy efficiency in Figure 4, both represent building energy consumption), the size of the sphere cannot well represent the research topic of the cluster, so the merging of similar keywords is particularly important for the hot topic analysis of the cluster. In addition, the connection between keywords in some clusters is weak, not suggesting any theme. Such clusters cannot express the research hotspot in this field, so they can be ignored in the hot spot analysis. Based on this, the research topics can be reclassified into the following four categories: First, air quality and human health, with keywords including health, symptoms, indoor air quality, PM2.5, etc.; second, thermal comfort and building energy consumption, with keywords including thermal comfort, energy, energy efficiency, etc.; third, behavioral management research, with keywords including behavior, management, etc.; fourth, the scope of research methods, with keywords including CFD, large-eddy simulation, turbulence models, wind tunnel experiment, etc.; these four clusters basically represent the main hotspots and methods of foreign research in the field of natural ventilation of buildings in the past 30 years.

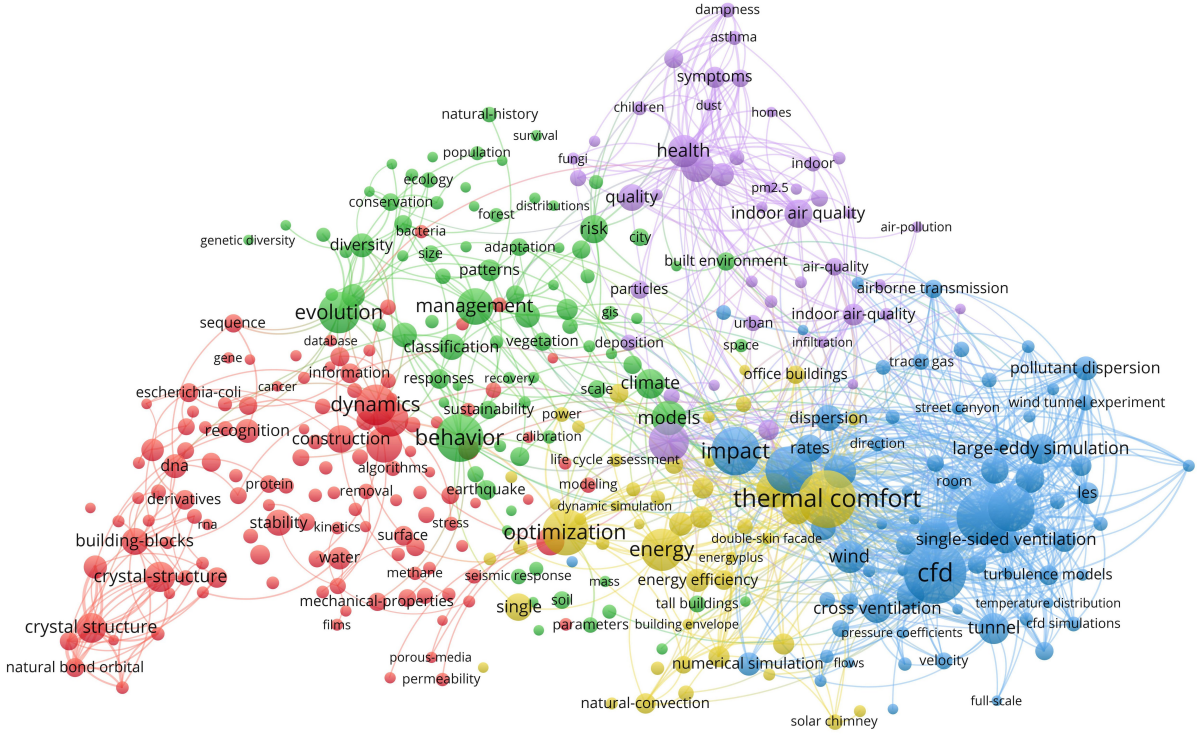

Figure 4 Co-occurrence analysis of keywords in foreign research on natural ventilation of buildings

(1) Air quality and human health

People spend 90% of their time indoors, and indoor air quality (IAQ) plays an important role in people's physical and mental health [8]. Natural ventilation is an important aspect of improving IAQ and reducing sick building syndrome [9]. Opening windows is a necessary condition for achieving natural ventilation, but this will reduce indoor thermal comfort [10]. Therefore, window opening must meet appropriate width and duration to ensure health and thermal comfort requirements. It is worth noting that IAQ will be affected by outdoor pollution due to window opening, so whether a building can be naturally ventilated is closely related to its surrounding microclimate environment. Traffic pollution is one of the important sources of street canyon pollutants. Yang [11] et al. explored the impact of traffic pollutants on the IAQ of buildings near traffic arteries under different window opening ratios, and Tong [12] et al. further explored the impact of different building parameters. In addition to the block scale, atmospheric pollution at the urban regional scale

will also reduce the natural ventilation potential of buildings. Tong [13] estimated the natural ventilation potential of major cities based on China's atmospheric environmental quality and found that the natural ventilation potential in the north in winter is smaller than that in the south. Therefore, how to improve the outdoor environmental quality in the north and thus improve the natural ventilation potential of buildings is a topic worthy of attention.

Keywords	Emergence intensity	Emergence time	1990 – 2020
sick building syndrome	6.59	1990-2002	
symptom	6.46	1990-2009	
prevalence	4.30	1990-2009	
indoor air quality	3.33	1997-2013	
cross-ventilation	6.64	2001-2010	
health	6.60	2002-2007	
exposure	3.49	2004-2006	
computational fluid dynamics(cfd)	5.61	2005-2009	
wind tunnel experiment	4.39	2008-2011	
discharge coefficient	3.06	2009-2010	
simulation	3.92	2009-2015	
thermal comfort	3.04	2011-2012	
efficiency	4.54	2012-2016	
urban area	2.72	2013-2014	
sustainability	2.59	2014-2016	
high-rise building	3.27	2014-2016	
hydrothermal synthesis	3.04	2015-2018	
validation	2.40	2015-2016	
emission	5.31	2015-2016	
pollutant dispersion	7.34	2016-2017	
sensitivity analysis	2.39	2016-2016	
solar chimney	2.46	2016-2017	
double skin facade	2.95	2016-2017	
large eddy simulation	3.50	2017-2018	
single sided ventilation	3.52	2017-2020	
framework	5.55	2017-2020	
china	2.36	2018-2020	
tropical climate	2.11	2019-2020	
convolutional neural network	2.47	2019-2020	
deep learning	2.88	2019-2020	
machine learning	3.28	2019-2020	
energyplus	2.47	2019-2020	

Figure 5 Burst detection of foreign research on natural ventilation of buildings

(2) Thermal comfort and building energy consumption

People's satisfaction with the indoor thermal environment is usually called thermal comfort, which is an important aspect of evaluating building performance. C. Andido [14] and Kwong[15] found that high wind speed can increase the thermal comfort range. Naturally ventilated buildings have a wider thermal comfort range due to their higher wind speed [16]. Generally, it is more difficult for single-sided ventilated buildings to obtain good natural ventilation conditions, resulting in poor indoor thermal comfort. Scholars have done a lot of research on this. Montazeri [17], D. Cui [18] and S. Omrani [19] found that the balcony of a single-sided ventilated building has a significant improvement on the thermal comfort of its attached space. While pursuing comfort, people inevitably use mechanical equipment, which increases energy consumption of the building. Therefore, research on thermal comfort and building energy consumption is carried out simultaneously. From the perspective of energy saving, natural ventilation is an ideal way, as it can achieve energy saving by cooling down the indoor space [20, 21], but its instability makes it difficult to meet the thermal comfort needs the whole time. Therefore, natural ventilation needs to be combined with HVAC. With the development of building equipment automation, the technology of controlling natural ventilation by using automatic window opening and closing systems has been widely studied [22, 23], the integration of which into mixed ventilation can save a lot of energy [24]. In future research, more attention will be paid to the role of intelligent control in reducing building energy consumption and

better promoting the sustainable development of buildings.

(3) Behavior management

Natural ventilation is closely related to human behavior. Therefore, the research on natural ventilation is inseparable from human behavior. The research on human behavior is mainly reflected in two aspects. The first is the impact of human behavior on building energy consumption [25]. Sorgato [26] and Cedeno [27] found that human window opening behavior has a significant effect on reducing building energy consumption. The second is the prediction and control of human window opening behavior. Zhang [28] et al. explored the method of predicting window opening and fan use in naturally ventilated buildings. Schulze [29] et al. tried to develop the most energy-saving window opening behavior control plan for naturally ventilated buildings while ensuring air quality and thermal comfort. It can be seen that human behavior is not only related to building performance, but also that the consideration of human behavior can mitigate the inaccuracy of natural ventilation performance prediction in the current design stage. Mining human environmental control behavior preferences through big data is a good research topic.

3.1.2 Research Trends

Burst detection is used to characterize the phenomenon of keyword transition in a short period of time, which helps to grasp the research hotspots in a certain field at different stages. Through CiteSpace, a keyword burst analysis of 4,068 English articles was conducted to obtain the research development trend of foreign countries (Figure 5). Foreign research on natural ventilation of buildings mainly includes four stages: (1) 1990-2004, the research focused on air quality and human health, and keywords such as sick building syndrome, prevalence, indoor air quality, and exposure appeared frequently; (2) 2005-2010, the research method was the focus of attention, and the newly emerging keywords included CFD (computational fluid dynamics), wind tunnel experiment, simulation, etc. (3) 2011-2015, the newly emerging keywords were relatively broad, mainly thermal comfort, efficiency, sustainable development, etc., and the research content mainly focused on building thermal comfort and building energy saving. (4) 2016-2020, the newly emerging keywords focused on pollutant dispersion and research methods. Keywords such as pollutant dispersion, large eddy simulation and deep/machine learning appeared frequently.

In general, the research on natural ventilation of buildings abroad shows two trends. First, the research content tends to be diversified, from the early focus on air quality and human health to the later focus on thermal comfort, energy saving, sustainable development, etc. Although the research on indoor air quality has not diminished, the research perspective has shifted from the mechanism of air quality's impact on human health to the diffusion pattern of pollutants. Researchers began to explore the impact of the surrounding environment of buildings on the cross-household transmission of pollutants [30] and the transmission pattern of pollutants in various indoor spaces [31, 32]. Secondly, more attention is paid to the introduction of new methods. In the latest published papers, interdisciplinary research is a prominent feature. For example, quantitative methods such as sensitivity analysis [33] are used to measure the correlation between architectural morphological elements and building environmental performance; computer artificial intelligence and numerical simulation platforms are introduced in the architectural design stage, and the natural ventilation performance is automatically generated in reverse based on computer artificial intelligence algorithms.

3.2 Domestic research progress

3.2.1 Research hotspots

Using the same method to conduct keyword co-occurrence analysis on domestic research on natural ventilation of buildings (Figure 6), the research hotspots of nearly 30 years can be reclassified into the following four categories: First, building energy conservation, with keywords including building energy conservation, energy-saving design, building energy consumption, etc.; second, thermal environment, with keywords including thermal environment, thermal comfort, indoor thermal environment, etc.; third, green building, with keywords including green building, building design, ecological building, low-energy building, etc.; fourth, the scope of research methods, with keywords including numerical simulation, CFD, computational fluid dynamics, etc.; these four clusters basically represent the main re-

search hotspots and methods of domestic building natural ventilation research in the past 30 years.

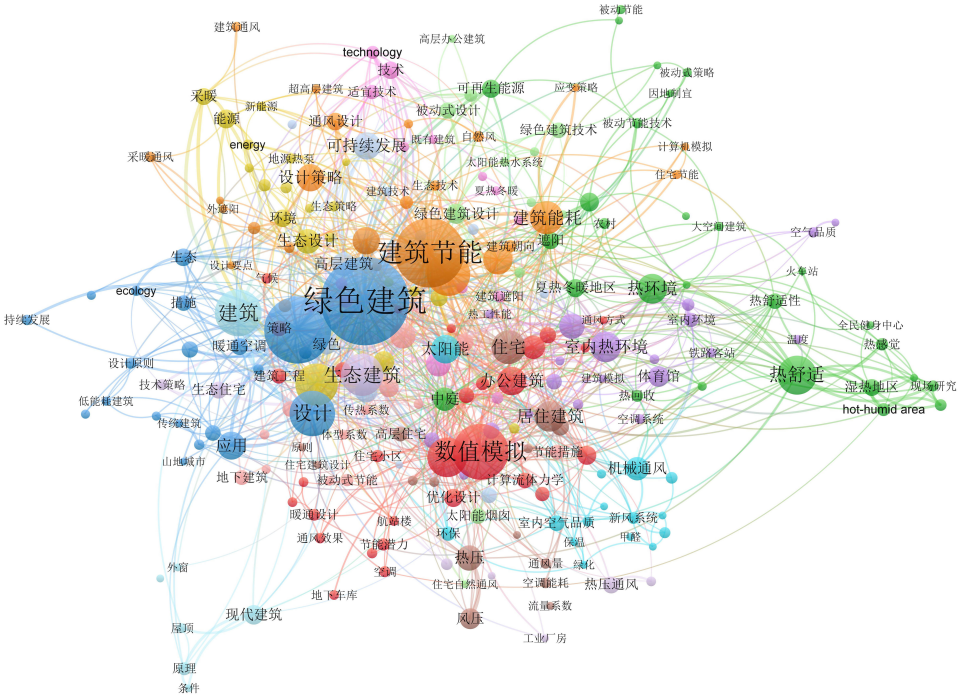

Figure 6 Co-occurrence analysis of keywords in domestic building natural ventilation research

Keywords	Emergence intensity	Emergence time	1990 – 2020
Wind pressure and heat pressure	4.94	2006-2010	
Indoor air quality	3.90	2006-2008	
Heat pressure	3.20	2006-2007	
Ecological building	3.27	2006-2008	
Solar energy	2.94	2006-2007	
Sustainable development	4.35	2007-2008	
Layout	3.11	2007-2009	
Residence	6.84	2008-2009	
Principle	3.01	2009-2011	
Shading	4.21	2009-2011	
Ecological strategy	3.20	2009-2011	
Underground building	2.79	2009-2011	
Indoor thermal environment	4.25	2009-2010	
Renewable energy	2.10	2009-2011	
Green building design	2.82	2010-2016	
Environmental protection	2.10	2010-2011	
Energy-saving technology	2.96	2011-2013	
Green energy saving	3.40	2013-2020	
Solar chimney	3.28	2013-2018	
Optimal design	2.81	2013-2020	
Computational fluid dynamics	2.72	2014-2016	
Areas hot in summer and warm in winter	3.21	2014-2020	
Application	3.50	2014-2018	
Simulation	4.48	2014-2018	
Office building	2.65	2014-2020	
Airflow organization	3.14	2014-2017	
Residential building	2.54	2015-2018	
Architectural design	3.20	2015-2017	
Natural ventilation	8.42	2018-2018	
Numerical simulation	3.74	2018-2020	
Gymnasium	4.08	2018-2020	
Ventilation frequency	3.44	2018-2020	

Figure 7 Burst detection analysis of keywords in domestic building natural ventilation research

(1) Building energy conservation

Natural ventilation can significantly reduce the use of air conditioning and reduce building energy consumption [35]48-49. That the focus of domestic research on natural ventilation of buildings is building energy conservation is mainly reflected in two aspects. The first is the energy-saving effect of natural ventilation. Studies have shown that natural ventilation can reduce the mechanical ventilation time of gymnasiums by about 84.7% [36], and it also has a significant energy-saving effect on bedrooms in residential buildings, especially south-facing bedrooms [37]. The second is the prediction of natural ventilation potential by energy-saving analysis. Since natural ventilation is an important means to reduce energy consumption, energy-saving analysis has also become an important method for evaluating the potential of natural ventilation [38]. Huang He et al. [39] developed the annual hourly simulation software DeST-Vent + for natural ventilation and building energy consumption. By simulating the annual air-conditioning energy consumption of buildings under different natural ventilation conditions, the energy-saving potential of different natural ventilation forms was analyzed. Research on building energy conservation has always been popular. In the context of our country becoming one of the countries with the highest energy consumption in the world, research on natural ventilation energy conservation is still worthy of attention in the future.

(2) Thermal comfort

Thermal comfort research mainly includes the evaluation of thermal comfort performance under natural ventilation conditions and the study of the impact of natural ventilation on thermal comfort. Thermal comfort performance research is usually carried out in the form of field surveys, and the research covers different cities [40], different seasons [41], and different populations [42]. It covers a wide range of building types, among which public buildings are the most common, residential buildings account for a large proportion, and other types of buildings are relatively few [43]. The research on the impact of natural ventilation on thermal comfort is mainly reflected in the two aspects of climate adaptability and building thermal performance. Yan Haiyan et al. [44] compared the impact of dry hot and humid hot climates on human thermal response. The results showed that under natural ventilation conditions, climate can change people's adaptability to the environment. Wind speed has different effects on improving people's thermal comfort under different climate conditions. Wind speed is more effective in humid and hot areas. Wang Xianling [45] 173-175 analyzed the impact of blinds parameters on indoor thermal comfort under the coupling of shading and natural ventilation. Yuan Liting et al. [46] revealed the influence of heat transfer coefficients of exterior walls and exterior windows on indoor thermal comfort of naturally ventilated buildings. When the window-to-wall ratio is less than 0.6, strengthening the insulation of exterior walls can more effectively improve indoor thermal comfort. When the window-to-wall area ratio is greater than 0.6, strengthening the insulation of exterior windows is more effective.

(3) Green buildings

The"green" in green buildings means that the building makes full use of passive technology to provide people with healthy, applicable and efficient use space. Green buildings include land saving, energy saving, material saving, water saving, and environmental protection. Energy saving is an important aspect of green building evaluation and has always been the focus of green building natural ventilation research. It also involves the regulatory effect of natural ventilation on the indoor environment [47] 170-171. At present, the natural ventilation research of green buildings is mainly focused on public buildings, including gymnasiums [47], transportation buildings [48], office buildings [49], etc. Related research is gradually using quantitative methods to study how to optimize building form, window opening, etc., to provide guidance for green building design. For example, using CFD to simulate the natural ventilation environment avoids the uncertainty of qualitative analysis, and also helps compare different building plans to select the best one [50].

3.2.2 Research trends

The development trend of building natural ventilation research was obtained byburst detection analysis of 3,049 Chinese documents through Citespace (Figure 7). Before 2006, domestic building natural ventilation research was in

its initial stage, and no emerging keywords appeared; it then went through three development stages: (1) 2006-2009, the research content mainly focused on the principles of natural ventilation and ecological sustainability; (2) 2010-2013, the research theme is green building and energy saving; (3) 2013-2020, the emerging research focuses on CFD numerical simulation and indoor environment.

In general, the research in the field of natural ventilation of buildings in China shows two trends. First, the research goal has shifted from building energy saving to improving indoor environmental quality. "Green building" has been the focus of many scholars in the past 10 years. As an important aspect of green building, building energy saving has always attracted much attention in the research of building natural ventilation. Keywords such as "green building design, building energy-saving design, green energy saving" have emerged in the past 10 years (Figure 7). With the country issuing the "Healthy China 2030" Planning Outline in 2016, healthy buildings have received attention. And the research focus of building natural ventilation has shifted to improving indoor environmental quality. As a result, keywords such as "airflow organization, air change frequency" have emerged (Figure 7). Studies have shown that natural ventilation fares better at creating a good indoor environment than mechanical ventilation [51, 52], so using natural ventilation to improve the indoor environment is the focus of future research. Secondly, the research objects are more diverse, and keywords such as "office buildings, residential buildings, and gymnasiums" have emerged. Further review of relevant literature shows that the research on natural ventilation of residential buildings focuses on the impact of windows [53], patios [54], balconies [55], building orientation and floor plan [35] 47-48 on ventilation effects, while those targeting office buildings focus on the improvement of ventilation effects by curtain wall ventilators [56], atriums and side courtyards [57], and those targeting large-space buildings mainly focus on vents [58, 59], building forms [60, 61], etc. Different from the previous research on the principles of natural ventilation and energy conservation, the later period pays more attention to improving people's quality of life through architectural design.

4 Comparison of domestic and foreign research

4.1 Comparison of research basis and research content

From the perspective of research basis, foreign research in the field of building natural ventilation has an absolute advantage, and the development is relatively mature, showing an overall exponential growth. In contrast, the research on natural ventilationof buildings in China is still in the early stages of development. The number of papers published only began to show an upward trend after the SARS in 2003 and has slightly declined in recent years with the fading of the SARS craze, showing a lack of sustained research (Figure 1). Affected by national policies and economic development, the number of articles is generally small, and the quality of the journals where they appear needs to be further improved.

From the perspective of research content and research trends, foreign academic circles focus on indoor air quality and human health in the field of building natural ventilation. Its development process has undergone a relatively obvious transformation: the research content has shifted fromthe mechanism of the impact of air quality on human health in the early days to the diffusion of pollutants under natural ventilation (Figure 8). However, the research content in the field of natural ventilation of buildings in our country is relatively extensive, with diverse hotspots. For a period of time, it focused on green building and building energy consumption. In recent years, it has begun to explore the improvement of indoor air quality based on numerical simulation technology (Figure 8). The regulating effect of natural ventilation on indoor air quality depends largely on the outdoor environment. The environmental pollution caused by heating in winter in northern cities in our country leads to limited natural ventilation potential of buildings. Therefore, it is of great significance to study the improvement effect of natural ventilation on indoor environmental quality based on the coupling of indoor and outdoor environments in our country.

The consideration of human behavior has always been a hot topic in the study of natural ventilation of buildings abroad, but domestic research has not paid much attention to human behavior. The natural ventilation of buildings directly affects indoor comfort, which in turn af-

fects the artificial control of indoor environment. In addition to environmental performance, human behavior is also affected by psychological factors such as privacy. The current building performance simulation platform oversimplifies the human behaviorprocess and cannot faithfully reflect the complexity of controlling environment artificially, which affects the accuracy of simulation prediction and makes it difficult to achieve the expected effect of architectural design after the building is put into use. In future research, we should make full use of data mining to collect information such as preferences and specific needs of artificially controlled environments and realize the exploration of differentiated needs of building users. Combining statistical data and questionnaire survey data, the optimization design of natural ventilation of buildings supported by multi-source data will become a trend in future domestic research.

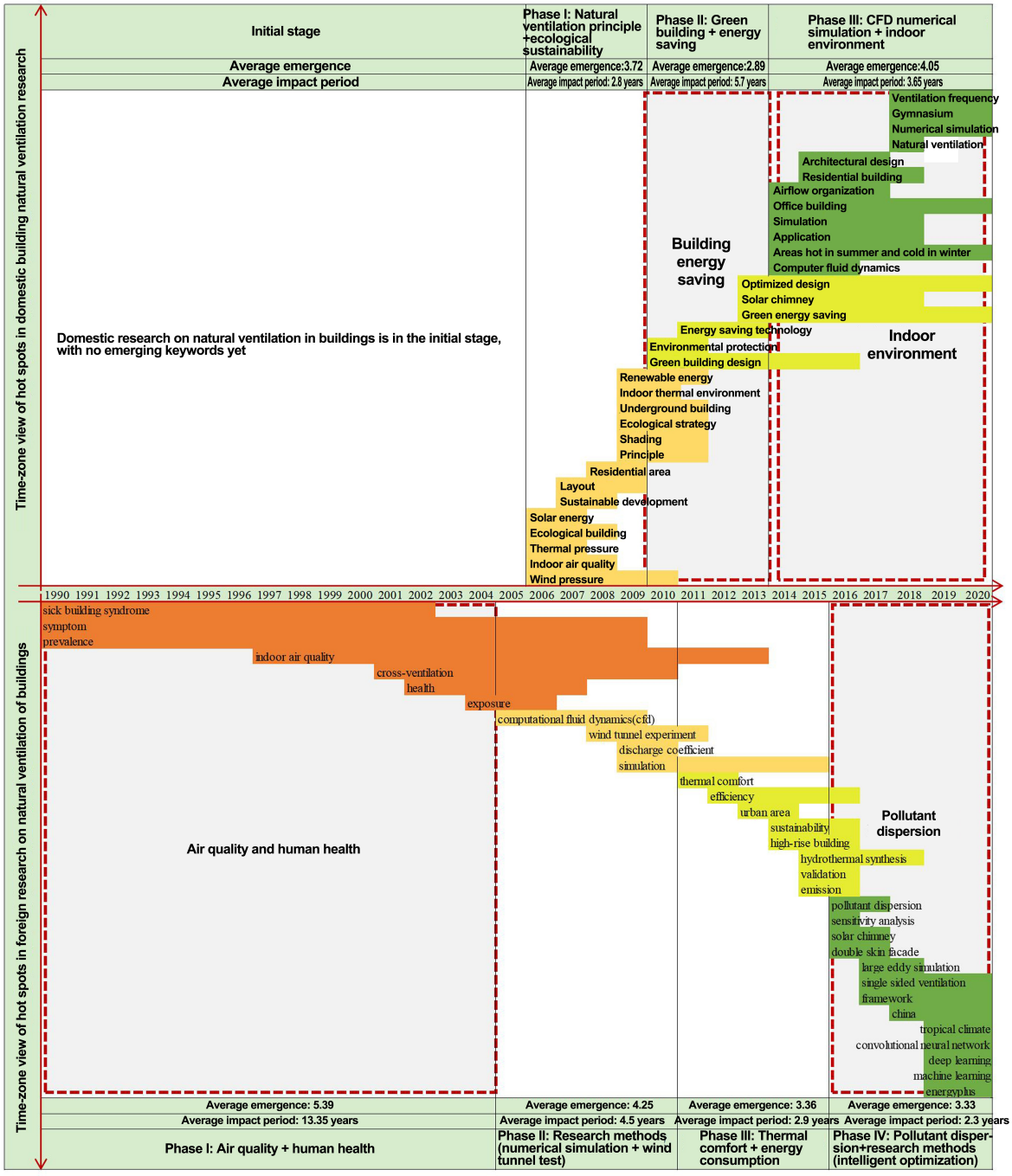

Figure 8 Time-zone view of hot spots in domestic and foreign research on natural ventilation of building natural ventilation

4.2 Comparison of research methods

From the perspective of research methods, foreign scholars have explored more research methods than domestic scholars. In theburst detection analysis of CiteSpace, a total of eight keywords related to research methods emerged in foreign countries, while only three were found in China. Whether it is experimental or numerical simulation methods, the relevant keywords emerged earlier in foreign countries than in China. Domestic research on research methods is still in its infancy. In the past two years, foreign countries have paid more attention to the introduction of new methods, and the exploration of research methods has turned interdisciplinary. Scholars have tried to introduce computer artificial intelligence and numerical simulation platform coupling in the architectural design stage, relying on computer artificial intelligence algorithms to automatically generate design plans. Compared with foreign countries, there are fewer studies in this area in China, and no relevant keywords have emerged in the burst detection analysis (Figure 9).

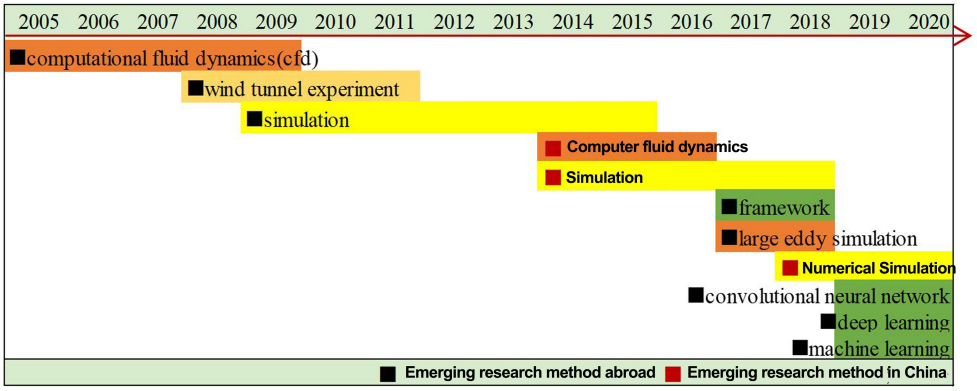

Figure 9 Time-zone view of methods in domestic and foreign research on natural ventilation of buildings

Traditional natural ventilation research methods include two categories: experiments and numerical simulations. Experiments include actual measurements and wind tunnel tests. Wind tunnel tests first appeared in foreign countries, and their results are usually compared with numerical simulation results to verify the validity of numerical simulation results [62]. Compared with numerical simulation, field measurement and wind tunnel testing are costly and time-consuming, and it is difficult to study different schemes at the same time. Therefore, there has not been much development in recent years. However, numerical simulation methods have the advantages of being fast, simple, accurate, effective, and low-cost, and are favored by researchers. At the same time, with the development of computer technology, the cycle and economic cost of numerical simulation have also been greatly reduced, and it has become a popular research method for studying natural ventilation at home and abroad in recent years.

Commonly used models for numerical simulation mainly include computational fluid dynamics model (CFD), multi-zone network model (multi-zone), and coupling model. Among them, CFD model has the highest accuracy, followed by coupling model, and multi-zone is the worst [63] (Table 1). CFD model is mainly used to predict indoor air flow and temperature distribution in the preliminary design stage, such as establishing a model to analyze the ventilation conditions of buildings with different orientations or geometric shapes and studying the influence of many influencing factors such as orientation, shape [64]59-62 and opening geometric parameters [65]18-22 on natural ventilation performance. The commonly used software for this model includes ANSYS Fluent [65]18, PHOENICS [64]58, Fluent Airpak [66], etc. The CFD model is the most used numerical simulation method in the field of building natural ventilation in the past 10 years, and its usage rate far exceeds that of the other two models. Foreign scholars are still enthusiastic about CFD models, while in China, the popularity has slightly declined in the past two or three years (Figure 10). The multi-zone network model started earlier in the United States, the United Kingdom and other countries, and has developed to a relatively mature stage. It is mainly used to

compare indoor environmental quality under different natural ventilation conditions [67]. CONTAM and COMIS are the most popular multi-zone models in natural ventilation research [68]. The coupling model is a new method developed in recent years to combine the advantages of the CFD model and the multi-zone network model. It is mainly used to explore the impact of traffic pollution on the indoor environment of street-facing buildings [69]. Foreign scholars use multi-zone models and coupling models much more frequently than domestic scholars. Relatively speaking, domestic scholars are more willing to use CFD models to study the natural ventilation of buildings (Figure 10).

Table 1 Brief list of research methods in the field of building natural ventilation

Simulation model	Principle	Accuracy	Advantages	Disadvantages
CFD model	A microscopic approach which uses conservation equations such as mass and energy to analyze the building velocity field, temperature field, and pollutant concentration field	* * *	Detailed description of the characteristics of indoor parameters	The amount of calculation is large, the calculation time is long, and therequirements for computers are high.
Multi-zone network model	A microscopic approach which uses conservation equations such as mass and energy to analyze the air flow, pressure distribution, and pollutantdispersion of the entire building	*	Fast calculation speed and short time, can be used for long-term dynamic simulation and air infiltration problems [70]	It is impossible to study the flow field, and the results are relatively rough
Coupling model	Dividing the space into CFD zones and multi-zone zones, using the multi-zone results as the boundaries of the CFD zone for CFD simulation, and then feeding the results back to the multi-zone for calculations in the remaining areas	* *	Higher accuracy than multi-zone model, shorter calculation time than CFD model	The simulation process is complex.

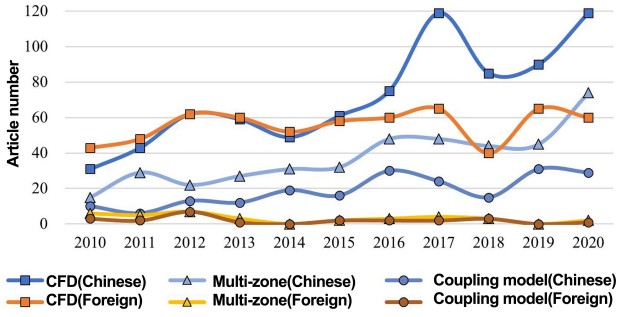

Figure 10 Comparison of numerical simulation methods in important journal articles at home and abroad in the past decade

Intelligent optimizationis a new method introduced in the field of natural ventilation in recent years. It appeared earlier in foreign countries, and there have been many related studies in recent years, with obvious keyword emergence (Figure 9). However, the development of intelligent optimization in China started later, and no keywords have emerged yet. Intelligent optimization can be divided into three types according to their different technical characteristics: "optimization based on CFD numerical simulation [71]", "optimization based on wind tunnel tests [72]" and "optimization based on proxy models [73]102-104". The CFD-based optimization method refers to the iterative optimization of coupling CFD and optimization algorithms at the scheme stage. However, since CFD simulation calculations are time-consuming, researchers have proposed optimization methods based on wind tunnel tests and proxy models to address this shortcoming. Existing studies have elaborated and compared the principles, technical characteristics, advantages and disadvantages of these three optimization methods in detail [73]100-104. The basic process of optimization is as follows: first, variables are selected as the optimization target; then, technical model tests were conducted to explore the influence of various influencing factors on the objective function; finally, the results obtained were evaluated to find excellent genes and form excellent schemes (Figure 11). This reverse generative optimization method based on building performance has become an important method for optimizing building performance design today and plays an important role in the optimization design at the scheme stage.

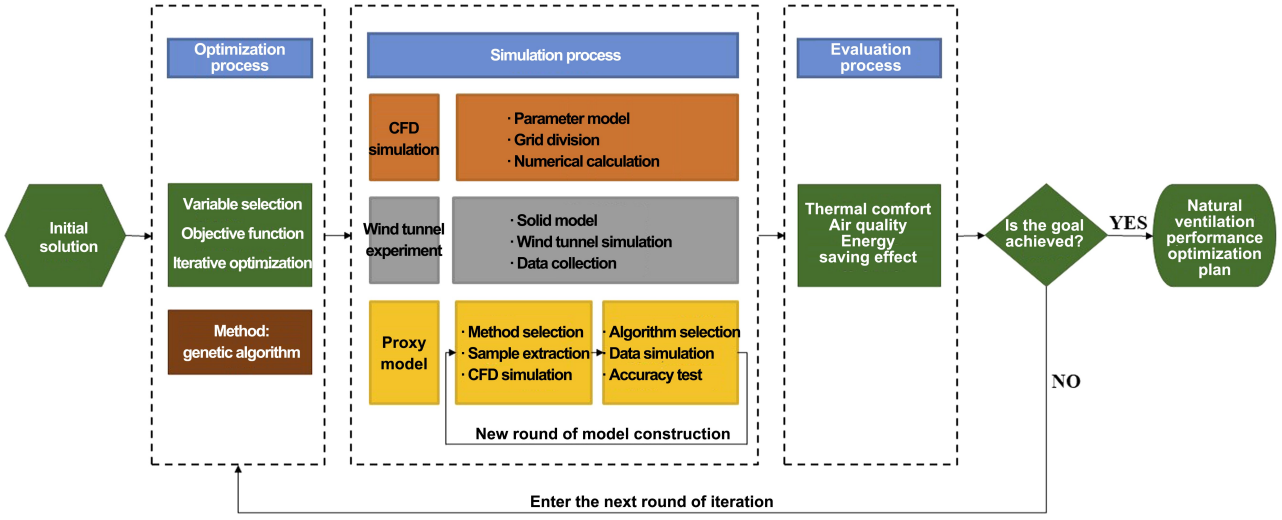

Figure 11 Optimization process for natural ventilation performance

Summary and discussion

By means of bibliometric and visual analysis of the research on natural ventilation of buildings at home and abroad from 1990 to 2020, the current status of research is summarized from the number ofarticles and journal distribution. Based on this, a comprehensive analysis of research hotspots and research trends is conducted. In summary, the characteristics of the current research on natural ventilation of buildings at home and abroad and the issues that need attention can be found:

Compared withother countries, the research on natural ventilation of buildings in China is still in the early stages of development, and there is still a lack of sustained research. In addition, a large number of domestic studies are still at the stage of energy-saving analysis and energy-saving design strategies for green buildings. As far as natural ventilation itself is concerned, there is little discussion on the issues of air quality and health under natural ventilation of buildings. In addition, the research process lacks consideration of user behavior, which will reduce the accuracy of the results in the prediction stage.

Combining practical understanding of the research field and the analysis of the diagrams, it can be seen that future research and practice can make innovative contributions in the following aspects:

(1) Explore strategies to improve indoor environmental quality under indoor and outdoor coupling. The microclimate environment around the building directly affects the wind field around the building and the ventilation capacity of the building. Therefore, it is necessary to fully consider the impact of the microclimate environment around the building on the natural ventilation of the building and conduct on-site measurements based on actual weather conditions to explore the impact of the outdoor microclimate environment on the indoor environmental quality.

(2) Conduct window opening behavior research based on new methods and technologies. Natural ventilation affects the frequency of artificial controls of environment by changing the indoor comfort level. At the same time, human behavior is also affected by psychological factors such as privacy. In future research, we should focus on analyzing and integrating complex user behaviors and explore the preferences and specific needs of artificially controlled environments in different regions and types through new methods and technologies, so as to explore the differentiated needs of building users.

(3) Pay attention to improving the health performance of buildings. The 2020 COVID-19 epidemic has pushed health concerns to a new level. As an emergency“shelter” during public safety incidents, whether buildings have “anti-epidemic” functions is the focus of future architectural design. Therefore, the relationship between the building form and the risk of cross-infection between indoor and outdoor air of buildings under natural ventilation will become a top priority in future research in the field of ar-

chitectural science.

Figure and table sources

Allfigures and tables are created by the authors.

Notes

1) In 2016, the CPC Central Committee and the State Council officially issued the Outline of the"Healthy China 2030" Plan, which put forward the vision and goals of China's health and medical development in the next 15 years.

2) In 2015, the Chinese government proposed the goal of "China will achieve carbon emissions peak around 2030 and strive to achieve it as soon as possible" at the Paris Climate Change Conference.

3) Important journals refer to high-quality scientific and technological journals in the field of architectural science (T1-T3 level) published by theArchitectural Society of China in 2020.

4) Accuracy: The numerical simulation results of different models are compared and verified with wind tunnel tests. The closer the simulation is to the actual measurement, the higher the accuracy. Among them, CFD simulation uses the large eddy simulation method.

References

[1] MA Tianci, XIE Xiaojian, HANG Jian, et al. Numerical Study of Inter- unit Dispersion of Pollutant in Single- sided Naturally Ventilated Buildings among Ideal Street Canyon[J]. Building Science, 2020,36(10):105-113.

[2] WANG Yiran, HUA Jinjing, OU Yangqin, et al. Human Thermal Comfort Under Simulated Natural Wind With Different Turbulence Intensities[J]. Building Science,2013,43(04):91-96.

[3] LIU Nianxiong, QIN Youguo. Building Thermal Environment (Second Edition)[M].Beingjing: Tsinghua University Press, 2016.

[4] DUAN Shuangping, ZHANG Guoqiang, PENG Jianguo, et al. Development in research of natural ventilation[J]. Heating Ventilating & Air Conditioning,2004,34(3):22-28.

[5] GAN Yangyang, LI Zhisheng. Review of Research on Cooling Effect of Indoor Natural Ventilation[J]. Intelligent Building & Smart City,2019,4:51-52.

[6] LAN Fei. Research Review on Application of Natural Ventilation for Architecture Field[J]. Nonferrous Metals Engineering & Research,2014,35(2):40-43.

[7] GUO Linlin, LI Baofeng, Chen Hong. A Review of Urban Microclimate Research on Block Scale in China[J]. Urban Development Studies,2017,24(1):75-81.

[8] JONES A. Indoor Air Quality and Health[J]. Atmospheric Environment,1999,33(28):4535-4564.

[9] FISK W J. How Home Ventilation Rates Affect Health: A Literature Review[J]. Indoor Air,2018,28(4):473-487.

[10] LEI Z P, LIU C P, WANG L, et al. Effect of Natural Ventilation on Indoor Air Quality and Thermal Comfort in Dormitory during Winter[J]. Building and Environment,2017,125:240-247.

[11] YANG F, KANG Y M, GAO Y W, et al. Numerical Simulations of the Effect of Outdoor Pollutants on Indoor Air Quality of Buildings Next to a Street Canyon[J]. Building and Environment,2015,87:10-22.

[12] TONG Z M, CHEN Y J, MALKAWI A, et al. Quantifying the Impact of Traffic-Related Air Pollution on the Indoor Air Quality of a Naturally Ventilated Building[J]. Environment International, 2016,89-90:138-146.

[13] TONG Z M, CHEN Y J, MALKAWI A, et al. Energy Saving Potential of Natural Ventilation in China: The Impact of Ambient Air Pollution[J]. Applied Energy,2016,179:660-668.

[14] CANDIDO C, DEDEAR R , LAMBERTS R. Combined Thermal Acceptability and Air Movement Assessments in a Hot Humid Climate[J]. Building and Environment,2011,46:379-385.

[15] KWONG Q J, ADAM N M, SAHARI B B. Thermal Comfort Assessment and Potential for Energy Efficiency Enhancement in Modern Tropical Buildings: a Review[J]. Energy and Buildings, 2014,68:547-557.

[16] BORGE-DIEZ D, COLMENAR-SANTOS A, PÉREZ-MOLINA C, et al. Passive Climatization using a Cool Roof and Natural Ventilation for Internally Displaced Persons in Hot Climates: Aase Study for Haiti[J]. Building and Environment, 2013, 59: 116-126.

[17] MONTAZERI H, BLOCKEN B. CFD Simulation of Wind-Induced Pressure Coefficients on Buildings With and Without Balconies: Validation and Sensitivity Analysis[J]. Building and Environment,2013,60:137-149.

[18] CUI D J, MAK C M, NIU J L. Effect of Balconies and Upper-Lower Vents on Ventilation and Indoor Air Quality in a Wind-Induced, Naturally Ventilated Building[J]. Building Services Engineering Technology,2014,35(4):393-407.

[19] OMRANI S, GARCIA-HANSEN V, CAPRA B R, et al. On the Effect of Provision of Balconies on Natural Ventilation and Thermal Comfort in High-Rise Residential Buildings[J]. Building and Environment,2017,123:504-516.

[20] WANG Y, KUCKELKORN J, ZHAO F Y, et al. A State of Art of Review on Interactions Between Energy Performance and Indoor Environment Quality in Passive House buildings[J]. Renewable & Sustainable Energy Reviews,2017,72:1303-1319.

[21] SPENTZOU E, COOK M J, EMMITT S. Natural Ventilation

Strategies for Indoor Thermal Comfort in Mediterranean Apartments[J]. Building Simulation,2018,11(1):175-191.

[22] EZZELDIN S,REES S. The Potential for Office Buildings With Mixed-Mode Ventilation and Low Energy Cooling Systems in Arid Climates[J]. Energy and Buildings,2013,65:368-381.

[23] MAY-OSTENDORP P T, HENZE G P, RAJAGOPALAN B, et al. Extraction of supervisory building control rules from model predictive control of windows in a mixed mode building[J]. Journal of Building Performance Simulation,2013,6(3):199-219.

[24] CHENARI B, CARRILHO J D, DA SILVA M G. Towards Sustainable, Energy-Efficient and Healthy Ventilation Strategies in Buildings: a Review[J]. Renewable & Sustainable Energy Reviews,2016,59:1426-1447.

[25] WANG L P，GREENBERG S. Window Operation and Impacts on Building Energy Consumption[J]. Energy and Buildings2015, 92:313-321.

[26] SORGATO M J, MELO A P, LAMBERTS R. The Effect of Window Opening Wentilation Control on Residential Building Energy Consumption[J]. Energy and Buildings,2016,133:1-13.

[27] LAURENT J G C, SAMUELSON H W, Chen Y J. The Impact of Window Opening and Other Occupant Behavior on Simulated Energy Performance in Residence Halls[J]. Building Simulation, 2017,10(6):963-976.

[28] ZHANG Y F, LIU Q N, MENG Q L. Airflow Utilization in Buildings in Hot and Humid areas of China[J]. Building and Environment,2015,87:207-214.

[29] SCHULZE T, EICKER U. Controlled Natural Ventilation for Energy Efficient Buildings[J]. Energy and Buildings,2013,56:221-232.

[30] CUI D J, MAK C M, KWOK K C S, et al. CFD Simulation of the Effect of an Upstream Building on the Inter-Unit Dispersion in a Multi-Story Building in Two Wind Directions[J]. Journal of Wind Engineering and Industrial Aerodynamics,2016,150:31-41.

[31] WU Y, NIU J. Numerical Study of Inter-Building Dispersion in Residential Environments: Prediction Methods Evaluation and Infectious Risk Assessment[J]. Building and Environment,2017, 115:199-214.

[32] LIU X P, LV X X, PENG Z, et al. Experimental Study of Airflow and Pollutant Dispersion in Cross-Ventilated Multi-Room Buildings: Effects of Source Location and Ventilation Path[J]. Sustainable Cities and Society,2020,52:101822.

[33] IZADYAR N, MILLER W, RISMANCHI B, et al. A Numerical Investigation of Balcony Geometry Impact on Single-Sided Natural Ventilation and Thermal Comfort[J]. Building and Environment,2020,177:106847.

[34] WANG J, MAE M, TANIGUCHI K, et al. Multi-Phase Framework for Optimization of Thermal and Daylight Performance of Residential Buildings Based on the Combination of Ventilation and Window Design[J]. Journal of Asian Architecture and Building Engineering,2020:1-21.

[35] GUO Fei, WANG Shiyuan. Study on Natural Ventilation and Energy Saving Design of High-rise Residence in Shanghai [J]. Building Science,2008,11:46-49.

[36] LI Lingling, CHENG Zheng, WILLIAM P, et al. Hybrid Ventilation Performance in Ashenfelter Multi Sports Facility in the Northeastern United States Based on Field Measurement and Simulation[J]. Urbanism and Architecture,2016,22:112-115.

[37] FU Heng, GONG Yanfeng, YU Xiaoen, et al. Natural Ventilation Influencing Residential Building's Thermal Environment and Energy Consumption in Hot Summer and Cold Winter Area[J]. Building Energy Efficiency,2013,41(8):21-28.

[38] WEI Jingzhu. Analysis on Natural Ventilation Potential in Exhibition Building[D].Harbin: Harbin Institute of Technology,2006.

[39] HUANG He, LI Xiaofeng, ZHANG Ming-rui, et al. Simulation Study on Annual Energy Consumption of Naturally Ventilated Buildings[J]. Building Science,2012,28(2):46-50.

[40] HUANG Xiaodan, LIU Jiani, GUO Wenzhi. Field study on indoor thermal comfort of naturally ventilated gymnasiums in Guangzhou[J]. Heating Ventilating & Air Conditioning,2019,49 (4):133-138.

[41] Test And Analysis on Indoor Thermal Environment in Natural Ventilation Residence During Summer in Qingdao [J]. New Building Materials,2018,45(11):73-78.

[42] LI Jin, LU-Pin, ZHENG Hailin. Indoor Thermal Comfort Range of Naturally Ventilated Sports Buildings in the Subtropical Regions[J]. Journal of Civil and Environmental Engineering,2019, 41(5):173-182.

[43] DUAN Mulin, SUN Xingwei, LI Xiangli, et al. Relationship Between Human Thermal Comfort and Indoor Thermal Environment Parameters in Various Regions of China[J]. Building Science,2017,33(6):115-122.

[44] YAN Haiyan, LIU Qianqian, Li Daoyi, et al. Comparative Study of Human Thermal Response in Naturally-Ventilated Buildings in Hot-Arid and Hot-Humid Climates[J]. Building Science, 2020,36 (02):104-112.

[45] WANG Xianling, ZHU Yiyun. Coupling Effect of Exterior Window Shaing and Natural Ventilation on Indoor Thermal Environment of Qinba Mountin Buildings in Summer[J]. Journal of Xi'an University of Technology,2020,36(2):170-175.

[46] YUAN Liting, YU-jia, KANG Yanming, et al. Sensitivity Analysis of Indoor Thermal Environment to Thermal Insulation of Wall and Window in Naturally Ventilated Room[J]. Journal of Donghua University(Natural Science),2020,46(01):128-133,155.

[47] QIAN Feng, TANG Shuoning. Study on Green Energy-Saving Buildings——A Case of Tongji University Jiading Sport Center [J]. Building Science,2018,34(8):106-111.

[48] QU Yan. Exploration and Practice of Natural Ventilation Optimization and Transformation Technology for Shanghai Hongqiao T1 Airport Terminal[J]. Building Science,2017,33(8):149-155,180.

[49] WANG Jing, DU Peng, WU Zhongping. Climate Responsive Design of High-Rise Office Building in Hot and Humid Climate——a Case Study based on the Guangdong Transportation Design Building[J/OL]. (2020-10-28)[2021-03-30]. http://kns.cnki.net/kcms/detail/44.1263.tu.20201028.1033.002.html.

[50] LI Yue, LIU Xuan, LIU Qian, et al. CFD for the in Indoor and Outdoor Ventilation of Green Building[J]. Building Energy Efficiency,2015,5:77-80.

[51] AN Jingjing, YAN Da, ZHOU Xin, et al. Simulation Analysis on Differences between Mechanical Ventilation and Natural Ventilation on Indoor Environment in Office Buildings[J]. Building Science,2015,31(10):124-133.

[52] FU Hao, LIANG Weihui, QIN Menghao. Simulation Analysis on Indoor Volatile Organic Compound Concentrations and Exposure Doses in Residences with Different Ventilation Modes in Eastern China[J]. Building Science,2016,32(08):20-26.

[53] SHI Feng, ZHAN Xueyuan. Study on the Influence of Window Opening Forms of Single-Sided Ventilation Room on Indoor Wind Environment in Xiamen Area[J]. Building Science,2017,33(8):74-82.

[54] SHI Feng, ZHUANG Tao. Simulation and Analysis on Interior Wind Environment of Middle Flats of High-Rise Residential Buildings Based on Xiamen Area[J]. Huazhong Architecture, 2018,36(6):38-43.

[55] LI Zhengrong, AI Zhengtao. Numerical Research on the Influences of Balcony on Natural Ventilation Under the Wind Pressure of Low-Rise Buildings[J]. Building Science,2011,27(2):87-91.

[56] LI Yanfeng, PAN Wenyu, ZHAO Meng, et al. Effectiveness Test and Optimization Analysis of Natural Ventilation Scheme for Highrise Office Buildings[J]. Building Science,2017,33(2):59-64.

[57] ZHOU Min, HOU Zhankui. Hybrid Ventilation Application and Energy Saving Design in the Atrium and Court Side of Office Building[J]. Heating Ventilating & Air Conditioning, 2012, 42(12):39-44.

[58] ZHAO Yang, MEI Hongyuan. Study on Optimization Design of Positions of Ventilating Windows for Gymnasium Buildings in the Severe Cold Areas[J]. Building Science,2014,30(2):83-88.

[59] CHENG Zheng, LI Lingling, QI Xiaolin, et al. Research on the Influence of Ventilation Opening Shape on the Wind Pressure Ventilation Effect of Gymnasium[J]. Building Science, 2020, 36(6): 106-111,146.

[60] LI Jin. Effect of Form Asymmetry of Gymnasium on Natural Ventilation and Thermal Comfort of Exercise Site[J]. Journal of South China University of Technology(Natural Science Edition), 2013,41(03):83-89,107.

[61] BAI Xiaowei, LIU Deming, ZHANG Lingling, et al. Sensitivity Analysis of Geometric Parameters of Ventilation Cavity in National Fitness Center to Natural Ventilation Performance[J]. Building Science,2020,36(08):114-122,159.

[62] JIANG Y, ALEXANDER D, JENKINS H, et al. Natural Ventilation in Buildings: Measurement in a Wind Tunnel and Numerical Simulation with Large-Eddy Simulation[J]. Journal of Wind Engineering and Industrial Aerodynamics,2003,91(3):331-353.

[63] LIU Nai-jian. Experimental comparison of three numerical methods for Wind-driven Natural Ventilation in Building Rooms[D]. Xi'an: Chang'an University,2018.

[64] HU Xiaojun, CAI Likai, YING Xiaoyu. A Study of the Impact of Inner Courtyard Layout on Interior Wind Environment of Middle Flats of High-Rise Residential Buildings with Multiple Flats Sharing One Staircase[J]. Architectural Journal, 2015, 6: 58-62.

[65] BAI Xiaowei, HUANG Yong, ZHANG Minyi, et al. Study on the Influence of Geometric Parameters of Façade Openings on Natural Ventilation of Large Space Buildings in Cold Regions: Taking National Fitness Center as an Example[J]. Journal of Human Settlements in West China,2020,35(2):15-23.

[66] SUN Bo, JI Xiang, GU Xianguang. Application of Indoor Natural Ventilation Simulation in Residential Space Layout[J]. Huazhong Architecture,2018,36(5):39-43.

[67] WEI Jingshu, ZHAO Jianing, CHEN Qingyan. Improvement of Indoor Air Quality Through Dual-Airflow Window Ventilation [J]. Building Science,2011,27(02):107-110.

[68] OMRANI S, GARCIA-HANSEN V, CAPRA B. Natural Ventilation in Multi-Storey Buildings: Design Process and Review of evaluation tools[J]. Building and Environment,2017,116:182-194.

[69] ZHU Jihong, LI Deying. Impact Analysis of Outdoor Traffic Pollutant on Indoor Environment of Builings Close to Street[J]. Environmental Pollution & Control,2015,37(11):1-5+ 10.

[70] WU Y, NIU J L, LIU X P. Air Infiltration Induced Inter-Unit Dispersion and Infectious Risk Assessment in a High-Rise Residential Building[J]. Building Simulation,2018,11(1):193-202.

[71] MUGHAL H, BEIRAO J. A Workflow for the Performance Based Design of Naturally Ventilated Tall Buildings Using a Genetic Algorithm (GA) [C]// 37th Conference on Education-and-Research-in-Computer-Aided-Architectural-Design-in-Europe (eCAADe), Univ Porto, 2019: 645-654.

[72] LIN Yuqiong, YAO Jiawei, ZHENG Jingyun, et al. Research on the Building Morphology Generation Method Based on the Wind Tunnel Visualization of Environmental Performance[J]. South Architecture,2018,2:24-29.

[73] BAI Xiaowei, WANG Chao, XIA Baishu. Research on Optimization Method of Building Natural Ventilation in Design Stag[J]. Architectural Journal,2020,S2:100-104.