Natural Ventilation in Beijing Courtyard Primary Room: A Comparison of Isolated and Non-Isolated Buildings

1 ABSTRACT

The primary room is the room where the head of family lives, and most important room in the courtyard, it's natural ventilation features are worth investigating, but there is a controversy when it is analyzed by CFD(computational fluid dynamics). This is largely because it is difficult to assess how the primary room is impacted by the nearby buildings, a problem that can be resolved in the field of CFD research of buildings by comparing isolated and non-isolated buildings. The purpose of this study is to analyze the natural ventilation characteristics and the positive or negative effects of its surrounding buildings on the ventilation performance of the primary room. The isolated primary room model and the conventional courtyard model are constructed separately in this research based on the typical architectural layout of a Qing dynasty Beijing Courtyard. Following discussion and review, major findings are established by comparing the simulation results of the two models: (1) The primary room and wing r on both sides must be included in the isolated model. (2) The surrounding buildings reduce the average wind speed within the primary room by around 50%, lowering the wind pressure on the building's surface. (3) The isolated building model is used to study the building's indoor ventilation characteristics.(4) The primary room has adequate natural ventilation. This study can generate fresh research ideas for the study of natural ventilation in traditional residential buildings, with the hope that the methodology of this study will be broadly applicable to courtyard-style buildings.

1.1 Keywords

Beijing Courtyard, Natural Ventilation, CFD Analysis, Isolation and Non-Isolation Buildings

1 INTRODUCTION

Enclosed residential styles may be found all throughout the world, with Beijing Courtyard being the most iconic in China. Beijing saw the rise of the three dynasties of the Yuan, Ming, and Qing, and the central urban area is made up of hundreds of courtyards arranged in a checkerboard pattern. The primary room is the most important architectural sequence room in the Beijing Courtyard, and it is also utilized as the main living room or the major meeting room, which is emblematic in the study of the living environment of Beijing Courtyard. Nevertheless, the primary room has become old and congested, and the original layout has been harmed, which surely has an impact on the residents' health. 72.8% of respondents to a questionnaire study of courtyard inhabitants in central Beijing believed that their home ventilation was subpar(Lu, 2013). CFD (Computational Fluid Dynamics) uses a relatively simple and efficient mathematical equation method to reproduce and simulate the complex three-dimensional air flow, and is a popular technological technique for studying the natural ventilation characteristics of buildings, such as block, single building, and internal parts of buildings, among others. Peiyan Guo et al. simulated with complete courtyard pattern(non-isolated buildings) to compare the ventilation of the courtyard of the Prince Kung’s Mansion in Beijing during summer, however, no separate control experimental model was set up for the analysis of courtyard ventilation(Guo et al., 2022). In their research, Sheng Liu and Chuahua Huang evaluated the natural ventilation characteristics and constraints of the "Yinzi" house in Hunan Province, the size and location of patios in this type of building were found to have an significant impact on ventilation and residents' comfort(Liu & Huang, 2016). Xiaoyu Du et al. examined the microclimate of a traditional Chinese residential building by comparing field measurements and CFD simulation results, and discovered that CFD simulations could forecast the building's microclimate, including ventilation(Du et al., 2014). As a result of investigating the variables and factors of the preceding study, it was discovered that focusing on one architectural element of the traditional building helps to obtain more precise conclusions, so this study used CFD to simulate the natural ventilation characteristics of the primary room.

The analysis of natural ventilation characteristics of buildings by CFD simulation has been widely recognized in the study of traditional residential house types, but a review of several kinds of literature reveals that there are unclear aspects of the study object modeling and the study structure in the study of natural ventilation of traditional residential houses, and it is unknown whether the surrounding buildings have a negative impact on the study object (Aydin & Mirzaei, 2017; Chen & Zhang, 2022; Hadavi & Pasdarshahri, 2020; He et al., 2019).As a result, the same study item subjected to different research methods may yield different results, and it is required to outline a set of research methods that can yield more accurate results.One clever way is to compare the surface wind pressure of isolated and non-isolated structures to determine the effect of nearby buildings on ventilation(Han et al., 2022), and this method efficiently fills a gap in prior studies.

In conclusion, this study's aims include examining the primary room's ventilation characteristics and solving the problem of simulation accuracy for both isolated and non-isolated buildings. The wind pressure on the surface of isolated and non-isolated buildings is first simulated by CFD to investigate the reliability of the results obtained when CFD simulates the ventilation characteristics of the traditional residential houses. The comparative analysis of wind pressure contour plots and wind pressure difference values can then confirm the validity of this research method proposed by Han et al. and can also remove the disparity between the isolated and non-isolated buildings.

2 RESEARCH OBJECTIVES

2.1 Natural ventilation characteristics of the primary room

The research goal of this study is to properly and effectively analyze the natural ventilation characteristics of Beijing Courtyard's primary room. Because Beijing's environment is dry and chilly in winter and humid and hot in summer, natural ventilation is critical in the primary room. Effective ventilation performance can improve indoor livability while also benefiting residents' health. The utilization of the thermal pressure of the air inside and outside the building, or the pressure differential created by the flow of outdoor air, to promote the entrance of fresh air to achieve ventilation and air exchange is referred to as natural ventilation. Natural ventilation is particularly significant in residential structures since it adds to energy savings and improves interior living comfort. As a result, the ventilation analysis of the primary room must know the wind speed incoming flow conditions, and use the relevant data to reflect the natural

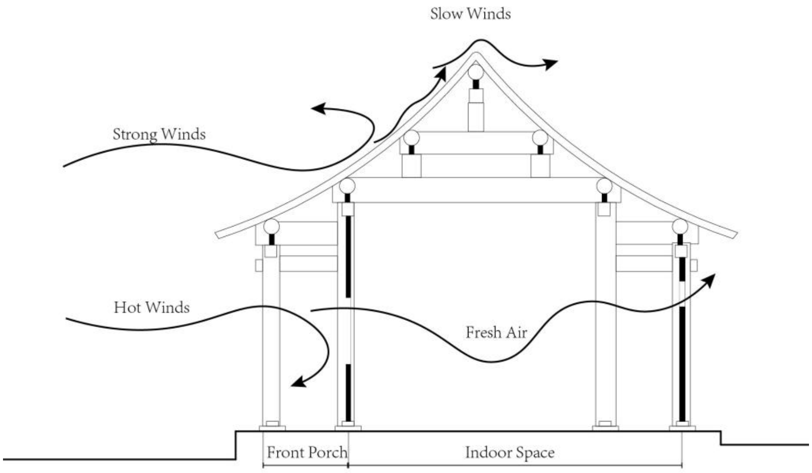

Figure 1. Natural ventilation system consisting of the main architectural elements of the primary room(2022).Diagram by the authors.

ventilation characteristics of the study object. It has been demonstrated that utilizing CFD technology, the wind environment results can be acquired more simply and readily, and the trustworthiness of the conclusions can be verified by using the data obtained from the simulation for the ventilation-related study(Blocken, 2014).The architectural characteristics of the primary room itself, such as the front porch to shade the sun and block the summer heat, the hard hill roof to prevent strong winds, and the location of open windows to efficiently increase inside ventilation, etc. (Tingli & DI, 2020), all have an impact on natural ventilation. The natural ventilation system of the primary room is investigated in the following study by merging the aforementioned architectural features. Diagram of the primary room's ventilation system in Beijing Courtyard (Figure 1).

As a matter of fact, the wind pressure on the roof surface, wind pressure on the windward and windward sides, wind speed near the windows, and airflow analysis of the primary room are all thoroughly examined using the CFD approach in this study. Of course, natural ventilation study must distinguish between indoor and outdoor cases. The building window openings are employed as openings to link with the outdoors in this research, and CFD simulations are performed; this research method is a coupled simulation methodology. Because it avoids introducing errors at the building openings and allows turbulent kinetic energy to dissipate more slowly in the vicinity of the building(Blocken, 2014). The goal is to increase the credibility of the simulation results. Both indoor and outdoor natural ventilation was analyzed in tandem to assess ventilation performance and summarize the characteristics of the courtyard's primary room, and the final conclusions obtained are also applicable to analyzing the natural ventilation characteristics of similar Beijing Courtyard buildings, and such conclusions are universal.

2.2 The influence of surrounding buildings on the primary room

The ventilation of interior and outdoor connected spaces is known by CFD modeling in this work for the investigation of natural ventilation of the primary room. The courtyard in Beijing is an enclosed building group, and the nearby structures will have unknown impacts on the primary room. The simulation findings of the isolated building and the wind field environment of the non-isolated building differ slightly because the airflow is influenced by other nearby buildings, and airflow with different velocities around the research item superimpose, cancel, and strengthen each other(He et al., 2019). The question of whether there is a significant difference between the CFD simulation results obtained from the two cases of isolated and non-isolated positive houses must therefore be clarified when carrying out the aforementioned research steps. Such differences refer to the same initial conditions at the same locations that produce opposite data or more different wind speed or wind pressure contours. If the results are identical, the study object can be separately evaluated and simulated, reducing the number of complex research procedures and allowing the following related studies to avoid wasting time and resources. One of the research goals of this study is to determine the extent to which the surrounding structures affect the findings of the primary room's wind environment simulation. To get the proper conclusions, appropriate comparative investigations must be carried out. In addition to offering a developed research idea and enhancing the research system for the ventilation study of Beijing Courtyard, this research seeks to identify an accurate and effective research methodology through comparison.

2.3 Universality of research methodology

A sound research strategy can give other researchers a research strategy and road map to follow and is generally applicable in studies with a comparable focus. In natural ventilation of buildings, there are primarily two forms of CFD study. The first type, known as basic research, simplifies the building into blocks, arranges the distribution, and analyzes the airflow characteristics. One is the applied study, which examines the intricate wind field environment of a particular case and determines how the wind environment is distributed(Blocken, 2014). Since the study of the ventilation of traditional residential houses necessitates the creation of models for particular architectural styles, layouts, and architectural styles, the coupling approach chosen above to analyze the natural ventilation performance of the primary room constitutes an applied study. It is still possible to analyze the natural ventilation characteristics of traditional buildings using a unified or comparable research process, and some academics have done so for three representative traditional houses in Indonesia. They did this by using the same research process for both their indoor and outdoor ventilation(Suhendri & Koerniawan, 2017). The same research process is used to analyze the ventilation performance of different roof forms of traditional buildings in the same area(Zune et al., 2020), this demonstrates that consistent research methodologies and processes ensure the accuracy of the study while also facilitating the production of similar studies. The following goals are intended to be achieved by this study: (1) Collect and analyze data on the primary room's natural ventilation. (2) Using a comparative study approach, verify and evaluate the extent of the influence of adjacent buildings on the natural ventilation of the primary room. (3) Simplify the research procedure or path for analyzing Beijing Courtyard's natural ventilation system. After fulfilling the following aims, develop an exemplary research approach and replicate it in the subsequent examination of natural ventilation in historic Beijing Courtyard dwellings. Because Beijing Courtyard are standard enclosed building complexes with representative architectural forms and courtyard layouts, the aforesaid study process or approach should have referable value for ventilation analysis of all courtyard-type traditional structures.

3 METHODS

3.1 Standard modeling

Beijing Courtyards are widely scattered throughout the city's center(Figure 2(c)). According to books(Bingjian, 1999), this study chooses typical courtyard in this area. CFD is utilized in this study to examine wind speed and pressure data from an isolated primary room and a non-insulated primary room. Two distinct models must be established. The calculation domain for the isolated building only includes the primary room(Figure 2(b)). Whereas the calculation domain for the non-isolated building includes the full courtyard, with wing rooms connected on both sides and a protruding eave in front of the entrance door to create a semi-outdoor space, the non-isolated building architectural model(Figure 2(e)) uses a three-entry courtyard to construct a building around the primary room, an important house in the central sequence in the courtyard. According to the profile and plan details(Figure 2(a), (d)), the standard model of the remote primary room is modeled 1:1. The model is simplified to depict the important aspects of the research object, such as the front porch, roof, windows, etc., that are projecting from the eaves of the primary room in the Beijing Courtyard and have a substantial influence on the wind environment and wind power.

The standard courtyard model serves two purposes in this research: it makes it easier to use CFD techniques to investigate the characteristics of wind distribution under the influence of buildings, and it offers experimental modeling ideas and derivation ideas for the analysis and study of the Beijing Courtyard building's technical direction.

3.2 Research structure

Three sections make up this study: the stage Ⅰ established the architectural model; the stage Ⅱ examined Beijing Courtyard's natural ventilation features; the stageⅢ provided a summary of the research approaches used. Tasks for the first phase: (1) Establish the courtyard's architectural specifications using books and literature as a guide; (2) Construct models of the primary room and the typical courtyard and reasonably reduce the experimental model. The stage Ⅱ 's goals are to (1) Investigate the impact of nearby structures on the ventilation of the primary room; (2) Compare the wind pressure results of CFD simulations of the isolated and non-isolated primary room; (3) Identify the modeling approach that can more accurately capture the primary room's natural ventilation characteristics. The study plan and technique for the Beijing Courtyard will be supported by a trustworthy and scientific reference from the second phase. The stageⅢ is to assess how well the aforementioned research techniques worked in studying the courtyard's natural ventilation features and to eliminate any unfavorable elements that impeded the investigation.

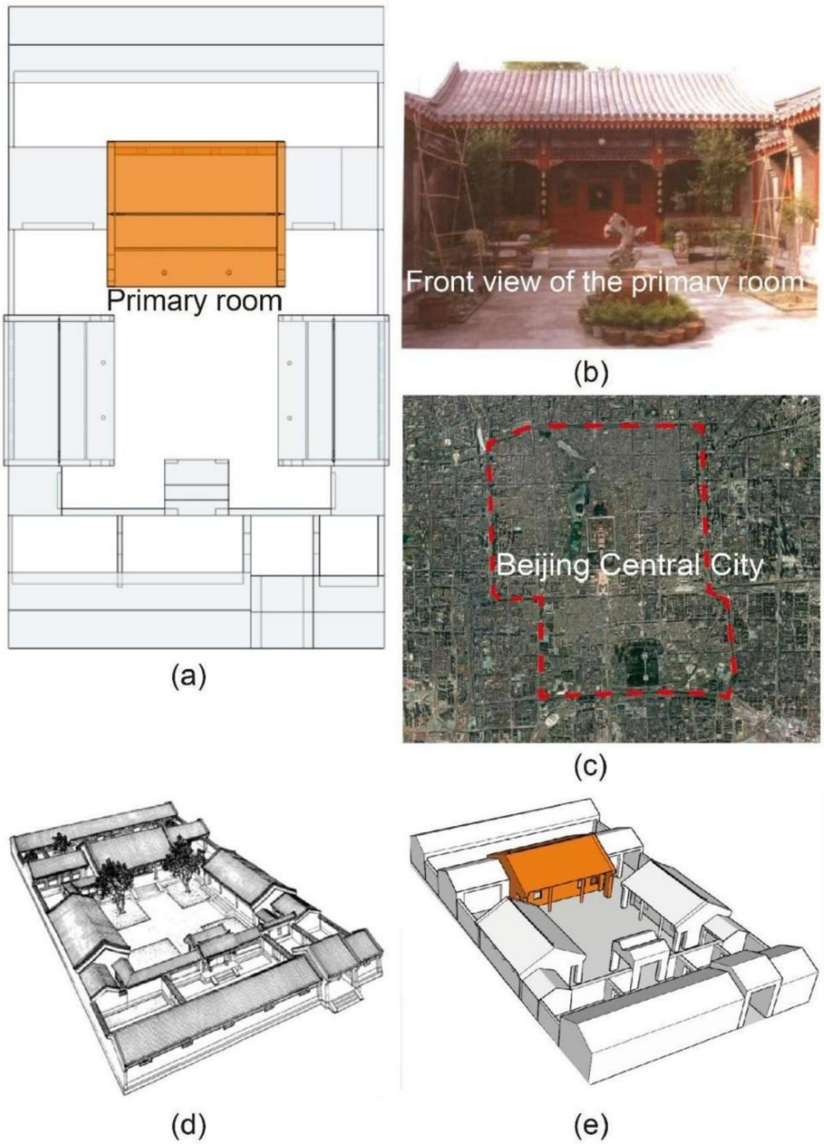

Figure 2. (a) Plan of a typical Beijing Courtyard(2022); (b) Photograph of a typical primary room(Bingjian, 1999), pp. 7 ; (c) Location of Beijing Courtyard(2022); (d) Typical courtyard of the Qing Dynasty(Bingjian, 1999), pp. 8 ; (e) Model of a standard courtyard(2022).Diagram by the authors.

3.3 CFD Setting

The advantages of CFD can be used to computationally analyze different scales of buildings in Beijing's courtyards to understand the overall environmental performance driven by wind and elaborate the causes, while its scientific visualization allows for a more effective evaluation of the study object, enabling designers and users to anticipate and understand the ventilation characteristics of the building(Hsu & Huang, 2022). The condition setting should take into account the method that the research has validated and keep consistent with the method used by the previous researchers in order to evaluate the wind environment of the primary room more scientifically. This is necessary to ensure that CFD operates effectively in the research. In this study, the standard RNG k-ε turbulence model is used with the confined geometry workflow in Fluent software, a module suitable for simulating indoor and outdoor wind environments, and the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm is chosen for the velocity-pressure decoupling equations, second order upwind schemes are employed for the convection and viscous elements in the governing equations, while second-order interpolation is used for pressure(Han et al., 2022).

The goal of the computational grid setting is to minimize unused grid distribution and speed up computational convergence, so this study encrypts the grid near the research object with a face size of approximately 80−100 mm^2 to make it have fine grid segments, while the edge area uses a rougher grid size of approximately 300–600 mm2. It also sets the expansion layer number 5 in the part of the boundary layer and building contacts, and the excess rate 1.2, which can simulate a boundary layer and building contact. The isolated primary room building's computational domain is 40 by 40 by 18 meters, while the conventional courtyard model's computational domain is 80 by 80 by 18 meters. The surface of the building in the computational domain is subjected to the no-slip condition. The average summer wind speed in Beijing is 5.5 m/s (WS 2018), which is adopted as the boundary initial condition and stated using the wind speed profile formula. This is because Beijing residents must utilize natural ventilation as much as possible in their homes during the hot summer months.

4 RESULTS

Two conditions are simulated by the CFD technique for the isolated primary room called Case 1. and the primary room with surrounding buildings called Case 2. The wind environment simulation results of the roof, front elevation, back, both sides, and indoor cross-section above the position of the primary room are selected to be shown in the form of comparison by CFD technology. The wind pressure contour and the contour of indoor ventilation environment with wind velocity vector direction are selected for comparative study in the simulation results (Figure 3). The results(Figure 3(b)) show that when the simulation is run with simply the primary room construction, the wind pressure contours at the roof are more complex and the pressure levels are more finely stratified. The difference in pressure contours between the two building models on the windward side roof is around 10pa, and the difference on the leeward side roof is approximately 3pa.

The wind pressure contour for the back of the building (Figure 3(c)) differ mostly in numerical values and have little bearing on pressure stratification. Case 1. exhibits a finer distribution of wind pressure contours near the windows (Figure 3(d)), and the similar pressure distribution can be seen in the columns, with an average pressure difference of roughly 3pa between the two examples. The pressure contours through (Figure 3(e), (f)) show that the average pressure difference between the two working conditions is 7pa and that under the influence of the wing room, the wall surfaces on both sides of the primary room produce the phenomenon of pressure contour distribution layer by layer, with the right wall producing an obvious low pressure. The influence of the surrounding houses is reflected in the negative pressure generated near the primary room and the wing room, and the right wall produces an obvious lo pressure. The primary room's maximum wind speed is 1.8 m/s near the floor and 2.1 m/s near the ceiling, according to (Figure 3(g)), which shows the internal ventilation under the isolated building settings. In the vicinity of 1.5 meters indoors, the average wind speed is 1.1 m/s. The length of the arrow corresponds to the length of the wind speed at that location, and the direction of the arrow corresponds to the vector's direction at that location. The maximum wind speed at the same indoor ventilation position close to the ground under the impact of the neighboring structures is 1.2m/s. Near the roof, the wind's greatest speed is 1.4m/s. At a height of 1.5 meters indoors, the average wind speed is 0.7 m/s.

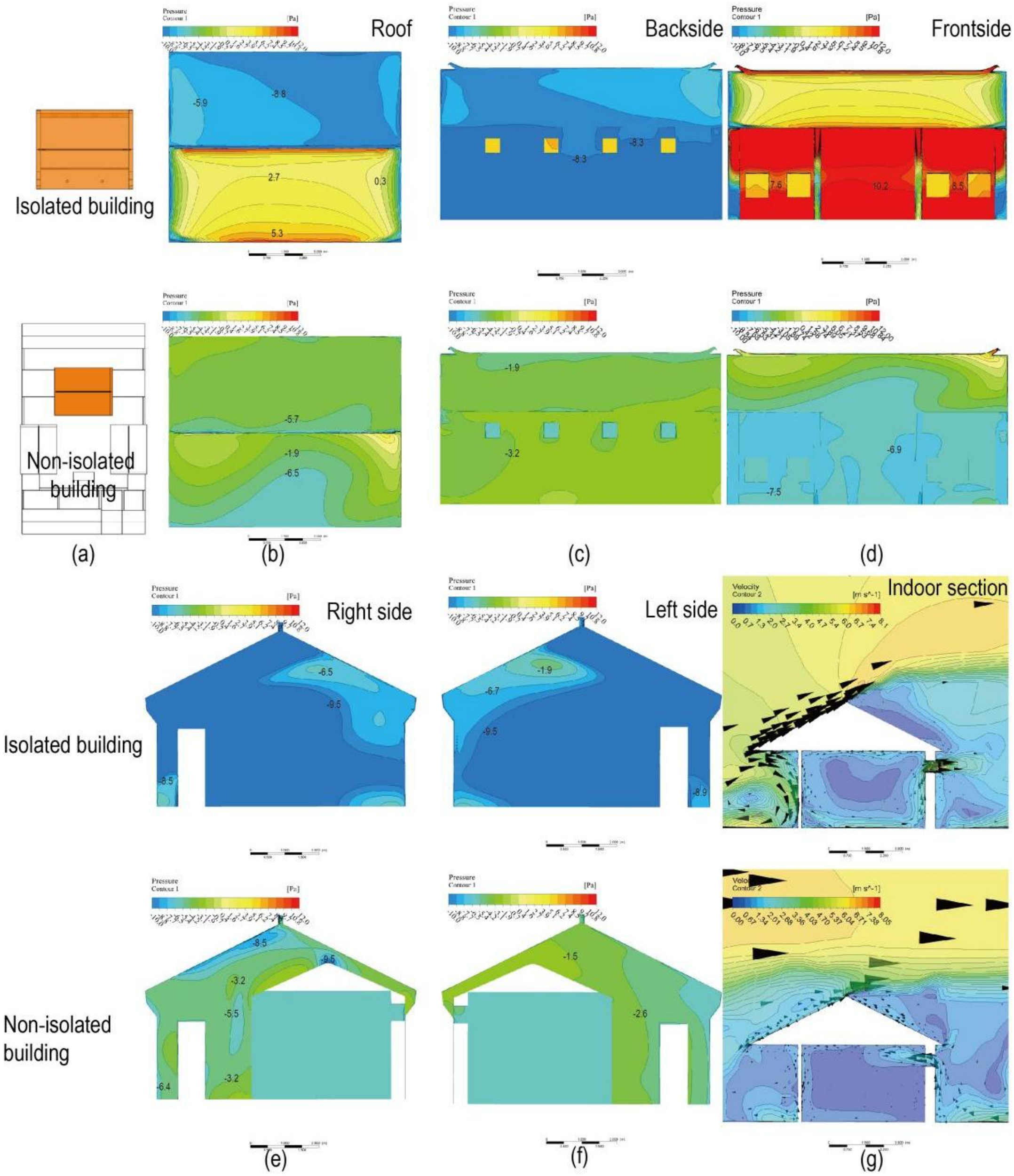

Figure 3. Wind pressure coefficient contour diagram for Isolated building and non-isolated primary room buildings(2022).Diagram by the authors.

5 DISCUSSION

The authors of this study examine the primary room's natural ventilation features in a typical three-entry Beijing Courtyard. The authors examined the impact of the nearby structures on the simulation outcomes of the primary room before simulating and analyzing it using CFD technology. The findings of the simulation are compared with those under the operating parameters of the traditional courtyard model. The authors made the assumption that there is just the primary room building in the computational region. Through this approach, it was found that:

Table 1. Wilcoxon matched-pairs signed rank test of isolated buildings and non-isolated primary room building surface pressure.

	Median difference	Sig.	Z
isolated buildings - non-isolated primary room	-4.0 pa	0.755	-0.312

- The surrounding buildings reduce the wind pressure on the building surface of the primary room. In order to compare the relationship between the wind pressure on the building surface obtained from the two working conditions, this study chooses to compare and study the wind pressure results of isolated buildings and non-isolated primary room buildings. Since the wind pressure data do not follow the law of normal distribution, the software Wilcoxon matched-pairs signed rank test was used to investigate the two groups of values. By using a statistical method, it is possible to determine whether there is a difference between the two groups of values under two different working conditions of the building at the edge of each surface and the same location in the middle of the point and record the pressure value data, resulting in two sets of data for analysis. According to the statistical findings (Table 1), the probability of a difference of -4 pa at the same location on the building surface is about 25%, while the median wind pressure difference between the two working conditions and the building surface is -4 pa, $Z = -0.312$, $P > 0.05$. This finding indicates that there is no significant correlation between the wind pressure data of the two working conditions.
- Since there is only one building in the calculation domain, the roof, walls, and eaves on the windward side of the building are under positive wind pressure, resulting in more pressure contour levels on the building surface, in (Case 1) a more precise wind pressure distribution is obtained at the windows, roof edges, columns, and other building structures of the primary room. The leeward side of the building, however, produces a larger wind shadow area and negative pressure area, so the wind pressure clouds lack contour distribution and only show differences in pressure values. As a result, the pressure changes on the leeward side of the building are not as obvious for either condition.
- The results from (Case 2)'s interior ventilation simulation are less obvious than (Case 1)'s results. The primary room is enclosed by the typical courtyard building model, which causes the wind to have a disturbance effect as it passes through the structure. Additionally, the wind speed will be locally amplified at the courtyard entrance by the narrow tube effect, where the fast airflow will collide with the slower airflow above, creating a local vortex that will weaken the airflow. However, there is no wind weakening in (Case 1)'s simulation since the wind enters the primary room through the open window at the front of the structure. Similarly, the reason for the fine pressure contours at the building's edges and openings is that there is a greater exchange of airflow at the front windows, as discussed above. We know that when calculating the building's indoor ventilation environment, we should appropriately ignore the building in the direction of the incoming flow to reduce or avoid airflow reduction, and the wind speed values obtained differ by 50%, indicating that the simulation results are more significant, and the wind pressure data on the building surface are more. The difference in wind speed values of 50% indicates that the simulation results are more significant, and the wind pressure on the building's surface is reflected in a more detailed manner, which is useful for analyzing the ventilation characteristics of the building interior.
- Most courtyards in Beijing include wing room on both sides of the primary room, which are built close to the walls on both sides of the primary room, resulting in noticeable pressure differences at the roofs of the wing room (Figure 3(e), (f)). The placement of the wing room's roof and the primary room's wall will cause a sharp change in the wind pressure contour. This shift in wind pressure might cause a difference in airflow and wind speed in the surrounding area, perhaps leading to mistrust in the simulation results for isolated buildings. Attention must be paid to the buildings close to the simulated object in the later CFD simulation study of the primary room, and the key change is the airflow and wind pressure distribution at the point where the roof of the wing room meets the side wall of the primary room.

6 CONCLUSIONS

This study proposes a method for studying the ventilation characteristics of the primary room in a Beijing Courtyard by gaining an understanding of the influence of the surrounding buildings on the ventilation characteristics of the primary room, and it attempts to assess the accuracy of this research method. Following the discussion results, numerous noteworthy findings are reported as follows:

- To construct the experimental model of the primary room, we must also construct the model of the wing room. If there are surrounding buildings in the study item, we must usually represent them as a whole, and we cannot disregard the effect of other structures.
- Only the model of the research object can be developed in the computational domain to examine the interior ventilation characteristics of the building, and the surrounding non-adjacent structures can be omitted. So that the resulting wind pressure and wind velocity vectors on the building's surface are more precise to assist the investigation of the research object's natural ventilation features, the CFD simulation should be performed in a linked manner with indoor-outdoor connectivity.
- Surrounding buildings so that the average wind speed inside the primary room decreased by about 50%, which made the building surface wind pressure decrease but there is no significant differential relationship.
- At the openings and margins of solitary buildings, the simulation results can be seen more clearly. CFD examination of the detailed structure of the studied object, such as the ridge, eaves, windows, etc. necessitates the production of isolated building models in the computational domain.
- The wind pressure difference between the windward side and the leeward side of the primary room of the courtyard is >0.5pa, whereby the wind-driven natural ventilation can be carried out by using the pressure difference between the front and back.

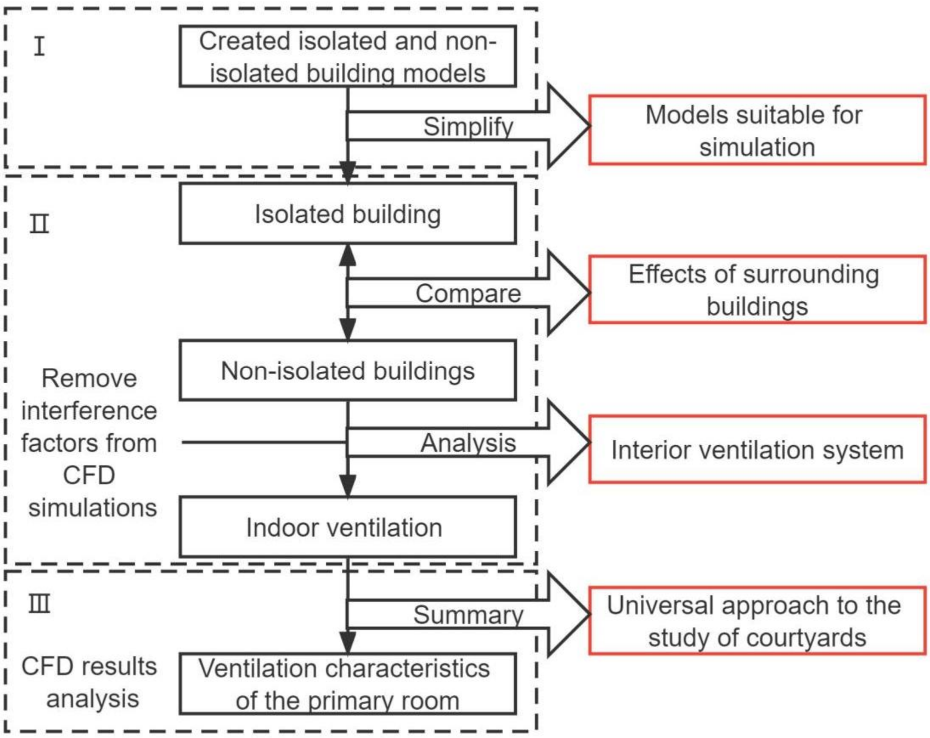

Figure 4. Workflow and method of CFD simulation of primary room(2022).Diagram by the authors.

Beijing Courtyard is a long-established traditional dwelling in the city's central area, marked by excessive housing density and unhealthful living conditions. This study contributes by suggesting the use of the CFD approach for isolated and non-isolated buildings to analyze the primary room. It also offers insight into the Beijing Courtyard's rooms' natural ventilation features, establishing the basis for enhancing the courtyard's livability. This is a novel approach used to evaluate the primary room's natural ventilation characteristics, and it shows how the experience can be broadly applied to studies of a similar type. This study's Innovation also enhances the CFD simulation methods of the primary room(Figure 4), which has significance for subsequent research. Nevertheless, for the other rooms, it is advised that the investigation be continued in depth using the approaches that have wide relevance in the aforementioned results.

7 REFERENCES

Aydin, Y. C., & Mirzaei, P. A. (2017). Wind-driven ventilation improvement with plan typology alteration: A CFD case study of traditional Turkish architecture. *Building Simulation*, 10(2), 239-254. http://doi.org/10.1007/s12273-016-0321-4

Bingjian, M. (1999). *The Architecture of the Quadrangle in Beijing*. TIANJIN UNIVERSITY PRESS.

Blocken, B. (2014). 50 years of Computational Wind Engineering: Past, present and future. *JOURNAL OF WIND ENGINEERING AND INDUSTRIAL AERODYNAMICS*, 129, 69-102. http://doi.org/10.1016/j.jweia.2014.03.008

Chen, H., & Zhang, X. (2022). Research and Simulation of Traditional Settlement Wind and Heat Environment Based on Computer Intelligent Computing Technology. *Computational Intelligence and Neuroscience*, 2022, 1-9. http://doi.org/10.1155/2022/3715730

Du, X., Bokel, R., & van den Dobbelsteen, A. (2014). Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case. *BUILDING AND ENVIRONMENT*, 82, 215-227. http://doi.org/10.1016/j.buildenv.2014.08.022

Guo, P., Ding, C., Guo, Z., Liu, T., & Lyu, T. (2022). Coupling CFD Simulation and Field Experiments in Summer to Prove Feng Shui Optimizes Courtyard Wind Environments: A Case Study of Prince Kungs Mansion in Beijing. *Buildings*, 12(5), 629. http://doi.org/10.3390/buildings12050629

Hadavi, M., & Pasdarshahri, H. (2020). Quantifying impacts of wind speed and urban neighborhood layout on the infiltration rate of residential buildings. *Sustainable Cities and Society*, 53, 101887. http://doi.org/10.1016/j.scs.2019.101887

Han, Y., Chun, Q., Xu, X., Teng, Q., Dong, Y., & Lin, Y. (2022). Wind effects on Chinese traditional timber buildings in complex terrain: The case of Baoguo Temple. *Journal of Building Engineering*, 59, 105088. http://doi.org/10.1016/j.jobe.2022.105088

He, B., Ding, L., & Prasad, D. (2019). Enhancing urban ventilation performance through the development of precinct ventilation zones: A case study based on the Greater Sydney, Australia. *Sustainable Cities and Society*, 47, 101472. http://doi.org/10.1016/j.scs.2019.101472

Hsu, H., & Huang, J. (2022). Passive Environmental Control at Neighborhood and Block Scales for Conservation of Historic Settlements: The Case Study of Huatzai Village in Wang-An, Taiwan. *Sustainability*, 14(19), 11840. http://doi.org/10.3390/su141911840

Liu, S., & Huang, C. (2016). Optimization of Natural Ventilation of "Yinzi" Dwellings in Western Hunan Based on Orthogonal Experiment and CFD. *Buildings*, 6(3), 25. http://doi.org/10.3390/buildings6030025

Lu, X. (2013). *北京四合院人居环境(Beijing Courtyard Living Environment)*. China Architecture & Building Press.

WS.(2018). In Weather spark. https://weatherspark.com

Suhendri, & Koerniawan, M. D. (2017). Investigation of Indonesian Traditional Houses through CFD Simulation. *IOP conference series. Materials Science and Engineering*, 180(1), 12109. http://doi.org/10.1088/1757-899X/180/1/012109

Tingli, J., & DI, G. (2020). Multi—Layered and Interconnected Design of Thermal Insulation System-A Case Study of the Historic Residential Area from the First to Tenth Hutongs in Dongsi， Beijing. *ARCHITECTURAL JOURNAL*(02), 102-107. https://doi.org/10.198194.cn

Zune, M., Pantua, C., Rodrigues, L., & Gillott, M. (2020). A review of traditional multistage roofs design and performance in vernacular buildings in Myanmar. *Sustainable Cities and Society*, 60. https://doi.org/10.1016/j.scs.2020.102240