The Climatic Design in Chinese Vernacular Courtyard House Settlement – A Wind Environmental Simulation

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ABSTRACT

The application of Chinese vernacular courtyard environment adaptability design strategies in Chinese contemporary architectural design are becoming more popular among Chinese architects. Starting from the climate consideration in architectural design, using CFD simulation to understand the wind environment in the Chinese traditional vernacular courtyard and settlement based on North China climate conditions (taking Beijing as an example). Firstly, the wind environment in the original courtyard building settlement is simulated. Secondly, parametric studies on the effect of width-to-length ratio (W/L) and north building height-to-south building height ratio (H₁/H₂) on the wind environment in courtyard house are conducted. Finally, several variants of courtyard house are also tested. This study is consummating the deficiencies of previous similar studies and digging the key points of how the same architectural form provide wind environment adaptability in different seasons with totally opposite weather conditions.

1. INTRODUCTION

With the development of building technologies, from 1950s, unified building forms of modernism (internationalism) swept the worldwide building industry and have been squeezing the survival space of the regional and vernacular buildings with traditional forms not only on cultural and aesthetic aspects but also on environmental aspects (Frampton, 1993). More dependence on unified modern building technologies leads to less local climatic considerations in architectural design. As building indoor environment is now universally conditioned by the HVAC system, energy consumption becomes higher and higher. In China, more than 1/3 of the total energy consumption directly derives from buildings. Considering both the severe global environmental situation brought by high energy consumption and the environmental quality needs from building occupants, the concept that to achieve better environmental quality, higher performance and more sustainable building by exploring climatic considerations and environmental strategies in the conventional vernacular building form has been put forward and got wider recognition (Givoni, 1998; Olgyay & Olgyay, 1963). As one of the most typical, conventional architectural forms-courtyard house was adopted in many contemporary architectural design by architects in China. The reason is that courtyard house has perfect climatic adaptability, especially with its natural ventilation and thermal environmental performance (Blaser, 1995).
Although ‘learning from tradition’ is generally recognized among architects, the climate adaptability of those new architecture design based on tradition can hardly be achieved without drawing the ancient wisdom into the new building design in the right way and suitable place. The courtyard house is one of the most widely distributed architectural forms in China. By adjusting the shape (such as changing the aspect ratio, building height etc.), this form can easily be adapted to totally different climate conditions. Therefore, it is essential to know how different types of vernacular courtyard can be adapted to different regional climate. Using a specific courtyard shape in a wrong place or only forming a ‘seemingly the same’ enclosure space will not work or will even make thing worse.

In this paper, computational fluid dynamic (CFD) simulations will be conducted for achieving better understanding about the wind environmental design characteristics of the Chinese vernacular courtyard and settlement based on North China climate conditions (taking Beijing and its specific courtyard form- ‘Siheyuan’ as the example). Related parametric studies will be conducted for consummating the deficiencies of previous studies on similar topic.

1.1. Climatic Condition in Beijing

Beijing is located in northern hemisphere warm and semi-humid continental monsoon, which can be regarded as the typical representative city of the North China. Climate characteristics of Beijing can be summarized as follows: In winter, it is dry and cold, the mean temperature is approximate -2°C; in summer it is hot, sometimes humid, the mean temperature can achieve 26°C or higher; in spring, it is warm and dry; in the fall which is the best season of Beijing, the temperature falls and the sunlight is bright (CMA, 2006). It can be observed that under Beijing’s climate condition, high air temperature with relatively high humidity will reduce both the indoor and outdoor thermal comfort level in summer if there is no enough ventilation; and in winter, the cold temperature climate condition will trial the building wind-protection and insulation performance.

![Wind Rose Chart of Beijing](image)

**Figure 1** Summer time (left) and winter time (right) wind rose chart of Beijing.

As to the wind, what can be seen from Figure 1 is that during the summer, highest frequency wind direction is from southeast (135°, N = 0°), the average wind speed is approximate 5.5m/s. In winter, frequencies of winds from different directions are relatively uniform. However the worst condition - highest frequency of excessive wind speed appears at direction of northwest (315°), in which the wind speed can reach 8.0m/s or even more. High wind speed which exceeds the wind comfort threshold of peoples will decrease both the indoor and outdoor thermal comfort, meanwhile put negative influence on peoples’ activities (Penwarden & Wise, 1975).

1.2. The Vernacular Courtyard in Beijing - Siheyuan

The courtyard is a central opening enclosed by buildings which is the most basic elements for Chinese traditional built environments, including cities, houses, and gardens (Xu, 1998). The vernacular courtyard house (also called ‘Siheyuan’ or ‘Chinese quadrangles’) is a conventional type of residence, which was widely adopted throughout the North China (Figure 2).
2. LITERATURE REVIEW ON PREVIOUS STUDY

In worldwide, many studies on CFD simulation for vernacular buildings in different climate regions have been conducted. However, regarding to the traditional courtyard in North China, although there are a lot of research and practice on the architectural design issues (such as spatial design, cultural context inheritance and heritage conservation, etc.), there are only two studies on the wind environment based on CFD simulation. In the first study (LIN, WANG, ZHAO, & ZHU, 2002), the effects of different courtyard shapes on their wind environment were tested based on only four different simplified “box” models without indoor space, the conclusion are descriptive not quantitative. Another study which focus on the wind environment in a single courtyard house was conducted by the author (SHI, 2013), which is the initial part of the study shown in this paper. The previous study draws the conclusion that the optimized courtyard shape should has the width-to-length ratio (W/L) of 1.0 and the north building height-to-south building height ratio ($H_1/H_2$ in Figure 3) of 1.2-1.4; when the overall amplification of courtyard building scale is three times of the original scale or more, appropriate precautions on wind-proof design must be taken to keep the pedestrian level wind environment comfort around the building. However, these results are acquired based on the simulation for a single courtyard house model without surroundings (Figure 3). Instead of the single courtyard house model, this study will validate the previous conclusion based on a courtyard array model and also take more design parameters into consideration. Therefore, this study can be regarded as the extension and also the improvement of the previous one.

3. WIND ENVIRONMENT IN TRADITIONAL VERNACULAR COURTYARD HOUSE

Reynolds-averaged Navier-Stokes (RANS) equations with standard K-$\varepsilon$ turbulent flow model is used to simulate the wind environment of the traditional vernacular courtyard house. The most basic courtyard house form in Beijing, which has one single inner central courtyard, is taken as subject investigated. The wind velocity field inside and around the courtyard house is studied with CFD simulation to understand the climate adaptive design strategies.
One important thing should be clarified about this simulation study is that the buoyancy effect is not taken into account at this stage. It is true that buildings are receiving certain solar radiation, which will lead to spatial temperature difference thus affect the whole pattern of air movement. However, for the courtyard house in cold regions of North China, the thermal mass of buildings is considerable. Therefore, the air movement due to the temperature difference is relatively insignificant compare with the air movement due to building geometry.

3.1. Physical Model and Simulation Setting

As mentioned, the simulation and parametric study are based on a courtyard array model (Figure 4). Simulation was conducted under summer and winter condition separately. The distance between courtyard houses (street width) is set based on the traditional urban texture of Beijing old cities (WANG, 2007). Following the climate analysis in Section 1.1, for summer time simulation setting, the initial temperature is 26℃, the wind condition is 5.5m/s with southeast direction based on the prevailing wind condition; and for winter time setting, the initial temperature is -2℃, the wind condition is 8.0m/s with northwest direction based on the most negative condition for thermal comfort and building wind-protection. Initial wind environment is generated based on the logarithmic wind profile with a reference height of 10m. At first, the wind environment in the original courtyard building settlement is simulated. Then, parametric studies on the effect of width-to-length ratio (W/L) and north building height-to-south building height ratio (H1/H2) on the wind environment in courtyard house are conducted. Finally, several variants of courtyard house with different entrance direction are also tested.

For all simulations, both under summer and winter conditions, the wind speeds mean value and maximum value of all inner courtyard and indoor spaces in the courtyard house array is calculated and taken as the evaluation index. Therefore, for one type of courtyard geometry, there are total four indicators of wind speed.

3.2. Wind Environment in the Original Courtyard Building Design

Figure 5 (left) is the wind environment in a courtyard house array in the summer time. In summer, the average wind speed in all inner courtyard space of the house array at the 2m-height position is about 2.0m/s under the background wind with a speed of 5.5m/s at 10m-height, which can provide satisfying natural ventilation. In winter time, Figure 5 (right) shows that the average wind speed of all regions of the nine courtyard houses at the 2m height position still keep the level of 2.5m/s, even the maximum wind
speed is lower than 4.0m/s under the background wind with a speed of 8.0m/s at 10m-height.

![Wind environment simulation results: wind velocity field at the 2m height level (m/s) in courtyard house array in summer (left) and winter (right).](image)

**Figure 5**  *Wind environment simulation results: wind velocity field at the 2m height level (m/s) in courtyard house array in summer (left) and winter (right).*

4. **FURTHER PARAMETRIC STUDY BASED ON PREVIOUS RESEARCH**

4.1. **The Width-to-Length Ratio (W/L)**

Wind environment in five courtyard house array models with different W/L ratio (range from 0.5-2.0) under summer and winter condition were simulated separately. Figure 6 shows the parametric simulation results comparison. Compare with the simulation of a single courtyard model, the overall wind speed for whole parametric test decreases, but the trend keeps unchanged. Taking the W/L ratio of 1.0 (original ratio of basic conventional courtyard house) as the baseline, what can be observed is that increasing the W/L ratio will slightly increase wind speed in the courtyard both in summer and in winter, but the effect of wind speed change on people is non-significant; when decreasing the W/L ratio, the wind speed is increased distinctly. In a courtyard where the W/L is equal to 0.5, even the maximum wind speed reaches the comfort threshold. Therefore, when architects attempt to design an enclosure courtyard space, quadrate shape whose W/L ratio approximates 1.0 is preferred. Long and narrow space along with the prevailing wind direction should be avoided.

![Comparison of wind speed in inner courtyard space with different W/L ratio (m/s).](image)

**Figure 6**  *Comparison of wind speed in inner courtyard space with different W/L ratio (m/s).*

4.2. **The Building Height Layout (H1/H2)**
The second parametric study is regarding to the building height layout. Considering the prevailing wind direction both in summer and in winter, the north building height-to-south building height ratio ($H_1/H_2$) was selected as the variable in this parametric study.

Six different $H_1/H_2$ ratios are simulated for comparison range from 1.0 to 2.0 under both of summer and winter condition (Figure 7), taking the original $H_1/H_2$ ratio of conventional courtyard house (1.2) as the baseline. Under summer condition, courtyard arrays with the $H_1/H_2$ ratio of 1.2, 1.4 and 1.8 have basically same performance better than others ($H_1/H_2 = 1.0, 1.6$ and 2.0). They have appropriate average wind speed for ventilation, and meanwhile the peak value doesn’t affect peoples’ activities negatively. However in winter, the $H_1/H_2$ ratio of 1.8 have maximum value of wind speed which will decrease the thermal comfort level and increase the heating energy consumption. Thus, the $H_1/H_2$ ratio from 1.2 to 1.4 is the preferred choices for designing courtyard space.

**Figure 7**  Comparison of wind speed in inner courtyard space with different $H_1/H_2$ ratio (m/s).

Above simulation study results based on basically validate the correctness of previous simulation based on the model of a single courtyard house that the optimized courtyard shape should have the width-to-length ratio ($W/L$) of 1.0 and the north building height-to-south building height ratio ($H_1/H_2$) of 1.2-1.4. There are some feedbacks on the previous study query that why the roof shape is not taken into consideration. The answer is that the roof shape of courtyard house was designed based on the daylighting (especially the accessibility of sunlight in winter) and summer shading, which is not the main factor of wind environment design.

4.3. Different Variants of Courtyard House

Although most Beijing courtyard houses are built to follow the basic layout that the overall orientation along north-south (positioned in the north and facing south) and four buildings of a courtyard house are arranged along the north-south or east-west direction and the main entrance are located at the southeast, there are still different variants of courtyard house (MA, 1999). The most commonly seen variation is the adjustment of the main entrance location (shown in Figure 8).
Several most commonly seen variants form of Beijing courtyard house. The basic layout doesn’t change, but the location of main entrance are different (Source: Based on (MA, 1999)).

Using the same setting with above simulation, a courtyard house array model consists of four different variants of the courtyard house with different entrance location are simulated. Figure 9 shows the simulation results. The results show that the difference among four kinds of variants of courtyard house is also non-significant, which means that the entrance location is not the main impact factor of wind environment in courtyard house buildings. To further explain, in winter time, even the entrance has the same direction with winter time prevailing wind, by adding an additional corridor, the wind speed in the inner courtyard space still can be kept in the comfortable range of building occupants.

Simulation results of the most commonly seen variants form of Beijing courtyard house: wind velocity field at the 2m height level (m/s). Left: summer time, right: winter time.

5. CONCLUSION AND DISCUSSION

This study improves the previous study on the bioclimatic architectural design of the Chinese vernacular courtyard building. The optimized courtyard shape which has the width-to-length ratio of 1.0
and the north building height-to-south building height ratio of 1.2-1.4 is validated by the parametric study based on a new created Beijing courtyard houses array model. The simulation for several variants of courtyard house also shows that the location of courtyards’ main entrance will not affect the wind environment in the central courtyard space, if appropriate design measures are conducted.

In the section 3.1, the author implies that higher wind speed is preferable in summer. Nevertheless, higher wind speeds are not chosen from results shown in Fig. 6 and 7. The reason is that for a residential building designed under climatic conditions with significant seasonal variation, it is important to make a balance between different needs in different season. It this case, both higher wind speed in summer or lower wind speed in winter is essential for a comfortable wind environment. Therefore, the trade-off has been made when determining the optimal choice.

By understanding the key impact factors of wind environment in the courtyard house building form, architects can apply this vernacular architectural form and its climatic adaptability strategies into the environmental building design properly and wisely. This study focus on the influence of the building geometry, therefore, more future works will be conducted on the thermal aspects for comprehensive understanding of vernacular building climatic design strategies.

REFERENCES


