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Coupling CFD Simulation and Field Experiments in Summer to Prove Feng Shui Optimizes Courtyard Wind Environments: A Case Study of Prince Kung's Mansion in Beijing

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Abstract: Feng shui in ancient China was harmonized with the natural environment. The layout of houses following feng shui is conducive to a comfortable wind environment. To explore the positive influence of feng shui on ventilation, this study takes Prince Kung's Mansion, which has the characteristics of a feng shui layout, as the research object. In parallel, the study assumes a dissimilation layout that has lost the feng shui layout characteristics. Comparing the ventilation of courtyards in the summer for both the feng shui layout and the dissimilation layout through CFD simulation, the results were as follows: (1) the wind speed values in the summer, taken from 60 points in Prince Kung's Mansion by way of CFD simulation and field experiments, were well coupled, which proves that PHOENICS is suitable for the courtyard wind environments simulation in this study. (2) The CFD simulation results show that the average wind speed and the comfortable wind speed zone ratio in the courtyards of the feng shui layout were higher than those of the dissimilation layout during the summer, and the courtyard wind speeds of the two layouts were linearly related. Therefore, the feng shui layout is more conducive to the comfort of courtyards' wind environment than the dissimilation layout. (3) The front and rear wind pressure differences of the main houses in the feng shui layout can optimize the indoor ventilation better than those of dissimilation layout in the summer. (4) According to the evaluation criteria for the wind environment, the wind speed and wind pressure of the feng shui layout are superior to those of dissimilation layout in the summer. In summary, this study verifies that the layout of feng shui optimizes the courtyard wind environment in the summer, which embodies the ecological concept of the Chinese ancients in the layout of houses.

Keywords: wind environment; CFD simulation; field experiment; courtyards layout; feng shui

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1. Introduction

In traditional Chinese culture, feng shui can be traced back to the beginning of the primitive society period. During the Shang and Zhou dynasties (BC1600~BC221), the phenomena of XiangZhai and XiangMu (finding good places for houses or tombs) appeared. During the Qin and Han dynasties (BC221~AD220), with the emergence of feng shui theory, feng shui culture was developed. During the Wei, Jin, Sui, and Tang dynasties (AD220~AD907), feng shui entered its mature stage. During the Song, Ming, and Qing dynasties (AD960~AD1911), feng shui dispatched many branches and entered its heyday. Many feng shui works were written during this period.

Since the Song dynasty, according to the different application principles, feng shui produced two schools: the Form School and the Compass School. The Compass School emphasizes the balance between yin and yang, the unity of heaven, Earth and man, and five elements. The

Compass School flourished in Fujian Province, hence it was also called the Fujian school. The Form School, which became the mainstream school of feng shui, advocates the use of the natural landscape, reasonable site selection, and suitable house and tomb layouts. It flourished in Jiangxi Province, hence it was also called the Jiangxi school.

Ancient Chinese followed the Form School of feng shui in site selection and the layout of houses and tombs. The site selection principles of Fuyin-Baoyang (which means "back to the shadow and face to the sunshine") and Cangfeng-JuChi (which means "hiding wind and gathering chi") create a comfortable living environment. The feng shui layout studied in this paper refers to the Form School layout of feng shui.

The literature review was carried out for two aspects: feng shui research and the CFD simulation application. At present, few researchers have studied the characteristics of ancient the feng shui layout using scientific methods. These studies focus on ancient cities, villages, classical gardens, buildings, mausoleums, etc. Researchers have used field experiments and simulation calculation methods to evaluate temperatures, humidity, solar radiation, and ventilation in the physical environment within buildings. Taking Shuiyu Village as an example, L. Qi et al. proved that the mountain–water pattern optimizes its microclimate environment through field experiments and numerical simulation [1]. Taking Yuyin Garden as another example, S. H. Xu et al. verified that the Chinese traditional Lingnan garden adapts to the local hot and humid climate by using a numerical simulation of the ENVI-met model [2]. Michael Y. Mak and S. Thomas Ng discussed the consistency between feng shui models and contemporary architects' ideas on site selection and interior layout through a case study conducted in Sydney and Hong Kong [3]. Giulio Magli used satellite imagery to study the application of feng shui and ancient astronomy in royal mausoleums of the Tang, Ming, and Qing dynasties [4]. Li Tang et al. analyzed the feng shui model of Shang-gan-tang village using CFD simulations. Their study verified that the village layout is suitable for the local specific environmental conditions [5]. Albert and Jane investigated a typical residential building in Hong Kong using CFD simulations to verify feng shui masters' suggestion: the doors of the bathrooms and lids of the toilets must be closed whenever possible [6]. Kyoung illustrated in a case analysis that Korean classical architecture reflects certain feng shui thought in site selection and in the layout of houses [7]. These previous studies have analyzed the application of feng shui in the site selection and layout of ancient houses and tombs, as well as the influence of feng shui on the physical village environment. However, it can be seen that there are few studies exploring the impact of feng shui on the wind environment of courtyards, making it necessary to carry out the study.

CFD simulation is widely used in the study of the physical environments of buildings at different scales, such as blocks, villages, buildings, indoor areas of buildings, etc. Taking the East Village in the London Olympic Park as example, Azin Hosseinzadeh and Amir Keshmiri provided a quantitative tool to evaluate the wind microclimate and optimize the design and layout of trees around buildings to improve pedestrian comfort using CFD simulation [8]. Through CFD simulation, Z. T. Ai and C. M. Mak verified that the flow field inside an urban street canyon can be well-predicted using a T-shape computational domain, wherein the street canyon is connected to a free flow layer above the canyon [9]. Sari and Cho discussed the difference efficiency of BIWTs (building-integrated wind turbine) in buildings of different shapes through wind tunnel experiments and CFD simulation [10]. Conceicão et al. discussed the difference in ADI (air distribution index) between six people and twelve people in a classroom using CFD simulation, so as to provide a reference for the arrangement of air terminal devices [11]. Villagrán et al. analyzed the effect of air flow and thermal distribution generated by the increase in the height of the over gutter of a Colombian multi-tunnel greenhouse using CFD simulation [12]. Bo Hong et al. investigated the effects of outdoor trees on indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} dispersion in a naturally ventilated auditorium using CFD simulation [13]. Yifei Zhao et al. investigated the effect of trees on improving the microclimate and mitigating the urban heat island (UHI) effect using an ENVI-met model of an enclosed courtyard in North China [14]. Taking the geometry (convent typology) of large courtyards in the historical center of Camagüey as an example, José et al. discussed the effects of courtyard geometry on their outdoor thermal conditions in a warm–humid climate using the RayMan model [15]. Almhafdy et al. verified the significant effects of aspect ratio and cantilever roofs on courtyard wind speeds and thermal comfort through CFD simulation [16]. Previous studies also used CFD simulation to discuss aspects of the physical environment, such as wind, temperature, and air quality from both inside and outside of the buildings, which verified the reliability of using CFD simulation in research on physical building environments. Based on the above research experience, both CFD simulations and field experiments were used in this study to explore the courtyard wind environments of the feng shui layout.

This study focuses on the influence of the feng shui layout on courtyard wind environments by comparing the feng shui layout with a dissimilation layout. Courtyard ventilation during the summer is very important for ancient houses, therefore, the CFD simulation and field experiment of Prince Kung's Mansion were carried out only in summer. The study of courtyard wind environments in the winter is also important for the analysis of feng shui layouts, and is discussed at the end of this paper. Further studies will be carried out in the future.

Coupling CFD simulation and a field experiment of Prince Kung's Mansion in the summer, this paper discusses the influence of the feng shui layout on the courtyard wind environment and aims to verify the ecological design of the Chinese ancients in the layout of houses.

2. Research Objects and Methods

2.1. Research Objects: Feng Shui Layout in Prince Kung's Mansion

Prince Kung's Mansion is located in the northwest of the inner city of Beijing, China. Beijing is located at 115.7°–117.4° E and 39.4°–41.6° N, with an average altitude of 43.5 M. It has a warm, temperate, semi-humid, and semi-arid monsoon climate. Its annual average temperature is 11~13 °C in the plain area. July is the hottest month, and the monthly average temperature in the plain area is about 26 °C. January is the coldest month, and the average monthly temperature in plain area is −4~−5 °C. The wind direction has obvious seasonal variation. The southeast winds prevail in summer and northwest winds prevail in winter. The annual average wind speed is 2.1–2.2 m/s.

The houses were first built in 45th year of Qianlong period of the Qing dynasty (1780 AD) as HeShen's mansion. In 1852, Prince Kung YiXin lived there, and it became known as Prince Kung's Mansion. The mansion faces 8° south by east, with a Fuyin-Baoyang layout. The main entrance is located in the southeast, conforming to the feng shui theory of Kanzhai-Xunmen [17]. Some houses have been destroyed over the past hundreds of years. After a renovation from 2004 to 2008, all the houses in the mansion were restored to their original layout [18].

Prince Kung's Mansion consists of 15 courtyards, and the terrain of this area gradually increases from the south to the north. The height of the eaves on these houses also increases gradually from south to north. This group of houses uses the Four Emblems feng shui layout.

The Form School of feng shui is composed of the Black Turtles in the north, Vermillion Phoenixes in the south, Azure Dragons in the east, and White Tigers in the west, which are together called the Four Emblems. The Four Emblems originated from ancient Chinese astronomy that divided 28 stars into four groups according to their directions in the sky. Each group of stars was connected and abstracted into an emblem for that direction (Figure 1a). The Four Emblems are a primitive cosmic cognition of ancient China. The running water on the left side of the house is called the Azure Dragon, the road on the right side of the house is called the White Tiger, the pond in front of the house is called the Vermillion Phoenix, and the hill at the back of the house is called the Black Turtle [19]. The content of the Four Emblems varies according to the house's environment; they may be hills, ponds, long roads, or rivers (Figure 1b) [20]. This layout reflected the application of ancient cosmology to the layout of houses and tombs, and was used in ancient cities, villages, and mausoleums in China.

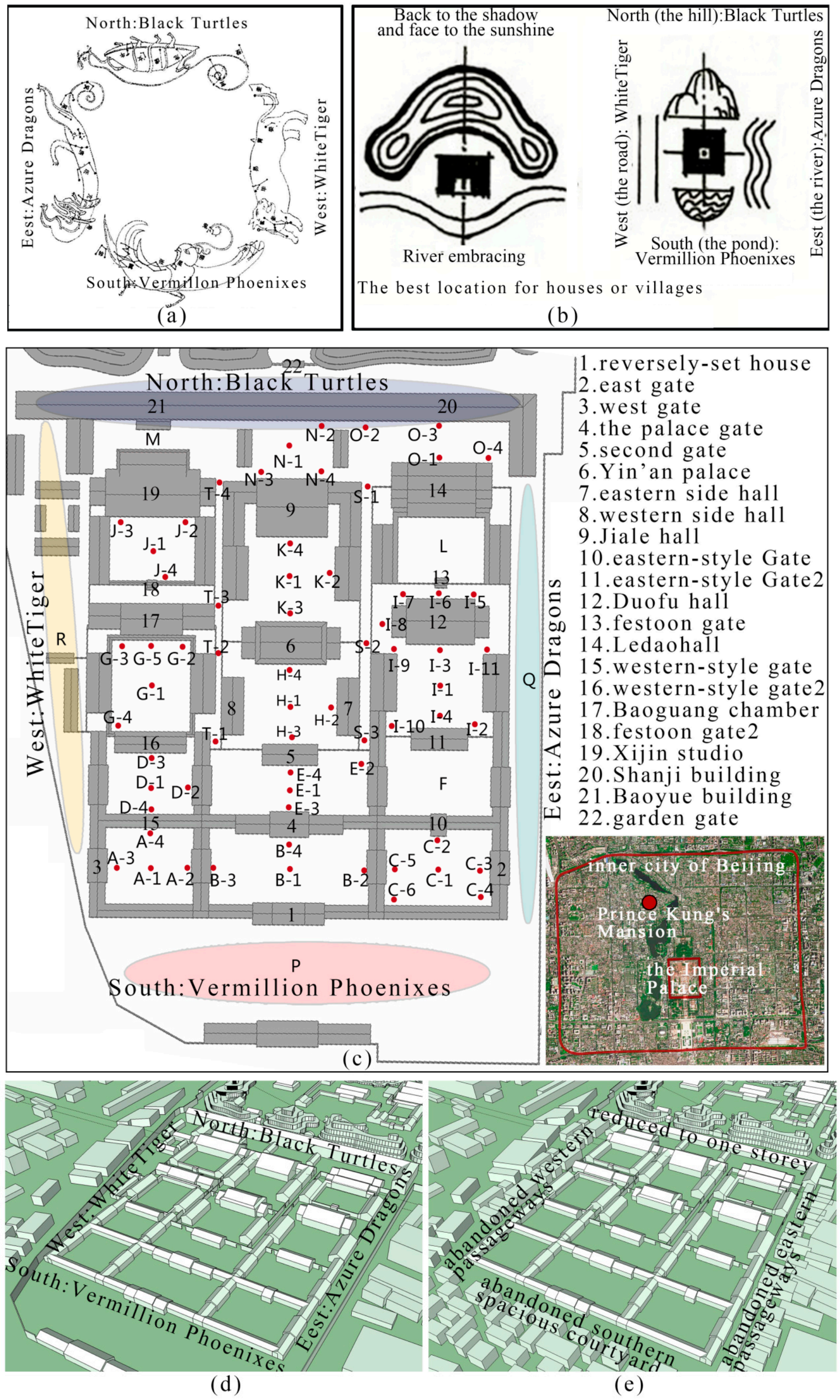

Figure 1. (**a**) The 28-star chart depicting the Four Emblems; (**b**) the Form School feng shui layout in ancient China; (**c**) the Form School feng shui layout of Prince Kung's Mansion; (**d**) the feng shui layout; (**e**) the dissimilation layout.

The northernmost side of Prince Kung's Mansion is a two-story house, which has eaves that are 7 m high. This house is the tallest in the whole mansion, runs east–west across this area, and forms the backer of the mansion. Thus, the two-story house becomes the Black Turtle of the feng shui layout. The entrance courtyard, between the inverted house and the south wall, is more than 30 m wide and runs east–west. Therefore, this spacious courtyard becomes the Vermillion Phoenix of the feng shui layout. Between the east houses and the east wall, there is a passageway that is more than 6 m wide and 110 m long. This eastern passageway becomes the Azure Dragon of the feng shui layout. Between the west houses and the west wall, there is an oblique, specially shaped passageway. This western passageway becomes the White Tiger of the feng shui layout [21,22] (Figure 1c). The eastern passageway is wider than the western passageway, which conforms to feng shui theory: the Azure Dragon is winding, and the White Tiger is condescending [23]. It can be seen that Prince Kung's Mansion with the Four Emblems conforms to feng shui layout.

2.2. Comparative Study Method

Prince Kung's Mansion, with characteristics of the feng shui layout, was selected as the research object. At the same time, a layout—referred to as the dissimilation layout in this paper—which does not conform to the Four Emblems feng shui layout, was developed. A comparative study of the summer wind environments of the courtyards for the feng shui layout and the dissimilation layout was conducted.

For the dissimilation layout, the southern spacious courtyard (the Vermillion Phoenix), as well as the eastern and western passageways (the Azure Dragon and the White Tiger), were abandoned. These sites were supplemented by new houses and the structure of the surrounding houses was extended. The northern two-story house (the Black Turtle) was changed into a one-story house. Thus, compared with the feng shui layout, the dissimilation layout lacks the Four Emblems.

The feng shui layout and the dissimilation layout were both modeled with Sketchup, as were the houses within a radius of 150 m (Figure 1d,e). The details of the houses, such as dougong (a system of brackets inserted between the top of a column and a crossbeam), were omitted to meet the requirements of PHOENICS. The models were input into PHOENICS as the prototypes of the feng shui and dissimilation layouts for simulation calculations.

2.3. Research Framework

The simulation calculation results of the feng shui layout and dissimilation layout were analyzed using mathematical analysis and comparative research methods. The results of the CFD simulation were the instantaneous wind speeds at the site [24]. Therefore, a coupling analysis between the measured wind speed values and the simulated wind speed values was conducted to verify the reliability of the CFD simulation. The research framework of this study is depicted in Figure 2.

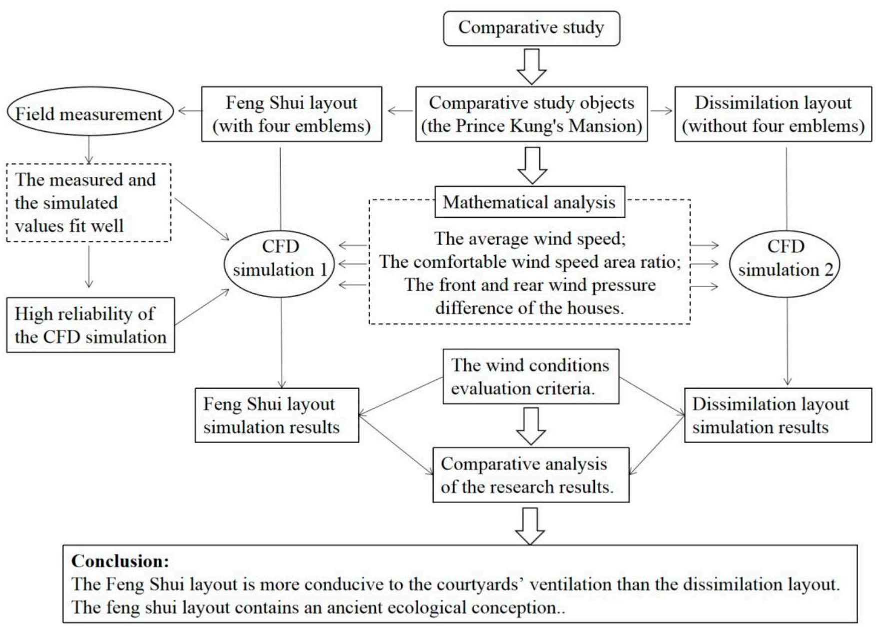

Figure 2. Research framework.

3. Evaluation Criteria and Experiment and Simulation Details

3.1. Wind Environment Evaluation Criteria in Summer

The wind environment evaluation criteria of this study refer to China's green building evaluation system as well as the criteria established in previous studies.

Only the summer wind environment of the courtyards is discussed in this paper, therefore, only the summer evaluation criteria were established. The criteria of the front and rear wind pressure differences of the houses (formulated for better indoor ventilation of houses) were defined according to the Green Building Evaluation Criteria (GB/T 50378-2019, China). The ratios of the comfortable wind speed, low wind speed, and strong wind speed zones were defined according to criteria from Murakami and Morikawa [25] and Hua Zhang [26]. The evaluation criteria for the outdoor wind environment are summarized in Figure 3.

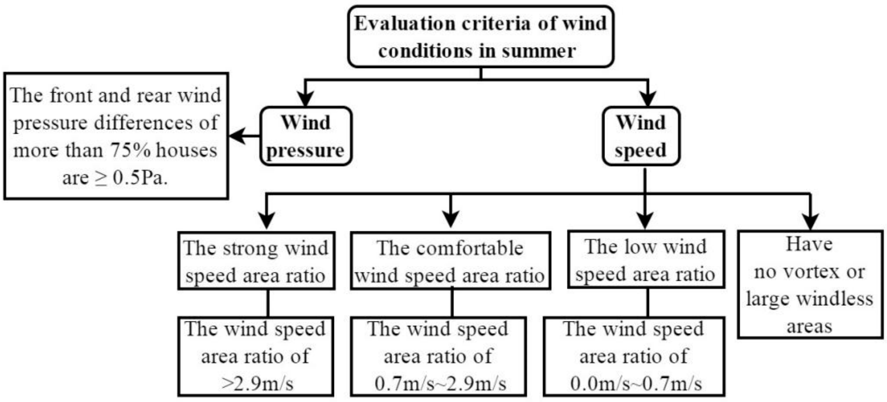

Figure 3. Diagram of the evaluation criteria for the outdoor wind environment.

The height of most human activities is within 2 m from the ground. Based on previous research experience, a horizontal plane 1.5 m [27] above the ground was selected as the object of the wind environment evaluation.

3.2. Wind Environment Experiment and Simulations Details

3.2.1. CFD Simulation Settings

There are many kinds of software tools for CFD simulation, such as PHOENICS, FLUENT, ENVI-met, and LadyBug. PHOENICS can be used to simulate wind environments, solar radiation, etc. FLUENT requires the cooperation of special grid-generation software. FLUENT can be used to simulate things such as fluids, heat transference, and chemical reflections. ENVI-met relies on the principles of hydrodynamics and thermodynamics, which can be used to simulate wind and thermal environments. LadyBug is a building meteorological data analysis software, which is built into rhino and grasshopper. Its analysis system can be used to simulate sunshine, wind environments, and urban heat islands, among other things.

Many researchers use PHOENICS to simulate the wind environment of places such as residential districts, ancient villages, classical gardens, courtyards, and buildings. S. P. Zeng et al. summed up the "wind resistance index formula" of the building volume density index and urban ventilation environment with CFD simulation using PHOENICS [28]. J. N. Liu summarized the strategies for optimizing the wind environment of multi-story residences around high-rise residential areas from the aspects of building monomer, group layout, site design, and plant distribution with CFD simulation using PHOENICS [29]. S. Liu put forward the principles and strategies of spatial form optimization of urban residential blocks based on CFD simulation using PHOENICS [30]. H. W. Yang proposed the optimization design method and transformation sensitivity prediction model for the green transformation of buildings, in which the wind environment simulation calculation was conducted using PHOENICS [31].

PHOENICS is suitable for the research of outdoor wind environment simulations, and the calculation results are accurate and reliable. Therefore, this study used PHOENICS for the CFD simulation. The CFD simulation settings and the models are as follows.

Turbulence model and equations [32]: The Flair module of PHOENICS, which uses the turbulence model RNG k-ε, was selected for simulation in the study. The coupling algorithm of velocity and pressure adopts the discrete equation PRESTOL. The built-in PARSOL function can automatically set the small-scale mesh, so as to improve the calculation accuracy. The automatic convergence detection function of PHOENICS can make the calculation results have a reasonable convergence effect. The convergence accuracy of the PHOENICS simulation calculation is 10^{-4}.

Mesh settings [33]: The settings of the mesh are based on the software description and researcher's experience [34]. In order to improve the simulation accuracy and reduce the number of mesh segments, the calculation area was divided into the central area (with fine mesh segments) and the edge area (with coarse mesh segments). The length and width of the boundary were three times those of the model [35]. The boundary height was three times the maximum house height of the model. The simulated object was located in the center of the area. The simulation was conducted by gradually increasing the number of mesh segments until the calculation error became convergent.

The mesh size of different areas varied, as the different areas demand different calculation accuracy. Therefore, the mesh size settings are as follow: On the XY plane, the study object area located at the center had 1 m × 1 m segments (the dark blue house area in Figure 4); the surrounding area with auxiliary houses had 2 m × 2 m segments (the light blue house area in Figure 4); the fringe area without houses had the coarse segment, 5 m × 5 m. Along the vertical Z-axis, the mesh of the area, with or without houses, was set at 1 m and 2 m, respectively. The above differentiation mesh size setup can not only guarantee the calculation accuracy but can also increase the time efficiency during the simulation. Along the wind inlet and outlet (Y axis), the size of the mesh segments was set from coarse, (5 m) to fine (1 m), then back to coarse (5 m), according to the calculation accuracy requirement of different areas (Figure 4). The tensile ratio at the transition between fine mesh and coarse mesh areas was 1.3. The number of mesh segments was 5.448 million.

According to "the Design code for heating ventilation and air conditioning of civil buildings" (GB50736-2012, China) and the on-site wind conditions in Beijing, the average wind speed of 2.1 m/s (southeast) in summer was selected as the inflow boundary condition. The iteration number was 2000. The inner city of Beijing consists of low ancient courtyards, so "select terrain type: Parkland, bushes, numerous obstacles" [36]. By CFD simulation calculation using PHOENICS, the wind speed and pressure of the feng shui layout and the dissimilation layout were extracted for analysis and comparison.

3.2.2. Field Experiment Method

To verify the coupling between the measured and simulated wind speed values, the summer wind speed values of Prince Kung's Mansion were measured. The date of 22 August 2016, a typical summer day, was chosen for the field experiment. It was a cloudy day, the wind was southeast to east, the temperature was 31~33 °C, and the relative humidity was 46%~51%. The Kestrel 4500 hand-held weather station (United States) was selected as the measurement tool. The on-site wind speed measurement lasted from 9 a.m. to 4 p.m.

Due to the instantaneous and unsustainable characteristics of the field wind speed, B. Y. Liu and X. L. Peng [37], as well as Fei Guo et al. [38], used the method of simultaneous measurements by multiple people for multiple points, with each measurement lasting for a sufficient period to obtain the average values of wind speed. These studies show that the method is feasible. Therefore, the field experiment method in this study was determined as follows: four people measured four different points in the same courtyard at the same time, reading the wind speed values once per second for one minute, and taking the average value as the measured wind speed of that point. In this way, the measured wind speed values of 60 selected points (Figure 1c) in courtyards of Prince Kung's Mansion were obtained.

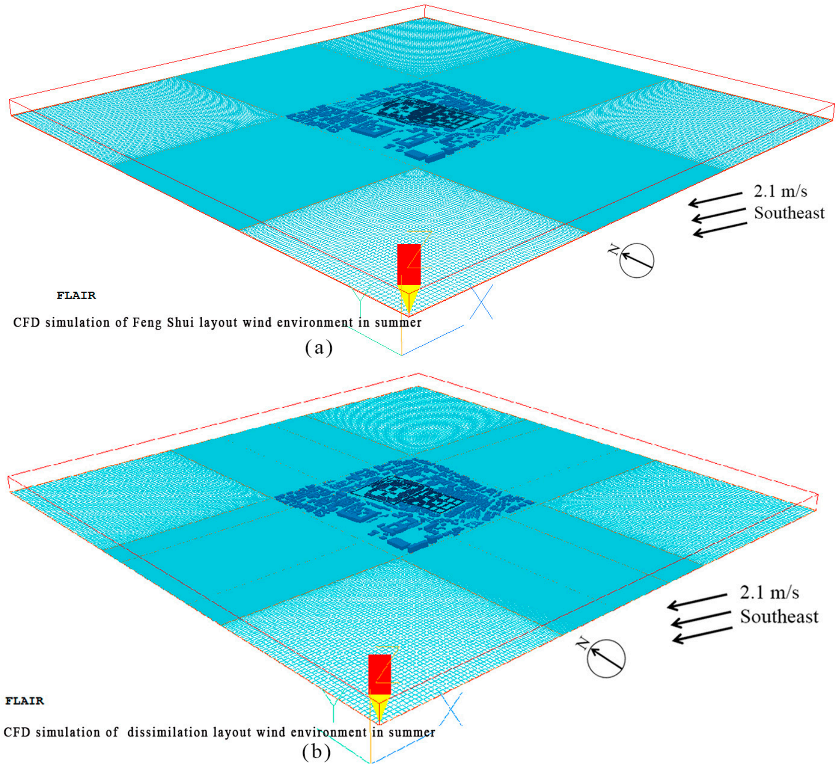

Figure 4. PHOENICS mesh settings: (**a**) the feng shui layout; (**b**) the dissimilation layout.

4. Results and Discussions

4.1. Comparative Study of Measured and Simulated Wind Speed Values

4.1.1. Measured Points Selection

For the coupling of the CFD simulation and field experiment, some specific points in the courtyards of Prince Kung's Mansion were selected. On the one hand, measured values of wind speed were obtained by field experiment on a typical day in summer. On the other hand, simulated values were obtained by CFD simulation. Thus, measured values and simulated values were compared.

Because a temporary exhibition hall was built in the courtyard of the East Gate (marked with "F" in Figure 1c), the courtyard of Ledao Hall (L in Figure 1c) was not open, meaning that the wind speed values of these two courtyards could not be measured. The remaining 12 courtyards and 2 passageways (S and T in Figure 1c) were selected for the experiment, and 60 points were arranged there (Figure 1c). The analysis of measured and simulated values was based on the selected 60 points. The positions of measured points and simulated points were the same, the points were marked as A-1~T-4 (Figure 1c) in the plane of Prince Kung's Mansion (that is the feng shui layout of this study).

4.1.2. Analysis of Measured and Simulated Values

The measured and simulated values of the wind speed at 60 points were plotted in a broken line chart for comparative study (Figure 5,). On the day of the measurement, the average wind speed in the area where Prince Kung's Mansion is located was 0.3~1.5 m/s, according to the weather forecast. In the CFD simulation, a wind speed of 2.1 m/s was used as the inflow boundary condition. Obviously, the wind speed of the CFD simulation inflow boundary condition was greater than the average wind speed of the measurement day. Therefore, most of the simulated values in the chart are greater than the measured values.

The difference between the simulated value and the measured value of the point G-2 was the largest, at 0.38 m/s. Only the measured values of the four points H-3, I-4, K-3, and O-1 were larger than the simulated values. The common characteristic of these four points is that they are close to the door of the main houses. In the CFD simulation, the door was closed. However, the door would be intermittently opened on-site, which would promote air circulation at these points and increase the measured wind speed values. For the other 56 points, the simulated value was greater than the measured value.

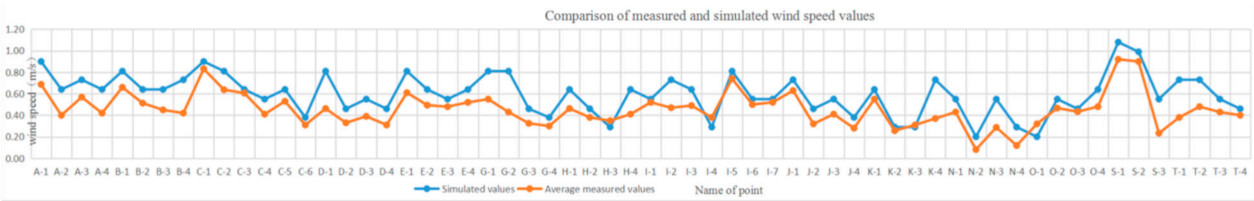

Figure 5. Comparison of the measured and simulated wind speed values of 60 points in Prince Kung's Mansion (Fengshui layout, the point names are from Figure 1c).

There was a linear regression between the measured values and the simulated values. The regression formula is y = 0.759x (Figure 6). The regression formula shows that the measured values are 0.759 times the simulated values. The distribution characteristics of the points in the chart (Figure 6) illustrate that the simulated values of the wind speed were read based on colors in the simulated results (Figure 7), and the simulated values increased by an equal difference. The simulated values read by the same color in the wind speed cloud chart were the same, and many of the 60 selected points had the same wind speed value. As shown in Figure 7b, the simulated wind speed value of the color between blue and green was 0.64 m/s, and 13 of the 60 selected points simulated wind speed values were 0.64 m/s, which was the maximum number of the same wind speed values in the 60 selected points. These points are A-2, A-4, B-2, B-3, C-3, C-5, E-2, E-4, H-1, H-4, I-3, J-4, and O-1.

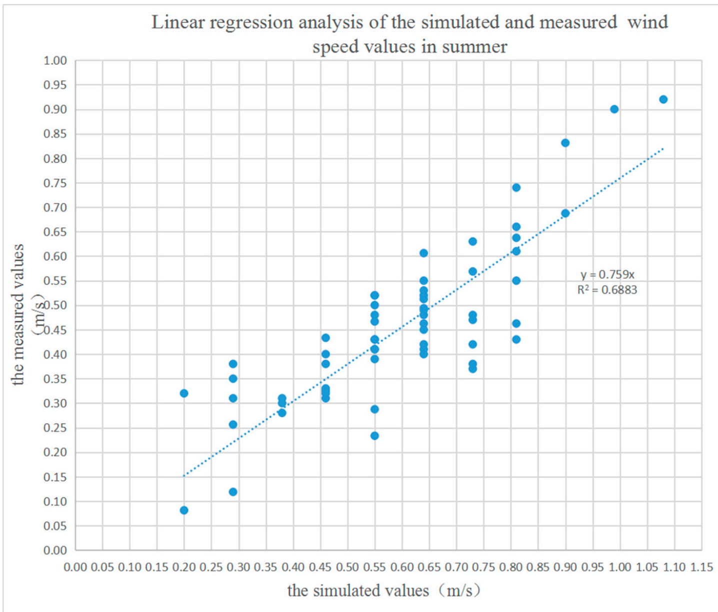

Figure 6. Linear regression of the wind speed simulated and measured values of Prince Kung's Mansion (Fengshui layout).

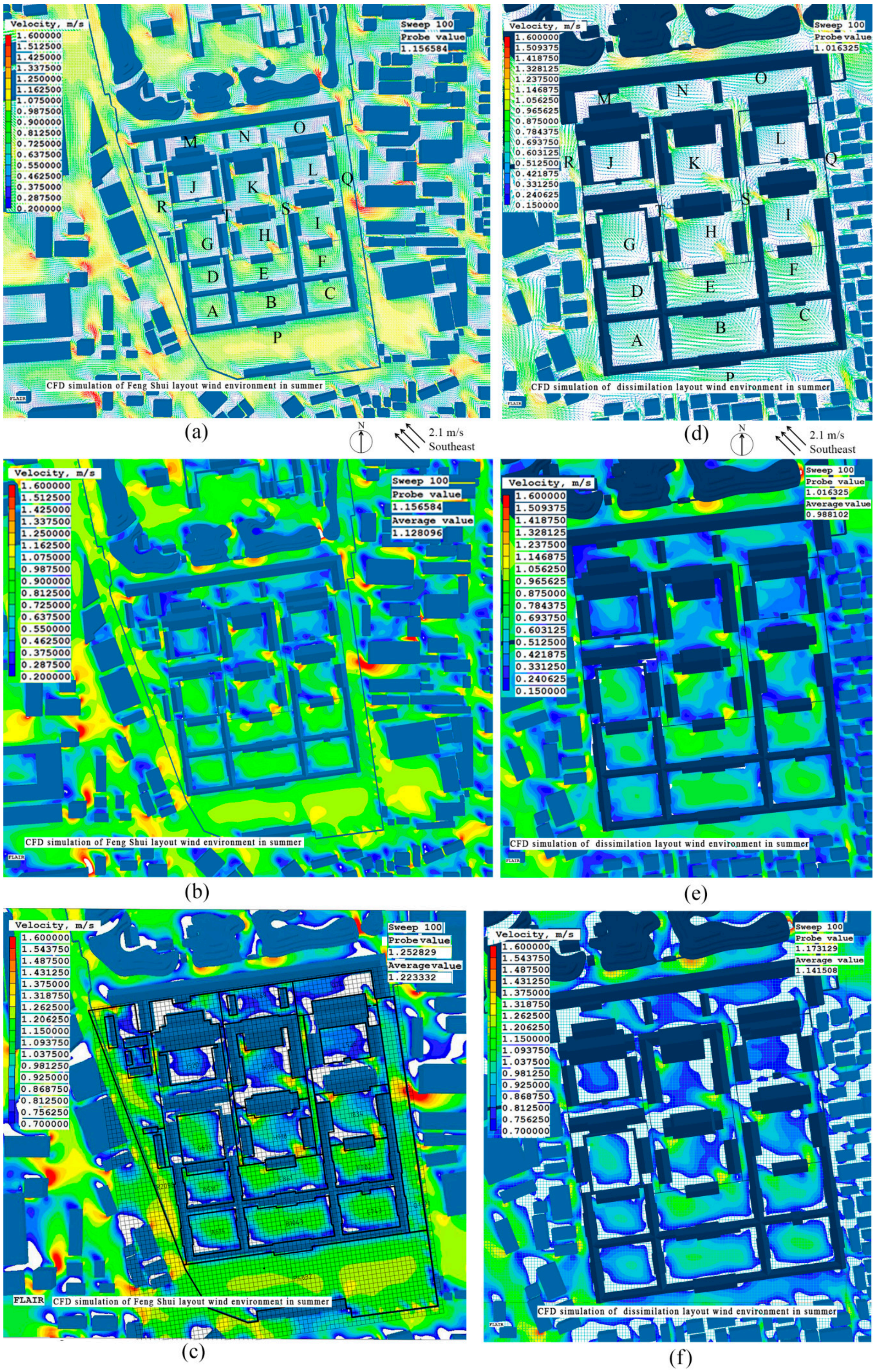

Figure 7. (**a**) Wind speed vector chart of feng shui layout. (**b**) Wind speed cloud chart of feng shui layout. (**c**) Comfortable wind speed zone cloud chart of feng shui layout. (**d**) Wind speed vector chart of dissimilation layout. (**e**) Wind speed cloud chart of dissimilation layout. (**f**) Comfortable wind speed zone cloud chart of dissimilation layout. The figures were obtained by CFD simulation.

The regression analysis chart shows R^2 = 0.6883, which proves that the regression fitting degree between measured and simulated values is good. It can be judged that the simulated wind speed values by PHOENICS are in good agreement with the wind speed values measured on-site. The coupling of CFD simulation and field experiment proves that PHOENICS is suitable for courtyard wind environment simulations.

4.2. Comparative Study of Courtyards Wind Environment between Feng Shui Layout and Dissimilation Layout

4.2.1. Comparative Study of Courtyards Wind Speed

The wind speed vector, wind speed cloud, and comfortable wind speed zone cloud of the feng shui layout and dissimilation layout were obtained using PHOENICS (Figure 7). Through data analysis, the following results are drawn.

(1) The wind speed cloud charts show that the wind speed of the feng shui layout was higher than that of dissimilation layout, which optimizes the ventilation of the courtyards in the summer. The maximum wind speeds in the courtyards of the two layouts were 1.43 m/s and 1.15 m/s. Every courtyard was weighted according to the percentage of the area occupied by different wind speeds to obtain the average wind speed of each courtyard, and a broken line chart was plotted (Figure 8, the courtyard names are from Figure 7a,d).

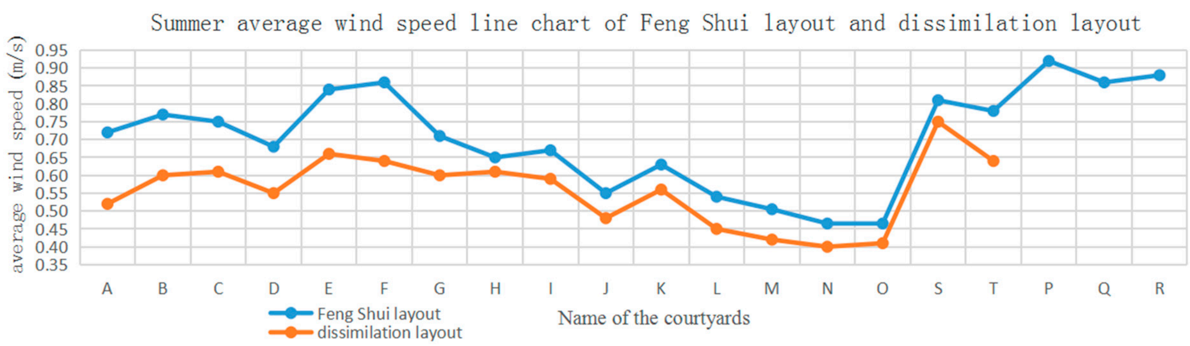

Figure 8. The average wind speed line chart for the courtyards of feng shui layout and dissimilation layout. The values of the figure was based on CFD simulation results.

Through a comparative study, it was found that the average wind speed of the courtyards of feng shui layout was higher than that of dissimilation layout. The regression formula shows that the average wind speed of each courtyard in dissimilation layout was 0.8286 times that of feng shui layout, and R^2 = 0.809 proves that the regression degree of fit is good.

The main reason for the above results is that the open space of the Azure Dragon, White Tiger, and Vermillion Phoenix in the Form School feng shui layout optimizes ventilation, while the dissimilation layout abandons the Four Emblems feng shui layout, which reduces the wind speed of the courtyards in summer (Figure 9).

(2) The comfortable wind speed zone cloud charts show that the maximum wind speeds of both layouts were less than 2.90 m/s, and the ratio of the strong wind speed zone was 0%. The white zone in the figure is the zone where the wind speed was less than 0.70 m/s, that is, "the low wind speed zone". The ratio of the comfortable wind speed zone was then obtained and a broken line chart was plotted for both layouts (Figure 10, the courtyard names are from Figure 7a,d).

Through a comparative study, it was found that the ratio of the comfortable wind speed zone of the courtyards in feng shui layout was higher than that of dissimilation layout. For both feng shui layout and dissimilation layout, the courtyard with the highest ratio of the comfortable wind speed zone was courtyard F, with ratios of 99% and 94%, while the courtyard with the lowest ratio of the comfortable wind speed zone was courtyard

M, with ratios of 64% and 61%. The ratio of the comfortable wind speed zone ratios of these two layouts is linear: y = 0.9117x. The regression formula shows that the ratio of the comfortable wind speed zone in the dissimilation layout is 0.9117 times that of the feng shui layout. The formula R^2 = 0.8524 proves that the regression degree of fit is good (Figure 11). According to the statistics of all the courtyard data obtained in Excel, the ratio of the comfortable wind speed zone of all the courtyards in feng shui layout was 93.04%, while this value was 80.75% for dissimilation layout. It shows that the feng shui layout provides a larger comfortable wind speed area than the dissimilation layout.

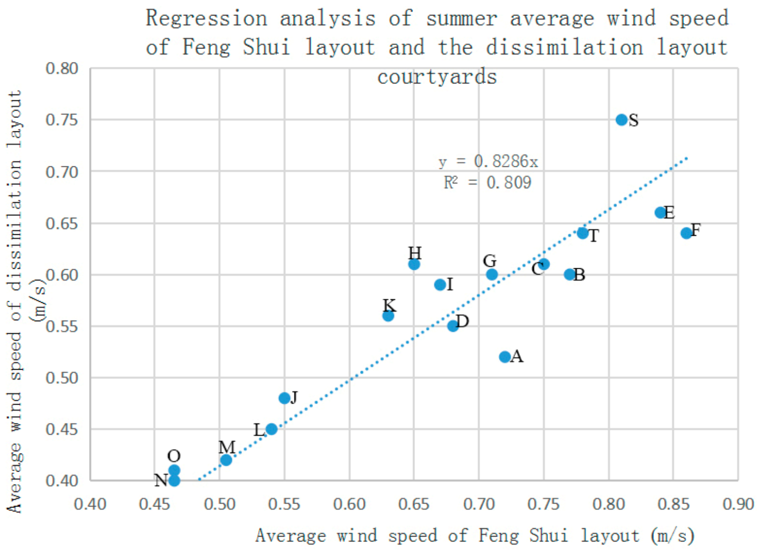

Figure 9. The regression analysis of the summer average wind speed for the courtyards of feng shui layout and dissimilation layout. The values of the figure was based on CFD simulation results.

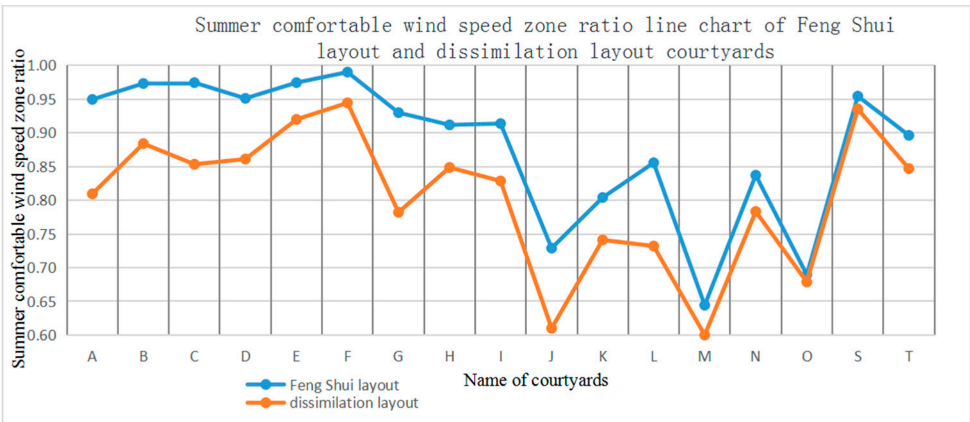

Figure 10. The comfortable wind speed zone ratio line chart for the courtyards of feng shui layout and dissimilation layout in summer. The values of the figure was based on CFD simulation results.

(3) The average wind speed in the courtyards of the feng shui layout gradually decreased from south to north. The wind speeds of the courtyards along the three axes were all linear (Figure 12, the courtyard names are from Figure 7a). This was mainly determined by the summer wind direction. Therefore, the feng shui layout with low south houses and high north houses was conducive to the summer ventilation of the courtyards. The average wind speed of the south courtyards was higher than that of the north courtyards.

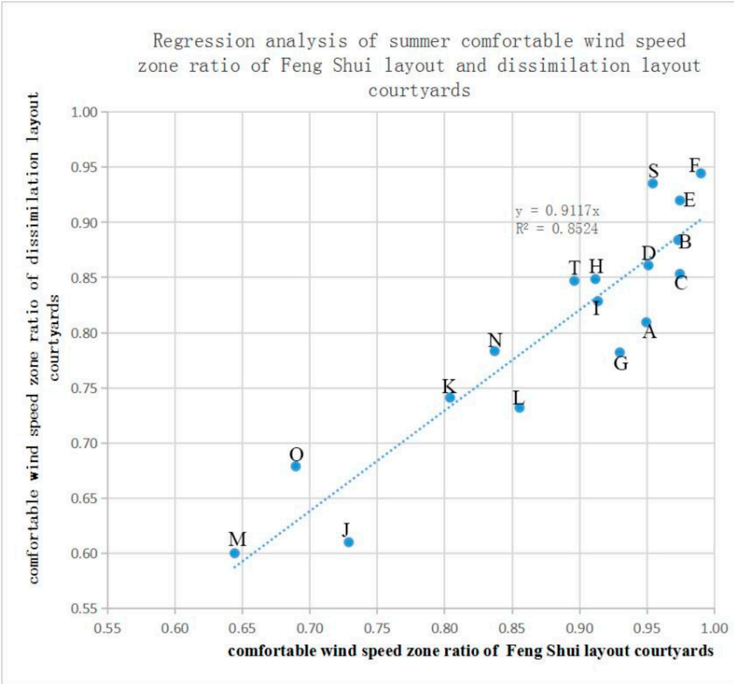

Figure 11. The regression analysis of the comfortable wind speed zone ratio for the courtyards of feng shui layout and dissimilation layout in summer. The values of the figure was based on CFD simulation results.

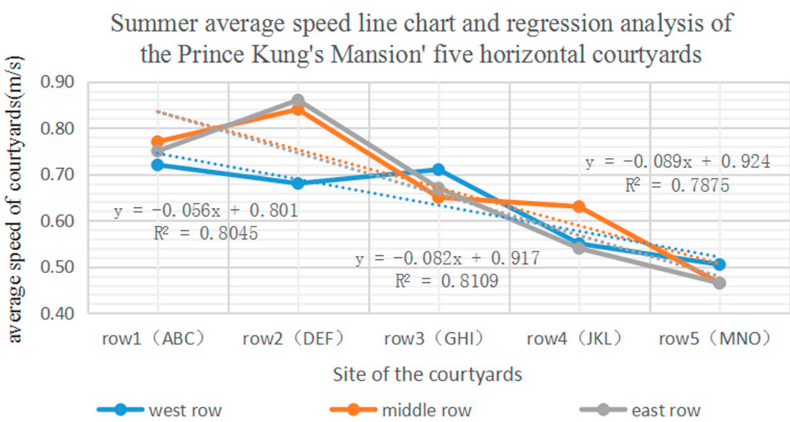

Figure 12. Average speed line chart and regression analysis of Prince Kung's Mansion' five horizontal courtyards in summer. The values of the figure was based on CFD simulation results.

(4) The wind speed vector charts show that there were no obvious vortices or large windless areas in the courtyards of the two layouts, which satisfies the evaluation criteria for the wind environment. The wind speed in the courtyard decreased from the middle to the periphery. Therefore, the middle area of the courtyard became the main outdoor activities area, with high wind speed in summer, since Chinese ancients used to carry out family activities in the courtyard.

The above analysis shows that the courtyard wind speeds and comfortable wind speed zone ratios of the feng shui layout were both higher than those of dissimilation layout. The feng shui layout provides a more comfortable outdoor wind environment in the summer.

4.2.2. Comparative Study of Courtyard Wind Pressures

The following results can be drawn from the wind pressure cloud charts of the feng shui layout and the dissimilation layout (Figure 13):

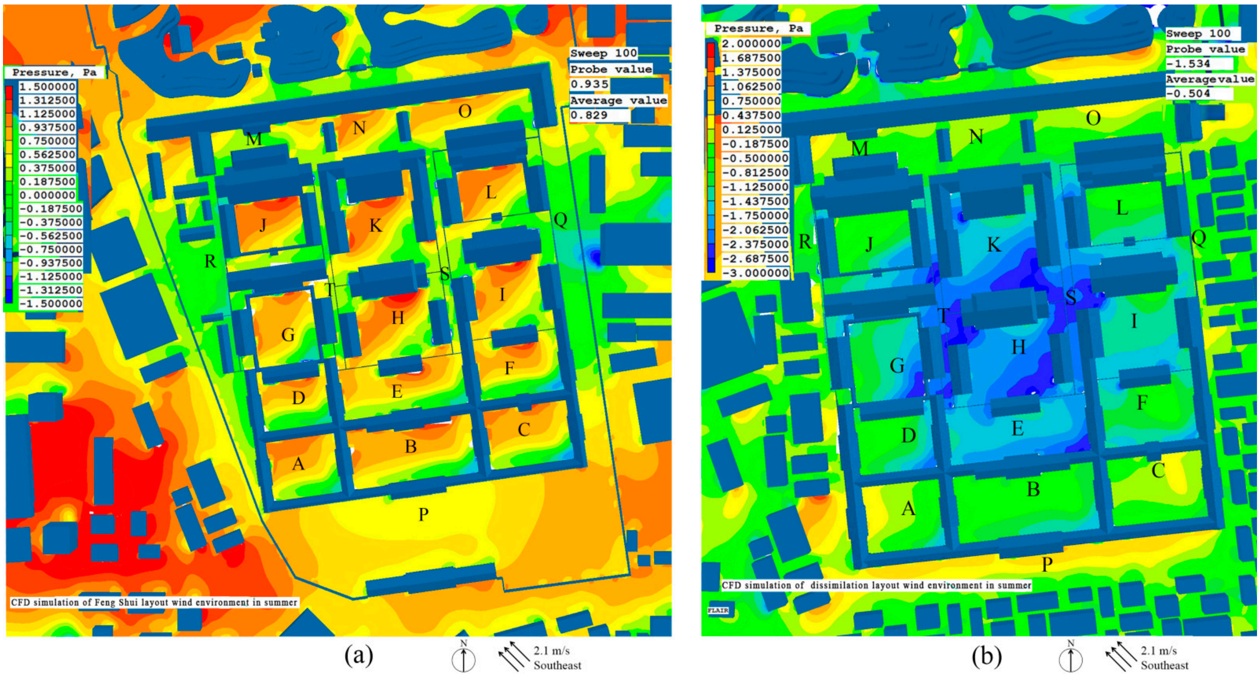

Figure 13. (**a**) Wind pressure cloud of feng shui layout in summer. (**b**) Wind pressure cloud of dissimilation layout in summer. The figures were obtained by CFD simulation.

The threshold of the wind pressure in the courtyards of the feng shui layout was −0.56 Pa~1.31 Pa (Figure 13a A~T). The distribution of the wind pressure in every courtyard regularly and gradually decreased from northwest to southeast. The front and rear wind pressure differences of the main houses (15 houses of Figure 13a A~O courtyards) were 0.75 Pa~1.5 Pa, which meets the evaluation criteria that the front and rear wind pressure differences of more than 75% of the houses are ≥0.5 Pa.

The threshold of the wind pressure in courtyards of dissimilation layout was −3.00 Pa~1.38 Pa (Figure 13b A~T). The lowest negative pressure was −3.00 Pa around Yin'an Hall (houses in Figure 13b H courtyard). The negative wind pressure gradually increased to a positive pressure around Yin'an Hall, and the courtyard P on the southernmost side had a totally positive pressure. The front and rear wind pressure differences of the two main houses of Xijin studio (houses of Figure 13b J courtyard) and Ledao Hall (houses of Figure 13b L courtyard) were less than 0.5 Pa, and the pressure differences for the other main 13 houses were more than 0.5 Pa (accounting for 86.7% of the total main houses), which satisfies the evaluation criteria that the front and rear wind pressure differences of more than 75% of the houses are ≥0.5 Pa.

The above analysis shows that the front and rear wind pressure differences of the houses in the feng shui layout and dissimilation layout were all superior to the wind environment evaluation criteria of this study, however, the feng shui layout (with all the main houses) is more conducive to indoor house ventilation than the dissimilation layout (with 86.7% of the main houses).

4.3. Wind Environment Evaluation of Feng Shui Layout and Dissimilation Layout

Based on the mathematical analysis of the above simulation results and the evaluation criteria for the wind environment proposed in this study, the evaluation results for the wind environment of the feng shui layout and the dissimilation layout in summer are summarized as follows (Figure 14).

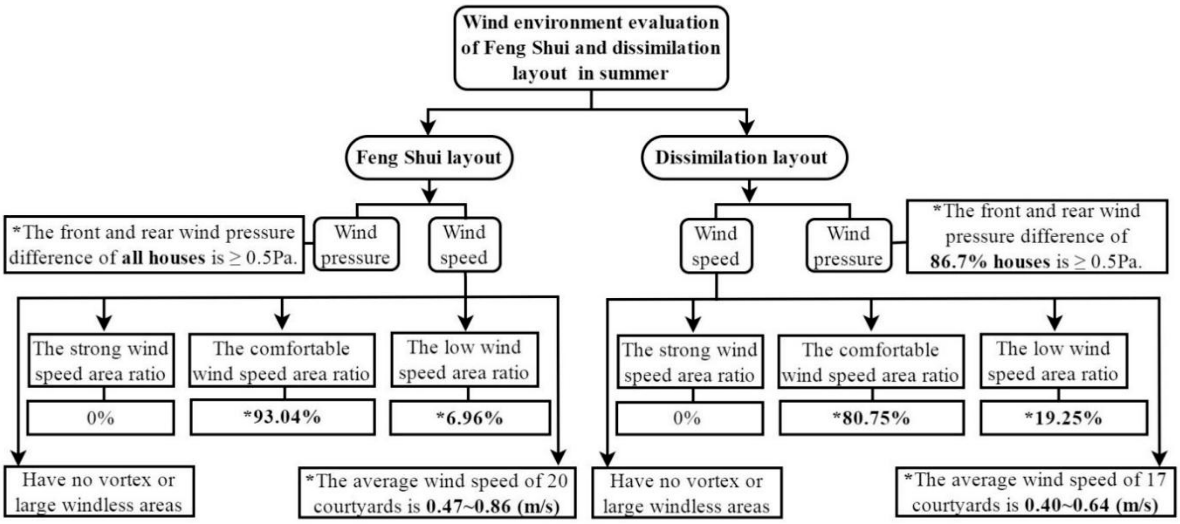

Figure 14. Outdoor wind environment evaluation of the feng shui layout and the dissimilation layout in summer (items with * mean that there is a big difference between the two layouts).

The figure shows that the ratio of the comfortable wind speed zone, average wind speed values of all courtyards and the front and rear wind pressure differences of the main houses in feng shui layout were better than those for dissimilation layout (the item with * in the figure). These are the main indicators of the outdoor wind environment. The result verifies that the wind environment of the feng shui layout is better than that of the dissimilation layout in the summer.

5. Conclusions

This study analyzed the Four Emblems feng shui layout in Prince Kung's Mansion, and then abandoned the Four Emblems to assume a dissimilation layout for the comparative study. The evaluation criteria for the courtyard wind environments in the summer were determined. Based on the coupling of the CFD simulation and a field experiment, PHOENICS was selected for the CFD simulation in the outdoor wind environment research. The wind speed and pressure values of the feng shui layout and the dissimilation layout in the summer were then obtained through CFD simulations, and a comparative study was conducted. The following conclusions can be drawn:

(1) The measured wind speed values of 60 important points in the Prince Kung's Mansion showed linear regression with the simulated values. It proves that PHOENICS is suitable for CFD simulations of the research object. The CFD simulation results in this study are therefore credible.
(2) The CFD simulation results show that the average wind speed of courtyards in dissimilation layout was only 0.8286 times that of the feng shui layout. The feng shui layout had higher average wind speeds, which was more conducive to courtyard ventilation in the summer.
(3) The ratio of the comfortable wind speed zones in the courtyards of the dissimilation layout was only 0.9117 times that of the feng shui layout. The feng shui layout therefore provides a larger area of a comfortable wind speed zone for use during the summer.
(4) As for the evaluation criteria that "front and rear wind pressure differences of more than 75% of the houses are ≥0.5 Pa", all the main houses in the feng shui layout satisfy the evaluation criteria, while 86.7% of the main houses in the dissimilation layout satisfy it. Therefore, the feng shui layout better optimizes the indoor ventilation of the main houses in the summer.

(5) The average wind speed in the courtyards gradually decreased from south to north and was linear. Therefore, the feng shui layout, with lower south houses and higher north houses, optimizes courtyard ventilation in the summer.

As can be seen from the above conclusions, the feng shui layout optimizes the courtyard wind environments in the summertime. In the present study, only the summer wind environment was analyzed. The feng shui layout is also conducive to reducing the invasion of strong wind in the winter. The direction of winter monsoon wind in Beijing is northerly, meaning that the two-story building on the north side of Prince Kung's Mansion blocks monsoons in the winter. The height of the houses decreases from north to south, which reduces the wind speed in the courtyards in the winter. Therefore, the lower wind speed in the courtyards provides a comfortable environment for residents' outdoor activities in the winter. In the future, we will continue to conduct comparative studies of the courtyards' winter wind environments between the feng shui layout and the dissimilation layout.

The above conclusions verify that the courtyards of the feng shui layout are more livable than those of the dissimilation layout. The feng shui layout contains an ancient ecological conception.

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