RESEARCH ON SELF-FORMATION WIND TUNNEL PLATFORM DESIGN BASED ON DYNAMIC GRIDDING MECHANICAL DEVICES

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Abstract. Nowadays, climate problems, such as urban ventilation, heat island effect are becoming increasingly serious. Performance-oriented buildings that respond positively to the environment are constructing a sustainable future of the living environment. This research introduces an autonomous Self-Formation Wind Tunnel (SFWT) platform based on 120 dynamic grid mechanical devices, and its building cluster morphology generation workflow in the conceptual design stage, for the rapid and mass formation experiments. The Self-formation wind tunnel plat-form, which has the advantages of both perceptive and real-time data, is able to use the techniques of machine learning to provide a new design paradigm, from environmental performance to physical morphology.

Keywords. Self-Formation Wind Tunnel; Building Cluster Morphology; Dynamic Models; Mechanical Grid Devices; Environment Performance Design.

1. Introduction

In the urbanization process, the modern high-density urban space provides us convenient and intensive living space. While at the same time, it also aggravates the deterioration of urban ventilation, heat island effect, air pollution, and so on. The formation of the numerous building clusters, which leads to local eddies as well as local strong winds, impacts malignantly on wind environment comfort of pedestrians as well as the location and strength of the air pollution (Ng, Yuan et al. 2011). Therefore, the optimization of environmental performance, the adjustment of the morphology and layout of the building cluster, play a really important role to improve the urban climate and atmospheric environment.

To adjust the platform to more complex terrain and massing schemes of complex building group morphologies, we develop a small-scale and self-formation wind tunnel (SFWT) based on the transmission principle of lifting machinery, which is movable, easy-disassembled, and three-unit designed, built by aluminum alloy profiles and acrylic boards. The platform is composed of the inlet unit (including stable section and contraction section), experimental unit (including smoke section, mechanical device) and the outlet unit (including

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diffusion section, fan section), also can be divided into the physical morphogenesis system, wind environment simulation system and data acquisition system.

With the rapid development of artificial intelligence technology and sensing technology in the post-Internet era, the customed physical wind tunnel has the dual advantages of perceptuality and real-time data. It can promptly generate a large number of physical and environmental data in a short period of time, cooperating with the big requirement of data sets in machine learning for the prediction from wind environment performance to architectural form, providing a new design paradigm combing physical experiment tools and machine learning algorithms, which is different from wind environment performance design method based on CFD (Yuan and Lin 2019).

2. Design Strategy of Dynamic Gridding Mechanical Devices

2.1. WIND TUNNEL ONTOLOGY DESIGN

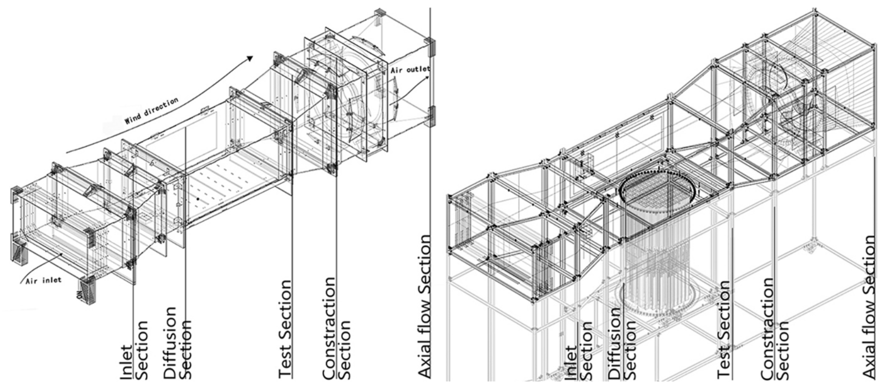

Figure 1. Wind tunnel ontology of previous work(Zheng, Yao et al. 2017) (left) and Self-formation wind tunnel proposed in this paper (right).

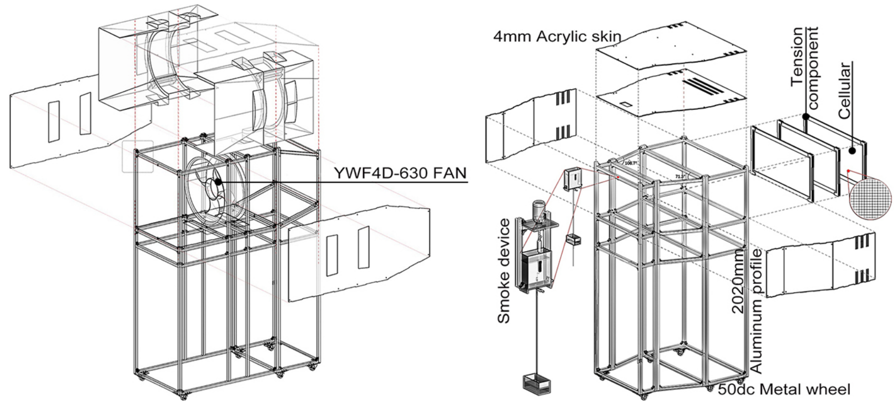

Figure 2. Construction diagram of fan section (left) and stability section (right).

The self-formation wind tunnel developed in this research is a low-cost mini customed wind tunnel as shown in Fig.1. It is totally improved on the basis of the team's previous researches (Zheng, Yao et al. 2017, Lin, Zheng et al. 2018), whose overall structure remains a five-segment structure, which is consisted of the fan section, con-traction section, test section, diffusion section, and stability section. The total length of SFWT is 3 meters while the test section is 1000mm long, 570mm wide, and 390mm high. It is constructed by 2mm thick transparent acrylic sheets and 2020 aluminum alloy profiles. The main differences between the two, mentioned above, are as follows: (1) The diffusion section integrates an improved smoking de-vice with an adjustable-rate; (2) The test section integrates the mechanical system under its bottom plate; (3) From the perspective of handling and disassembly, the wind tunnel is designed as a three-stage disassembly, composed by air inlet, experiment and air outlet. Each section is equipped with casters for movement; (4) A layer of profiles at the same horizontal level is added to the upper and lower parts of the wind tunnel so that the upper and lower parts can be separated, and the traditional use function can still be achieved without mechanical devices.

2.2. PRINCIPLE OF MECHANICAL TRANSMISSION

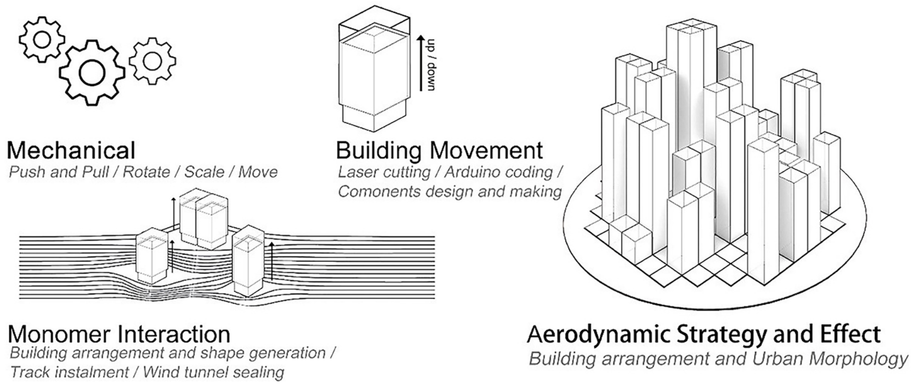

Figure 3. Principle of mechanical transmission.

The mechanical transmission of the lifting-up modular actuators provides the feasibility of diverse urban space formation. The Arduino electronic control system, which is based on the servo system, acts as the core mechanical transmission of this experiment. With the help of an electronic signal which is generated by a wind speed sensor, the device controls different morphologies. The detailed workflow is as follows: (1) The servo receives the signal source and drives the motor to rotate. (2) The gear set receives the motor signal and processes it to rotate the corresponding angle. (3) The rack is driven by gear, whose corresponding moving distance is determined both by the rotation angle and diameter of the gear. The experiments completed the morphological changes of the experimental model by gears or other parts (Rui-yan 2012).

2.3. MECHANICAL DEVICE DESIGN BASED ON DYNAMIC GRIDDING

2.3.1. Dynamic gridding unit

A primary need of the physical experimental platform is to ensure the accuracy of the wind environmental simulation as well as the accurate presentation of the building morphology in the wind tunnel. In order to achieve better universal experimental applicability, the dynamic model mechanical system is designed base on the gridded mass units. This paper is committed to studying how to implement the sensor placement and installation in the smallest block, and the selection of the servo steering gear to achieve the precise driving of each grid unit.

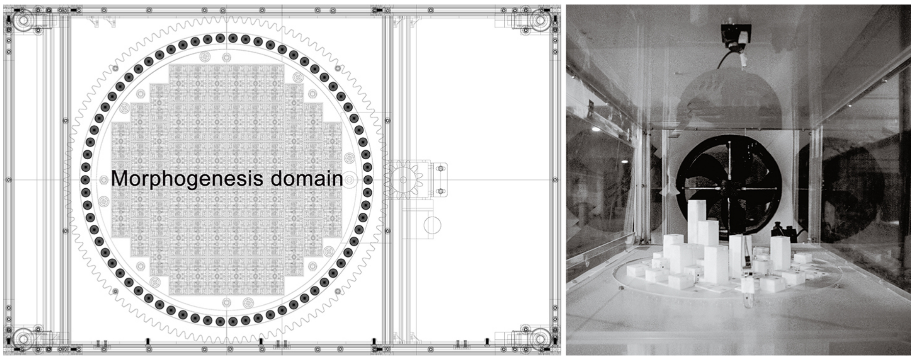

Figure 4. Morphogenesis domain.

Within the test section (1000mm length, 570mm width, 390mm height), this research developed mechanical lifting-up devices, which is composed of 120 dynam-ic grid units. To prevent interference with airflow from the inner wall (Hernández, López et al. 2013) and the morphogenesis domain is controlled in the space above 100mm from the wall. The windward area of the tested model is less than s ≤3.3×104 mm², to make true indicators of blockage within 15%. The lifting-up units group lo-cates on the chassis center of the test section, about 2/3 of the way from the inlet of the test section, forming the morphogenetic domain of the wind tunnel together with the chassis.

Since the simulation of the wind environment around building requires a standard test of a specific range of environmental masses around the measured building, and the experiment of urban morphology formation needs to consider the impact of roads, landscapes, and other open spaces, the 120 dynamic units, as a unit to simulate the smallest surrounding environment, could rise to a maximum of 250 mm at the same time in the windward direction. The average maximum height of all gridding units is 110mm, with the area of the windward surface with a maximum of 30000 mm². If using a maximum scale ratio of 1: 1000 to set the model size of the building group and setting the minimum floor height to 3m, the maximum plot ratio can be reversely calculated to obtain the experiment. In this case, the maximum plot ratio in the site was 36.67, which is far exceeding the maximum plot ratio of any high-density city center in reality. If then adding the influencing factors of the interior space and con-trolling the building density at 70%, the plot ratio comes to be 25.67. This data also meets the simulation demand for the maximum plot ratio of high-density urban centers. Therefore, for the application of the dynamic gridding mechanical model system in a mini wind tunnel, this paper developed a morphology test section with a diameter of 456mm composed of 120 grids, whose single side length is 34mm (certified after multiple tests). The center 64 units are the primary test area and the rest are the surrounding areas of the test subject. This method of determining the range of a dynamic grid system can be applied to physical wind tunnels of any different scales, and the size can be controlled by back-calculation based on its blocking degree.

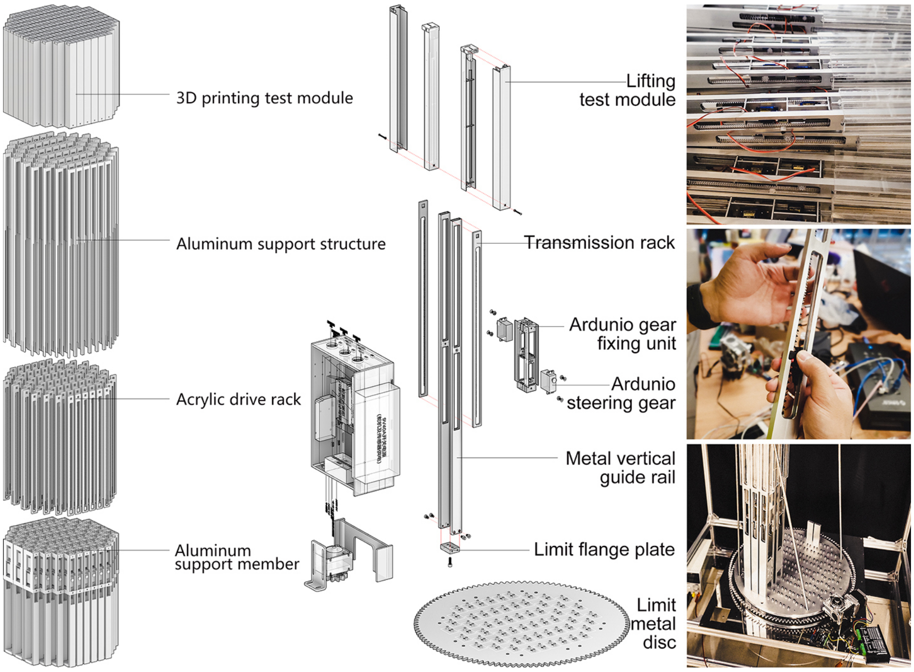

Figure 5. Construction diagram and pictures of dynamic model mechanical system.

Each unit in the dynamic model mechanical system can be divided into two main parts according to different functions: the 3D printed testing unit and the metal mechanical transmission unit. The ‘testing unit’ is mainly a part of the wind environment simulation experiment which is made of high stiffness PLA resin. This unit will change its lifting height, following the program instructions during the experiment. Every change in the morphology affects the airflow in the test section. The ‘mechanical transmission device’ is the driving device, which is located below the wind tunnel test section and does not interfere with the wind field environment in the wind tunnel. The mechanical transmission device is composed of vertical guide rails, internal drive racks, driving gears, and steering gear modules (including two steering gears arranged in opposite directions). Due to the size limitation of the dynamic griding, the size of a single servo has exceeded.

Therefore, merging the mechanical space of the adjacent units is necessary. The experiment arranges the servos in different layers to integrate the lower mechanical transmissions of the neighbor dynamic units. The assembly sequence also needs to be specially designed. The design and assembly of the experimental unit must ensure complete connection and airtightness to avoid affecting the environment in the wind tunnel.

2.3.2. Mechanical transmission device

The mechanical transmission system is the key technology of SFWT platform. In this research, we choose wind sensors, mechanical actuators and the Arduino open-source control software to build the mechanical transmission system with feedback capabilities and barrier-free perceptual acquisition.

The mechanical actuators such as servo steering gear offer the driving force for test models. Mechanical actuators such as servo steering gear offer the driving force for test models. Within the control by program instructions, the steering gear turns parameters 'n' are converted into the movement distance of rack, driving test units up and down '$h=2\pi r\times n$ (r is the radius of steering gear)'. The experiment uses 120 ZL-361S single-axis servos to control different units' height and a DM542 stepper motor driver to control the rotated angle of the morphogenetic domain. By many experiments, we find that all dynamic units can reach the maximum evolution height within 10s.

Researchers always use sensors as the data perception devices to collect the real-time environment data and then input them into the processing software for further calculation (Kensek 2014, Prohasky, Castro et al. 2014). In this study, The rectangular hole with a length of 20mm and a width of 2.5mm is obligated to each unit, through which the sensor can pass to extend the probe with the sensitive element out of the unit. After empirical calculations, 8 Rev.P wind speed sensors are evenly distributed in the morphogenetic domain to obtain more accurate measurement data. To avoid experimental errors caused by unstable airflow, sensors run measurements within 10s after the mechanical grid keeping a stable state.

The mechanical transmission of each dynamic unit provides the feasibility for the characteristic stimulation of the diverse building morphology and the different layouts of the building group. So when designing the tested model unit and mechanical transmission unit, it is necessary to establish a digital model to estimate the feasibility of the component's motion logic and write actuators data and wind sensor data into the real-time digital environmental performance database. Arduino is a flexible cyborg-physical combination platform (Badamasi 2014), helping designers establish a 'real-world environment-digital performance-physical geometry' data transformation architecture. According to the achievement of the CAADRIA2018 Workshop, it is confirmed that the different morphology of a single building can be generated based on Arduino and Firefly (Zheng 2018, Lin, Song et al. 2019). So in this paper, on the basis of our previous study result, we still use Arduino and Firefly to control the whole experiment.

3. Interactive design workflow based on physical wind tunnel experiment

Some pioneering custom-made wind tunnel projects are emerging in advanced university laboratories, such as Rensselaer Polytechnic Institute (Menicovich, Gallardo et al. 2012, Menicovich, Lander et al. 2014) and RMIT University (Prohasky and Watkins 2014, Williams, Moya et al. 2015) in the last several years, verifying their advantages of simple visualization, quick feedback, and effective data collection. This paper proposes an SFWT-based building cluster morphology generation method-ology. Through the long-term exploration of wind tunnel formation by the author's team, DDRC, this design method can be summarized as the process of "Strategy expression-Simulation test-performance evaluation-design optimization-final formation" (Lin, Yao et al. 2018, Yuan and Lin 2019). The specific steps are shown as follows. First, different design strategies and optimization directions are selected for different types of research subjects. In this research, building porosity, including building density, floor area ratio, windward area index, and building height deviation are all suitable for building group morphology expression. Second, in the digital information space and the physical wind tunnel space, modeling language and static construction or dynamic change based on the mechanical device are used respectively to present the model of the subject under test. Finally, the wind tunnel is opened for the acquisition of wind speed or wind pressure data, and the Arduino and Firefly platforms were returned to Grasshopper and Rhino platform to realize further data processing and analysis. It evaluates the environmental performance of the tested scheme, generates the next scheme, and then visualizes and tests the scheme in the wind tunnel.

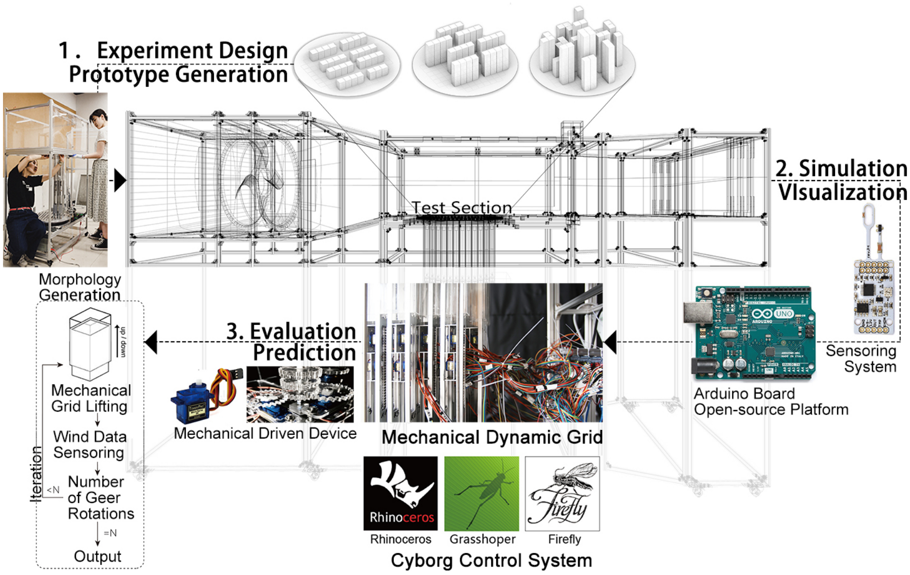

Figure 6. Interactive design workflow based on physical wind tunnel experiment.

The intervention of the dynamic mechanical devices essentially accelerates the process from the simulation test to design optimization. With the help of SFWT, designers can translate the digital geometric rules of building group morphology design optimization into the dynamic changes of the physical entities in real-time, making it possible to generate a large number of shapes and corresponding environmental data in a short time. This paper summarizes several popular building cluster formation design strategies for better wind environmental performance, including building density, floor area ratio, wind area index, and building height deviation, and uses different grid heights h to pixelated simulate buildings and open spaces (if h=0, the grid simulates the open space; if h>0, the grid simulates building). The workflow of building morphology generation experiment in SFWT is as follows: (1) Choose an apposite optimization engine (algorithms or software) around a specific design goal. Nowadays, because the input variables of environmental performance-based design have com-plex and non-linear interactions, designers usually choose the optimization engine which contains more than one iterative optimization algorithms, for a good solution with less time and effort. A large number of optimization methods have been developed, including genetic algorithms, machine learning algorithms, and artificial neural network algorithms, etc. (2) According to the selected design goal and optimization engines, the experimental programs are generated in Grasshopper. The morphological parameters are transformed by Firefly and Arduino into the driving parameters corresponding to the dynamic grid unit which means the steering angles of the steering gear. (3) Then start the SFWT experiment. Use the wind speed sensor to measure the speed in the wind tunnel; transmit and record the corresponding shape (the height data matrix of mechanical grids) and environmental data through the Arduino platform; and write to the evaluation system. The wind evaluation program automatically calculates environmental performance scores based on the wind environment evaluation indicators selected by the designer, such as the average wind speed values and wind speed discrete values of multiple sensor measurement points, thereby achieving wind environment data acquisition and evaluation translation. (4) Write the morphological parameters and wind environment parameters into the performance database in real-time. (5) Batch transfer the performance database parameters to the architectural functions of the optimization algorithm (in this study, we use a neural network algorithm model), to perform iterative training of the algorithm model. (6) Obtain an optimization algorithm (artificial neural network) with better prediction effect, into which input a large number of gradient building group index parameters and ideal wind environment data in the site environment to perform multiple predictions of building group morphological parameters; (6) Convert the predicted morphological parameters and the corresponding building group index parameters to possible morphological schemes, completing the prediction of morphology formation; (7) Convert specific morphological parameters into mechanical model parameters, present them in the wind tunnel and conduct smoke visualization experiments, and finally select the optimal scheme through the judgment of the designer to complete the “Human-machine collaborative generation” of building layout and volume height under the control of wind environment. The experimental photos of this process are as follows:

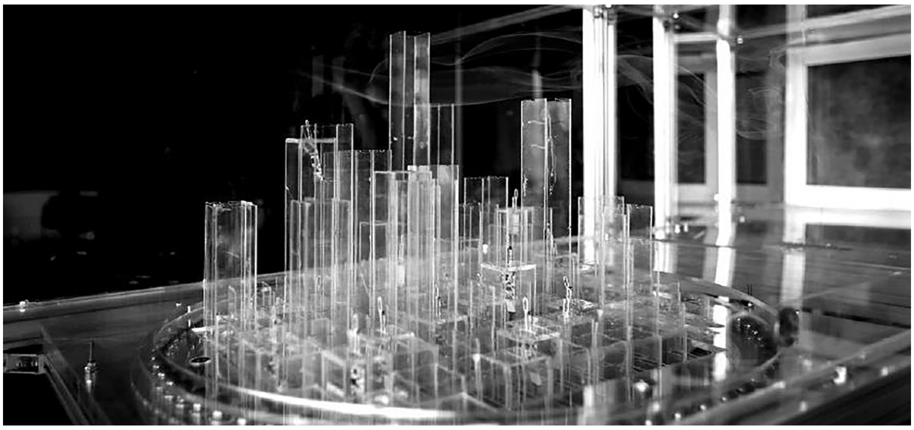

Figure 7. Picture of building cluster morphology generation experiment.

4. Summary

Based on the idea of a dynamic grid, this paper first develops a new self-formation wind tunnel with a set of morphogenesis machinery and then introduces an interactive building group morphology generation method which takes the urban wind environment performance as the entry point. On the simulation tool, we completed the digitization of the physical wind tunnel, and generate a feedback-type dynamic model of the sensors and actuators in order to use Arduino to set up a data feedback loop. On the design method, we aim to explore two aspects of wind performance-based design: quantitative data and qualitative streamlines. In this paper, the Grasshopper Firefly program is used to quantitatively associate the simulation data with the morphogenesis data of the building model. Under this open design frame, architects can adjust the morphological strategies, site environment, the positions of sensors, and data evaluation rules. With the introduction of some other sensors, for instance, wind pressure, wind temperature, humidity, and so on, the wind tunnel can upgrade to conduct a more comprehensive evaluation of the morphology, which enriches the significance of the physical environmental experiment and thus has high research significance and value.

By now, the wind tunnel simulation platform will no longer be only developed as a post-design testing and measurement tool, but enter the early design stage to generate the morphogenesis of the scheme design. Moreover, coupled with visualization tools, the SFWT, which performs real-time wind environment simulation, establishes a rapid feedback platform. Architects can clearly observe the aerodynamic effects of different building morphology in the three-dimensional space of the real scene. At the same time, the smoke flow lines were recorded as a series of diagrammatic auxiliary schemes for further research. Under this open design frame, architects can adjust the morphological strategies, site environment, the positions of sensors, and data evaluation rules. With the introduction of some other sensors, for instance, wind pressure, wind temperature, humidity, and so on, the wind tunnel can upgrade to conduct a more comprehensive evaluation of the morphology, which enriches the significance of the physical environmental experiment and thus has high research significance and value.

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