A spatial prototype of natural ventilation in underground public spaces combining courtyard with wind tower

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Abstract. Ventilation is the basis of controlling thermal comfort and air quality in underground spaces. Natural ventilation based on spatial designs can introduce wind, light, and scenery to improve environmental health and spatial experience, and reduce health risks and energy consumption of mechanical ventilation. This paper proposes a spatial prototype that combines courtyard with wind tower, two common spatial forms connecting aboveground and underground, and can provide effective natural ventilation to underground public spaces. Computational fluid dynamics simulations and genetic optimization were conducted in the common architectural software Rhinoceros and Grasshopper. First, spatial defects are identified and optimized by analysing the simulation results. Then, geometric variables of the spatial form that obviously affect the ventilation performance were selected and automatically optimized with the target of air volume per hour. Finally, three key issues for natural ventilation of underground public spaces are discussed including human comfort, air distribution, and ventilation reliability. This paper explores the coupling between the spatial form and ventilation performance of underground public spaces, which not only alleviates the potential conflict between energy saving and environmental health, but also provides an integrated design pattern to create more open, flexible, natural and sustainable underground spaces.

1. Introduction

Underground spaces have become an essential urban spatial system, accommodating an increasing number of urban functions and human activities. Underground spaces are surrounded by soil, rock and groundwater, with limited connection to the ground, making them prone to an unhealthy "hot, humid and polluted" indoor environment. Mechanical ventilation, the main method of environmental control in conventional underground spaces, consumes large amounts of energy and carries its own risks of contamination and disease transmission [1]. During the COVID-19 epidemic, the underground space with limited ventilation was very vulnerable and only relied on all fresh air system to reduce environmental health risks [2]. Natural ventilation is effective in improving indoor thermal comfort and air quality both in daily life and epidemics, and has great potential for control efficiency and energy savings [3,4]. However, it is difficult to obtain adequate and stable natural ventilation in a separate underground space. Especially in shallow underground public spaces (UPSs) and hot and humid climates, it is not obvious that buoyancy is generated by the vertical temperature difference between underground and aboveground [5,6]. Therefore, spatial connectivity and airflow paths need to be designed with the surrounding urban environment to introduce more natural winds and create the proper pressure differential to promote natural ventilation of UPSs.
Conventional UPSs often lack connections to the ground, making it difficult for natural winds to enter the underground. Connecting above and underground through special spatial designs is an essential method of optimizing the underground environment, such as courtyards, atriums, patios, wind towers, and solar chimneys [7–10]. Of these, the courtyard is a common and expressive form, providing enough space and openness to bring people, wind, light, sound, and scenery into the underground. In addition to improving the physical environment, courtyards have a positive effect on spatial experience and mental feeling. Integrated developments of new urban areas and the reclamation of existing urban areas provide opportunities for creating more comfortable, healthy and beautiful UPSs. Therefore, new design patterns are needed to consider both building space and ventilation performance [11].

This paper proposes a spatial prototype that combines courtyard with wind tower, two common spatial forms of aboveground and underground connections, and can effectively enhance natural ventilation of UPSs. The ventilation effectiveness of the spatial prototype was verified by computational fluid dynamics (CFD) simulations. Based on the simulation results, spatial defects were identified and optimized to achieve space forms that were more conducive to ventilation efficiency and human comfort. Further, air volume per hour (AVH) was taken as the optimization target to adjust some geometric variables through genetic algorithm. This paper explores efficient natural ventilation of UPSs, which not only alleviates the potential conflict between energy saving and environmental health of underground ventilation, but also inspires new design patterns of UPSs that integrated building space and ventilation performance.

2. Methodology

2.1. Geometrical models and numerical method

This paper used the numerical modelling function of Grasshopper to parameterize the spatial prototype of “courtyard + wind tower” (Figure 1). This was a simplified model that only built the wind tower, underground passages and courtyard. In fact, this model would be surrounded by other underground spaces whose ventilation were also provided by this prototype. The more air volume the spatial form provides, the more area of underground space is ventilated. This was also the reason for adopting AVH as the optimization target. Therefore, it was feasible to use this simplified prototype to conduct the simulation and analysis.

The Grasshopper is a mainstream visual programming language in the field of architecture, urban and landscape design [12]. It has multi-functional plugins for generating and simulating numerical models using program algorithms in the software Rhinoceros. In the Grasshopper, Ladybug includes multiple environmental analysis, data visualization and online weather data. Butterfly connects Grasshopper to the OpenFOAM engine to provide CFD simulations. Galapagos provides a genetic algorithm for single-objective optimization.

The numerical model, boundary conditions and computational domain (Figure 2) were set according to the CFD simulation requirements of urban wind environment in Chinese standard JGJ / T 449-2018, Standard for Green Performance Calculation of Civil Buildings [13]. RNG k-Epsilon model was utilized to simulate turbulence flow. The landscape of wind tunnel was calculated as “Skimming” in Davenport classification, which provided an effective terrain roughness in densely built-up area without much building height variation [9].

2.2. Research route and steps

The research route is shown in Figure 3 and is conducted in two steps. First step, the wind speed contours and vectors of the vertical profile and the 1.5m high plane were analysed to identify indoor wind environment defects. Further the spatial forms were adapted to resolve these defects and select key spatial variables that affect the natural ventilation performance of the space. Second step, for better coupling between spatial form and ventilation performance, AVH was set as the optimization target to automatically adjust the selected spatial variables through genetic algorithm. Specifically, first, the mean wind velocity was obtained by setting the monitoring section between Positions C and D. And
multiplying the velocity by the area of research area to calculate \( q \). Then, several geometric variables related to ventilation performance, including \( H_1 \), \( L_1 \), \( L_3 \), and \( W_3 \), were selected by analysing the simulation results of spatial prototype and the modified form. Next, based on architectural design experience, numerical boundaries were set for selected spatial variables, such as the maximum \( H_1 \) (less than 4 m floor height of above-ground building) and the minimum \( L_1 \) (more than 1 m required for personnel access), as well as the 8 * 8m column grid (taking into account construction cost and parking load). Finally, the genetic algorithm was used to automatically adjust these spatial variables to optimize spatial forms of "courtyard + wind tower" with better natural ventilation performance.

**Figure 1.** The axonometric profile of “courtyard + wind tower”

**Figure 2.** The setting of numerical model and computational domain

**Figure 3.** Research route and modelling parameters
3. Results

3.1. Prototype optimization

The simulation result (Figure 4) shows that "courtyard + wind tower" provided effective and sufficient natural ventilation for underground space under the set conditions. The AVH of spatial prototype was 223,286.7 m³/hour. And a clear airflow path formed in the model. Natural wind entered the wind tower from the inlet at Position A, turned at Position B, passed through the passage between Positions C and D, and finally exited the courtyard from Position F. However, the spatial prototype could still be improved. Some spatial forms conflicted with the airflow direction and caused wind energy loss, which was not conducive to natural ventilation under outdoor low wind conditions. And strong wind more than 3.0 m/s at Positions B to D in the pedestrian area would affect human comfort and health.

Specific analysis from four main issues: first, natural wind directly hit the vertical wall and consumed energy at Position A. Therefore, setting a circular wind deflector can guide natural wind to turn into the wind tower more smoothly. Second, according to the vertical profile, the longer L₁ caused three airflow layers in the wind tower. Airflows flowed efficiently on one side, and formed a reverse flow on the other side, with an intermediate region relatively static. Therefore, shortening L₁ appropriately can increase the ratio of ventilation volume to spatial section to save building volume and construction cost. Third, at Position C, in addition to the airflow directly hitting the ground and energy consumption, there were also high wind velocities in the pedestrian area. Similarly, the problem can be solved by using the wind deflector and transforming the space form. Finally, airflows mainly flowed to the aboveground at Position E. Therefore, it is feasible to build a glass roof from Position E to D to form an indoor-outdoor transition space that provides an outdoor activity area during rain or snow.

Based on the above analysis and design, a modified form was proposed and simulated under the same CFD conditions. Although the AVH of the modified form decreased from 223,286.7 m³/hour to 210,352.3 m³/hour, the above four issues were solved. First, wind vector diagram showed that the circular wind deflector at Position A changed the wind direction smoothly. Second, shortening L₁ eliminated the reverse airflow layer, but a relatively static area still existed. Third, at Position B, the increased spatial section and the circular wind deflector reduced the wind velocity to less than 1.5 m/s in pedestrian area. Finally, the glass roof at Position G in the courtyard did not obviously affect the wind environment of the underground space. In short, space optimization can effectively improve human comfort in indoor wind environments while ensuring adequate natural ventilation. The modified form with circular wind deflectors was used as the basic model for genetic optimization in the next stage.

![Figure 4. Vector diagrams of wind velocity in spatial prototype and modified form](image-url)
3.2. Genetic optimization

This paper adopted the evolutionary algorithm in Galapagos for automatic AVH-maximized optimizing of modified spatial forms. The selected geometric variables were bounded to take into account the common size for architectural design on the one hand, and to simplify combinations of these variables to reduce the amount of computation on the other. For example, the length (L3) and width (W3) of the courtyard were bounded to 8 m, 16 m and 24 m, in line with the common size of column grid in underground spaces. The air inlet of wind tower was kept at a width of 8 m, and the heights (H1) are bounded to 1 m ~ 4 m that were less than 4 m floor height of above-ground building.

Several spatial forms were obtained from automatic optimization with higher AVHs than the above modified form. Figure 5 presents the first four optimized forms in order of AVHs. Analysis of genetic optimization shows that the wind tower cross-sectional area and air inlet area significantly affect AVH and are positively correlated. But the courtyard area slightly affects AVH and is inversely correlated.

1. AVH = 212,709.4 m²/pen
2. AVH = 212,473.1 m²/pen
3. AVH = 212,255.1 m²/pen
4. AVH = 211,505.6 m²/pen

Figure 5. Vector diagrams of wind velocity in the first four optimized forms
4. Discussion
The practical design and application need to consider more factors including building function, ground buildings, fire control, outdoor air pollution, and urban microclimate. This paper only studied a spatial prototype that improved natural ventilation performance of underground space and proposed a design pattern that integrated spatial form and ventilation performance. On this basis, the next research will sort out a more complete tool library of spatial prototypes for natural ventilation of UPSs.

The courtyard and wind tower are both building forms with a long history, which have been used to control the natural environment to enhance the indoor experience. The natural ventilation they bring plays an important role in improving indoor air quality and acceptable thermal comfort, reducing the load of mechanical ventilation and the risk of equipment contamination. There are many studies on the courtyard and wind tower in aboveground buildings, which can provide references to optimize the spatial prototype [5,7,10,14–16]. These studies also showed that uncontrolled natural ventilation is changeable and unstable, and has inherent defects in human comfort, air distribution and ventilation reliability. Therefore, this paper discusses the possible optimizations and applications of “courtyard and wind tower” from these three aspects.

4.1. Human comfort
Wind comfort and thermal comfort closely relate to wind environment. Wind velocity and temperature significantly affects draught sensation and has potential health effects on cardiovascular, integumentary, respiratory and auditory systems, especially in summer and winter. Meanwhile, based on the international standard ISO 7730, Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria [17], ventilation affects thermal comfort directly from relative air velocity and indirectly from the air temperature and relative humidity. In addition, the comfortable temperature, humidity and wind velocity of different public places are different, so it is necessary to flexibly set the optimization targets to control natural ventilation. For example, piston wind induced by train movement in subway stations causes strong draught sensation, which can contribute to better thermal comfort when a large number of passengers are concentrated on the platform in summer. But the rest area of underground shopping needs relatively static wind environment.

In a specific indoor environment and ventilation scene, appropriate temperature and wind velocity are selected as the optimization targets. And spatial prototypes are optimized automatically to get high-performance and applicable spatial forms. If the outdoor wind is too cold, the air can be heated by solar chimney, photovoltaic heater, thermal mass and geothermal. If the outdoor wind is too hot, it can be cooled by soil, mist and thermal mass. If the outdoor wind is too fast, it can be moderated by filter screen, grille and baffle on airflow path. If the outdoor wind is too slow, other passive or active methods can be used to promote natural ventilation, which will be discussed in detail later [5,7,8,10]. In addition, more accurate control of the thermal comfort also needs to consider indoor heat sources and humidity sources including people, equipment, and function rooms such as kitchen, cleaning room and toilets.

4.2. Air distribution
Air distribution affects the freshness of air supply and the efficiency of pollutant discharge. Life of air and age of air are widely used to evaluate the ventilation efficiency, but there is a deficiency of evaluation and research applied to natural ventilation scenes. Variable natural winds and complex urban environments result in variable indoor airflow paths, which seriously affects the ventilation efficiency and even leads to air stagnation or pollutant backflow. Therefore, how to organize stable indoor air distributions in variable outdoor wind environment is a core problem of natural ventilation in UPSs.

This can be studied from two aspects: inlet/outlet and spatial connectivity. For small, simple buildings, a single path is recommended, which allows flexibility in organizing forward and backward movement depending on the coupling of wind and thermal pressures in winter and summer. For underground blocks or underground complexes, multiple courtyards and wind towers can be flexibly adjusted to form multi-path ventilation networks through integration with vertical structures such as
atriums, double-layered facades, stairwells, and shafts. After natural wind enters the underground space, displacement ventilation [18], laminar ventilation, and wall attachment jet can be used as references to design airflow paths into and out of the rooms to improve ventilation efficiency and human comfort. In addition, direct airflow shortcuts from underground to aboveground can reduce the adverse effects of underground pollution sources on UPSs.

4.3. Ventilation reliability
Ventilation reliability refers to the stability and cleanliness of natural wind. On the one hand, to achieve stable natural ventilation, urban and built spaces must be designed comprehensively in four ways: city, block, building, and detail. At the city level, urban planning should take into account the local climate and topography, using landscaped strips, rivers and streets to build ventilation corridors and networks. Similarly, at the block level, a secondary ventilation network should be built and connected to the city-level ventilation network. And residential, office, commercial, and activity areas where people gather or spend long periods of time should not have high pollution sources. At the building level, orientation, shape, layout and openings all affect the indoor wind environment. Flexible organization of air inlet, outlet and air distribution according to urban microclimates improves the stability of natural ventilation in different scenes. At the detail level, in addition to spatial optimization, multi-directional inlet and wind catcher can increase the air volume of wind pressure ventilation, especially in low-velocity scene. Increasing the temperature difference between air inlet and outlet is the basic principle of promoting thermal pressure ventilation, which can be achieved through height differences, photovoltaic heaters, geothermal heat pumps, water/soil cooling and thermal mass.

On the other hand, clean air is the premise of healthy ventilation, which can be considered from two aspects: air inlet position and air purification. Because most UPSs are located in the areas with dense traffic and high urbanization, keeping air inlet away from pollution sources have limited effect. Therefore, a comprehensive purification system must be used to build a complete natural ventilation "protection system" based on the type, source and quantity of air pollutants. There are many purification technologies available for specific pollutants: (1) fibre filtration for particulate matters (PMs), microbes, and radon, (2) activated carbon for PMs, nitrogen dioxide, and volatile organic compounds (VOCs), (3) photocatalysts for VOCs and microbes, (4) negative ion for PMs, bacteria, and fungi, (5) ultraviolet for bacteria and fungi, and (6) plasma for PMs, VOCs, bacteria, and viruses, (7) magnetic filtration for metallic PMs, (8) electrostatic purification for PMs, organics, and microbes [19–22]. But filtrations affect ventilation efficiency and heat exchange rates and needs further study.

4.4. Outlook and limitations
Spatial optimization, as the basis of efficient ventilation, has not received enough attention in the past due to limited construction technologies and immature professional cooperation. Unreasonable spatial connectivity and airflow path may cause a series of adverse effects and contradictions, which are hardly compensated by ventilation systems and devices. In the conventional design pattern of UPSs, space precedes ventilation, and ventilation remedies space, which should be replaced by a more integrated design pattern. The coupled design pattern between spatial form and ventilation performance can alleviate the potential conflict between energy saving and environmental health in underground spaces. This can be used not only for natural ventilation, but also for mechanical ventilation, compound ventilation and piston ventilation. Meanwhile, the methods for optimizing ventilation performance in this paper can also be applied to other space prototypes such as patios, shafts, solar chimneys, and wind deflector walls. Further, multi-objective optimizations such as thermal comfort, evacuation distances, and spatial layout can be studied to provide better indoor environments. And more sophisticated simulations that include multiple rooms and complex forms can provide a more direct reference to practical designs of UPSs.

Fire control is a focus not covered in this paper as it discusses natural ventilation for safety scenes. Fire doors, fire shutter, ceiling screen and smoke-preventing air curtains can effectively stop the spread of fire and smoke to provide sufficient time for the crowd to evacuate. Overlapping paths between
airflows and crowds are common in conventional underground spaces and pose serious health risks. Separating smoke from crowds is key to managing this risk and can be designed in two ways. On the one hand, increasing the height of the UPSs can keep smoke away from pedestrians to a limited extent. On the other hand, smoke exhaust passages and shafts connected directly to the ground, combined with mechanical smoke exhaust systems and zonal pressure control, can ensure that smoke kept away from crowds and exhausted quickly. Meanwhile, dynamic evacuation guidance is more applicable and safer according to smoke distributions and crowds positions [23,24].

5. Conclusion
This paper proposes a spatial prototype combining courtyard with wind tower to promote natural ventilation in UPSs, which is common and applicable in actual buildings. Ventilation effectiveness was verified by CFD simulation. And spatial forms with larger air volume were optimized by genetic algorithm. This paper initially explores the coupling between the spatial form and ventilation performance of UPSs, providing a concise design pattern for architects to integrate space and ventilation in early designs. Through continuing research, this pattern will create more open, flexible, natural and sustainable UPSs. This can resolve the issues of conventional underground spaces such as absence of natural elements, high energy consumption for environmental control, and uncomfortable indoor environments.

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References
[1] Wen Y, Leng J, Shen X, et al. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. *Int J Environ Res Public Health* 2020; 17.
[2] Yu X. Research in the prevention and control of urban rail transit public health epidemic, *CHINA ACADEMY OF RAILWAY SCIENCES*. Beijing, China, 2020.
[3] Chenari B, Dias Carrilho J and Gameiro da Silva M. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renewable and Sustainable Energy Reviews* 2016; 59: 1426–1447.
[4] Mukhtar A, Yusoff MZ and Ng KC. The potential influence of building optimization and passive design strategies on natural ventilation systems in underground buildings: The state of the art. *Tunnelling and Underground Space Technology* 2019; 92: 103065.
[5] Khan N, Su Y and Riffat SB. A review on wind driven ventilation techniques. *Energy and Buildings* 2008; 40: 1586–1604.
[6] Liu P-C, Lin H-T and Chou J-H. Evaluation of buoyancy-driven ventilation in atrium buildings using computational fluid dynamics and reduced-scale air model. *Building and Environment* 2009; 44: 1970–1979.
[7] Lomas KJ. Architectural design of an advanced naturally ventilated building form. *Energy and Buildings* 2007; 39: 166–181.
[8] Zhai XQ, Song ZP and Wang RZ. A review for the applications of solar chimneys in buildings. *Renewable and Sustainable Energy Reviews* 2011; 15: 3757–3767.
[9] Hammond DS, Chapman L and Thornes JE. Roughness length estimation along road transects using airborne LIDAR data. *Met. Apps* 2012; 19: 420–426.
[10] Moosavi L, Mahyuddin N, Ab Ghafar N, et al. Thermal performance of atria: An overview of natural ventilation effective designs. *Renewable and Sustainable Energy Reviews* 2014; 34: 654–670.
[11] Wen Y, Leng J, Yu F, et al. Integrated design for underground space environment control of subway stations with atriums using piston ventilation. *Indoor and Built Environment* 2020; 1420326X2094134.
[12] Xu X, Wu Y, Wang W, et al. Performance-driven optimization of urban open space configuration in the cold-winter and hot-summer region of China. Build. Simul. 2019; 12: 411–424.

[13] Ministry of Housing and Urban-Rural Development of the People's Republic of China. JGJ / T 449-2018, Standard for Green Performance Calculation of Civil Buildings.

[14] Horan JM and Finn DP. Sensitivity of air change rates in a naturally ventilated atrium space subject to variations in external wind speed and direction. Energy and Buildings 2008; 40: 1577–1585.

[15] Hughes BR, Calautit JK and Ghani SA. The development of commercial wind towers for natural ventilation: A review. Applied Energy 2012; 92: 606–627.

[16] Aflaki A, Mahyuddin N, Al-Cheikh Mahmoud Z, et al. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy and Buildings 2015; 101: 153–162.

[17] International Organization for Standardization. ISO 7730, Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[18] Ji Y, Cook MJ and Hanby V. CFD modelling of natural displacement ventilation in an enclosure connected to an atrium. Building and Environment 2007; 42: 1158–1172.

[19] Han Z, Wang J, Shao X, et al. Characteristics and eliminating strategies of contaminants in urban underground spaces. Heating Ventilating & Air Conditioning 2009; 39: 21–30.

[20] Son Y-S, Jeong J-H, Lee HJ, et al. A novel control system for nitrogen dioxide removal and energy saving from an underground subway stations. Journal of Cleaner Production, 133, 212-219 2016.

[21] Zhou H. Present Situation and Prospect of Air Purification Present Situation and Prospect of Air Purification Technology in Shanghai Rail Transpiration System. Environmental Science and Management 2018; 43: 57–62.

[22] Choi S in, Feng J, Kim SB, et al. Magnetization of Metal Mesh for Fine Dust Capture. Aerosol Air Qual. Res. 2018; 18: 1932–1943.

[23] James C and Markus B. Towards a dynamic evacuation system developing methodologies to simulate the evacuation capabilities of subway stations in response to a terrorist attack with CBRNE weapons. Chinese Journal of Burns Wounds & Surface Ulcers 2014; 1: 109–118.

[24] Brüne M, Charlton J, Pflitsch A, et al. The Influence of subway climatology on gas dispersion and the effectiveness of guided evacuations in a complex subway station. metz 2016; 25: 489–499.