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Research on the Influence Mechanism of Outdoor Wind Environment on Indoor Smoke Exhaust Efficiency in the Super-High-Rise Tower Crown Based on Airpak Simulation

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Abstract: The high wind pressure and velocity of the outdoor environment make super-high-rise tower crown space distinct from general tall through space. This segregation causes the crown space to be particularly prone to smoke short-circuiting influenced by the outside wind environment if a fire occurs indoors, and causes deficient smoke exhaust efficiency in a fire. The goal of this study was to investigate the general principle regarding the effect of the outdoor wind environment on smoke exhaust efficiency of such spaces under the crown space. We measured external wind direction and wind pressure in the smoke exhaust in the tower crown and developed setting plans for the exhaust outlets and make-up air inlet. Airpak was used to create the external wind environment and compare simulations to see if smoke short-circuiting occurred. We analyzed the causes, summarized solutions that did not result in short-circuiting of smoke flow, and made adjustments. We provide an ideal plan for the setting direction and vent velocity of the make-up air inlet and exhaust outlet in the crown spaces of super-tall towers to improve the design of smoke exhaust systems in such spaces.

Keywords: super-high-rise tower crown; wind environment; Airpak simulation; smoke exhaust optimal design

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1. Introduction

The development of the super-high-rise tower crown has evolved from early architectural image signage to the present, and has been presented a variety of composite functions such as integrating overlook, experience, exhibition, performance viewing, and dining. With the development of super-high-rise buildings and the increase in their height, the frequency of fires is also increasing. Because of the elevation of super-high-rise tower crowns, high external wind velocity, and strong surface wind pressure, the short-circuiting of smoke flow frequently occurs; short-circuiting significantly reduces smoke exhaust efficiency. Research on the external wind environment of super-high-rise buildings has been focused primarily on the effect of building form and facade shape on the airflow field and the effect of wind pressure on super-high-rise structures [1]. Research on the effect of the airflow field on the smoke exhaust is less prevalent. Some researchers have focused on smoke extraction equipment and examined the smoke exhaust outlet, smoke volume, and fan selection for tower crown spaces. Kun et al. [2] analyzed and summarized the common problems of China's smoke prevention and exhaust systems. Cheng [3] discussed the relationship between the maximum smoke exhaust volume of a single smoke exhaust port and the thickness of the smoke layer based on the standard data and fluid mechanics calculations. Xin [4] introduced the design points of the smoke exhaust system and discussed the selection of fans. Li et al. [5] analyzed various types of smoke exhaust fans according to the resistance of the air duct for different smoke prevention zones. Nevertheless, the foregoing studies did not include consideration of the external wind environment.

Research on smoke short-circuiting has been focused only on the tall space within 50 m above the ground [6]. The tower crown space is hundreds of meters above ground, which leads to stronger external wind velocity and a more complex airflow field and more serious short-circuiting of smoke flow. Thus, research is needed to assess the effects of the location, size, and air volume of the tower crown space's make-up air inlet and exhaust outlet.

The velocity, area, setting height, and position of the make-up air inlet and the exhaust outlet have also been studied. Fang [7] used CFD (computational fluid dynamics) to simulate the setting direction of the air vents on the refuge floor and proposed that the smoke exhaust vents should be set on the leeward side. Li [8] took the height of the smoke exhaust outlet as a variable, and by comparative experiments, she found that the exhaust efficiency of the outlet at the middle height of the building was better than at the top. George and Jain [9] proposed that the supplementary wind velocity should not be too high. The velocity of the make-up air should not be too large. When it exceeds a certain level, smoke leakage occurs, which is not conducive to exhaust. Li [10] proposed that the smoke exhaust effect was best at 75% of the mechanical air supply. Sun [11] proposed that the height of the supplementary air outlet was directly proportional to the smoke exhaust efficiency. Zhou et al. [12] proposed that the relative position of the make-up air inlet and the exhaust outlet affect the efficiency of the smoke exhaust. Dongmei et al. [13] used an FDS (fire dynamics simulator) to simulate the Influence of the orientation of the exhaust outlet on the smoke exhaust efficiency; they found that the smoke exhaust effect was best when the exhaust outlet was on the side wind side.

In current fire prevention regulations, the smoke exhaust in tall space is mainly concerned with partitions, exhaust volume, vents, and outlets. Specific rules are set for smoke exhaust volume and smoke exhaust outlet in the atrium, but no clear regulation is set regarding the smoke-proof and smoke-exhaust design of crown space. Both the tower crown and the towering atrium feature contain large space characteristics, to some extent. However, because of the tower crown space's unique external wind environment and continuous space characteristics, a significant pressure difference exists between the interior and the windward and leeward sides, and the exhaust outlet, smoke exhaust volume, and smoke exhaust equipment are all distinct from other tall spaces.

In order to explore the influence of short-circuiting on the smoke exhaust facilities in the super-high-rise tower crown space, optimize the smoke exhaust design, and determine the influence of external wind direction and wind pressure on the smoke exhaust in the tower crown space, we discuss how improper setting of the wind direction or the relative position of the vents leads to short-circuiting and how the high wind pressure on the vent's surface reduces exhaust efficiency. We used Airpak to simulate the external wind environment and describe alternative exhaust outlet and make-up air inlet setting plans. We compared simulations, analyzed the reasons for the short-circuiting of smoke flow, and devised plans for vent velocity that did not short-circuit. Lastly, we calculated the flow rate and velocity of the exhaust outlet and make-up air inlet under the influence of wind pressure for plans that were less likely to cause short-circuiting of smoke flow.

2. Outdoor Airflow Short-Circuiting and External Wind Pressure Texture of Super-High-Rise Tower Crown

In a fire, when the indoor smoke is discharged outside, the exhaust outlet fan is subject to the external wind direction, resulting in the exhaust smoke being sucked into the room by the make-up air inlet, that is, a "short-circuiting" of the outdoor smoke (see Figure 1). Many factors contribute to smoke short-circuiting, such as the horizontal and vertical distance between the exhaust outlet and the make-up air inlet and the atmospheric conditions [6]. The external wind velocity at the super-high-rise tower crown is significantly greater than that at the low building area; thus, compared with the low area, at the crown, the wind direction has a greater effect on the smoke dispersion range. If the exhaust outlet and make-up air inlet of the tower crown space are set improperly, smoke short-circuiting is more likely to occur. On the windward side of the tower crown, airflow is distributed upward, downward, and to both sides (see Figure 2). The vertical airflow propels the discharged smoke from the lower zone upward, while the horizontal and vertical airflows create vortices at the building's corners, spreading the discharged smoke to the area surrounding the make-up air inlet and easily pulling the discharged smoke back into the tower crown space.

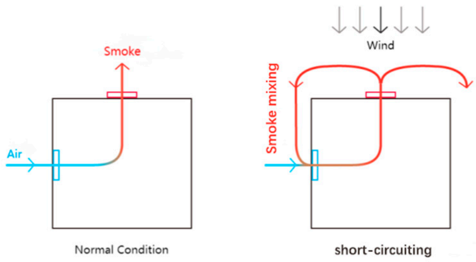


Figure 1. Smoke short-circuiting caused by external factors.

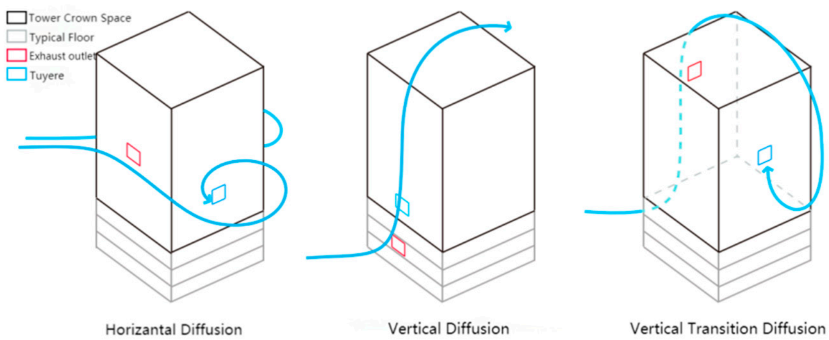


Figure 2. Effect of airflow field outside tower crown on smoke dispersion.

The exceptionally high external wind pressure at the super-high-rise tower crown varies with seasonal wind velocity, leading to a mismatch between the exhaust fan's set power and the wind pressure on the building surface. When a fire breaks out inside, the smoke exhaust system must produce adequate exhaust in the presence of exterior interference [14]. Furthermore, to create a visually towering and transparent appearance, the tower crown space is distinct from the high-rise building's standard floors. The inside cannot be split by fire barrier walls, which lead to a significant pressure difference between the interior and the windward and leeward sides; the area becomes even more integrated, which further boosts the vent pressure, thereby requiring stringent control of fan power [15]. By changing the orientation of the smoke exhaust port and the air supply port, combined with the external wind environment, we conducted a comparative simulation in which the smoke exhaust port and the air supply port were located on either the same side, adjacent side, or opposite side. This simulation was conducted to identify which exhaust outlet and make-up air inlet setting plan best avoids smoke short-circuiting and whether changing the orientation of the vents is an effective way to reduce the effect of wind pressure on the fan.

3. Methods

3.1. Introduction to Software

Airpak is professional environment simulation software that has a sound visual interface and the unique advantage of precisely simulating the motion of a flow field surrounding an item, heat transfer, and pollutant dispersion. Airpak provides a variety of mesh generation methods, so the user can freely choose the appropriate method according to the actual situation of the model. Airpak is also equipped with the Per-object meshing parameters function, which can be used to encrypt the mesh for specific objects individually to improve computational accuracy. In terms of calculation, Airpak is capable of both steady-state and non-steady-state calculations. Airpak is equipped with a variety of computational models. Airpak is also embedded with the most powerful CFD solver on the market today: FLUENT, for accurate and fast model solving [16]. Airpak has multiple applications in architecture. Airpak can simulate the external wind and heat environment of urban buildings and residential quarters, predict the dispersion of pollutants such as urban haze, and simulate a building's external wind environment, indoor wind pressure, wind velocity, temperature, and air age [17]. Zhang used Airpak to verify that ventilation configuration has a large influence on the distribution of condensation on wall surfaces [18]. In this study, Airpak was used to simulate the exterior wind environment of super-high-rise tower crown space and obtain crucial data from the exhaust outlet. Smoke short-circuiting was determined by introducing pollutants into the smoke flow and following the course of flow.

3.2. Comparative Simulation Plans

The simulation was conducted on two levels. First, we used Airpak to simulate the wind environment within 500 m of the super-high-rise building and to obtain data such as airflow field, velocity, and wind pressure at the building's surface. Second, the simulation used an exhaust outlet and make-up air inlet in different directions and positions relative to the tower crown space to create a contrasting smoke exhaust design. Then, we placed the tower crown space of each plan into the wind environment to obtain the airflow's movement trajectory and velocity and eliminate similar plans. Third, we incorporated the trajectory of pollutant particle movement, which determined in which plan(s) the smoke short-circuiting occurred.

Lastly, for the simulation of the effect of wind pressure and identifying plans lacking short-circuiting, Formula (1) was used to calculate the wind pressure at the vent from the pressure differential between the inside and outside of the vent. Formula (2) was used to calculate the vent flow rate under the effect of the surface wind pressure on the fan. To obtain the vent change velocity, the absolute value of the difference between the air outlet flow rate affected by the wind pressure and the fan set flow rate under static pressure was divided by the vent area. This velocity value was added to set the velocity vent under static pressure, and the revised vent velocity was calculated using Formula (3). Two low-noise cabinet centrifugal fans were selected for the simulation scene as the setting parameters of the smoke exhaust fan and the make-up air fan. The fan performance parameters are shown in Table 1.

$$P_1 = \Delta P + P\ (\mathrm{Pa}) \tag{1}$$

$$Q_1 = P_{fan} \times 1000 \times n_{exhaust}/P1\ (\mathrm{m^3/s}) \tag{2}$$

$$V = |(Q_0 - Q_1)/S| + V_0\ (\mathrm{m/s}) \tag{3}$$

Table 1. Fan performance parameters.

Fan	Rotating Speed (r/min)	Fan Flow (m^3/h)	Full Pressure (Pa)	Static Pressure (Pa)	Fan Power (KW)
make-up air fan	800	18,170	867	763	7.5
exhaust fan	650	37,670	978	804	15

In the formula, P_1 represents the wind pressure at the vent surface, ΔP is the pressure difference between the inside and outside of the vent, P represents the static pressure of the fan, Q_1 is the vent flow under external wind, P_{fan} is the fan, $n_{exhaust\ fan}$ is the efficiency ($n_{exhaust\ fan}$ is 0.5625, $n_{make\text{-}up\ air\ fan}$ is 0.5287), Q_0 is the fan flow, S is the vent area, V_0 is the vent velocity under static pressure ($V_{exhaust\ fan}$ is 10 m/s, $V_{make\text{-}up\ air\ fan}$ is 5 m/s), and V represents the revised vent velocity. The results of the formula determine the optimal orientation and vent velocity of the make-up air inlet and exhaust outlet in the super-high-rise building tower crown space.

Thus, we can determine the ideal direction settings for the exhaust outlet and make-up air inlet, and the setting range for the fan velocity. Figure 3 depicts the simulation procedure for the comparison of plans.

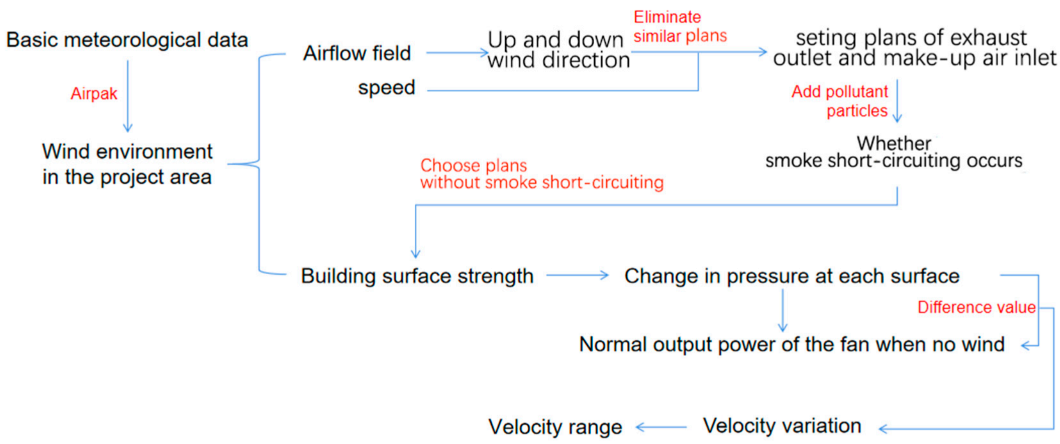


Figure 3. Schematic diagram of the simulation plan.

3.3. Construction of an Abstract Geometric Model

The simulation was modeled after the Ping An Financial Center in Shenzhen, actual scene as seen in Figure 4. This simulation's geometric model represented the tower crown region (height 512–600 m) as an abstract space of 60 m in length, 60 m in width, and 88 m in height. With this model as the focal point, we chose the surrounding region of 500 m as the simulation area, i.e., 4800 m $\times$ 6000 m $\times$ 1800 m was the computation area. To ensure that the simulation was accurate, we set the minimum mesh size to 0.52 m, and the maximum was 3.3 m. Local mesh refinement was conducted in the boundary area of the tower crown to ensure that there were 10 meshes on each boundary (see Figure 5). We consulted the Special Meteorological Data Set for Thermal Environment Analysis in Buildings of China, with a focus on the Shenzhen area. On the basis of the average wind velocity, wind direction frequency, and other parameters of a typical meteorological year, we chose for the boundary condition the winter wind it has the most unfavorable velocity for smoke exhaust. Its wind velocity was 3.4 m/s at a height of 10 m, and the wind direction was north–northeast [19]. To establish the actual wind field situation outside the tower crown, the wind velocity simulation employed a gradient wind setting and selected the parameters of the atmospheric boundary layer in the urban core area provided by Airpak; the ground roughness was set to 0.33 [20] and the boundary layer thickness was 1800 m (see Table 2). As shown in Figure 6, the wind velocity below the 460 m boundary layer changed proportionally to the height, whereas the wind velocity was held constant at 15.54 m/s as it reached 472 m, which shown in Figure 6 red dashed line. We used the numerical simulation approach of the k-ε two-equation model to simulate the wind environment around the building plan according to the dominant wind direction and wind speed in Shenzhen in a year. The k-ε two-equation model was proposed by Launder and Spalding in 1972. The advantage of the k-ε model is that the solution of the equations can be solved only by knowing the boundary conditions and initial conditions [21].

Figure 4. Actual scene [22].

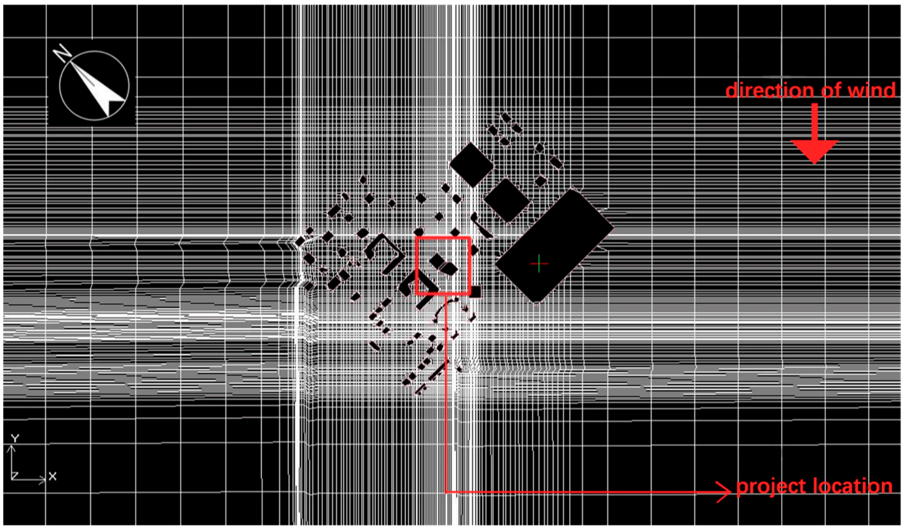


Figure 5. Meshing set-up.

Table 2. Airpak simulation basic settings.

Computational Field Size	4800 m × 6000 m × 1800 m
Project building size	60 m × 60 m × 600 m
Tower crown space size	60 m × 60 m × 88 m
Inlet boundary condition	Velocity-inlet
Outlet boundary condition	Outflow
Surface boundary conditions	No-slip wall
Wall boundary condition	No-slip wall
Meshing	Hexahedral unstructured mesh
Turbulence Model	k-ε two-equation model
Wind direction	NE
10 m high wind velocity	3.4 m/s
Ground roughness	0.33
Boundary layer thickness	1800 m

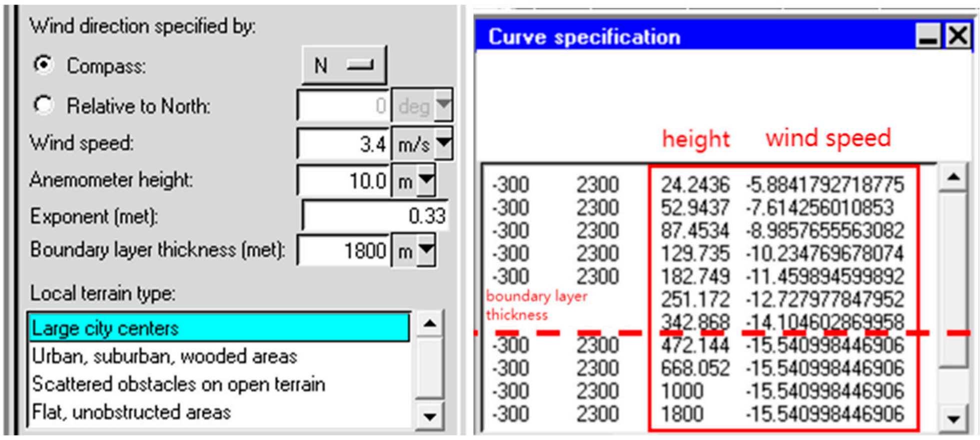


Figure 6. Set-up of atmospheric boundary layer and gradient wind.

Several exhaust outlets and make-up air inlets that fulfilled the requirements of the standard were installed according to the configuration requirements in the Technical Standards for Smoke Prevention and Exhaust Systems in Buildings [23]. In different directions and position, 12 groups of exhaust outlets and make-up air inlet were set (see Table 3 and Figure 7). When arranged horizontally on the same side, the make-up air inlet was at the bottom and the distance between the left and right edges of the smoke outlet was 5 m. When arranged vertically on the same side, the make-up air inlet was at the bottom and the distance between the upper and lower edges of the exhaust outlet was 5 m. When arranged on the adjacent side, the make-up air inlet and exhaust outlet were set on the adjacent facade, and the bottom edge was located 2 m from the vertical center line, and the horizontal edge spacing was greater than 10 m. When arranged on the opposite side, the make-up air inlet and the exhaust outlet were set on the opposite facade; the bottom edge was 2 m from the vertical center line and the horizontal edge spacing was greater than 10 m.

Table 3. Airpak simulation variables.

Position	**Specification**	**Make-Up Air Inlet**	**Exhaust Outlet**
		Size: Length 1 m × Width 0.5 m × 6 (pcs) **Wind Velocity: V = 5 m/s**	**Size: Length 1 m × Width 0.5 m × 6 (pcs)** **Wind Velocity: V = 10 m/s**
Same side	Horizontal	Side 2.5 m left (right) of vertical center line Bottom edge 2 m from the vertical centerline of the facade	Side 2.5 m to the right (left) of the vertical center line Bottom edge 3 m from the vertical centerline of the facade
	Vertical	Bottom edge 2 m from the vertical centerline of the facade	Bottom edge 8 m from the vertical centerline of the facade
Adjacent side		Bottom edge 2 m from the vertical centerline of the facade	Bottom edge 2 m from the vertical centerline of the facade
Opposite side		Bottom edge 2 m from the vertical centerline of the facade	Bottom edge 2 m from the vertical centerline of the facade

There were defined criteria for the amount of smoke exhaust volume in the specification, but no standards were set for the size and quantity of exhaust outlets. We chose a rectangular air exit in Ventilation and Air-conditioning Vent JG/T14-2010 sized 1 m by 0.5 m that had a height-to-width ratio of 1:2. There were six smoke outlets, three in each of two rows, with a total surface area of 3 m^2 [24].

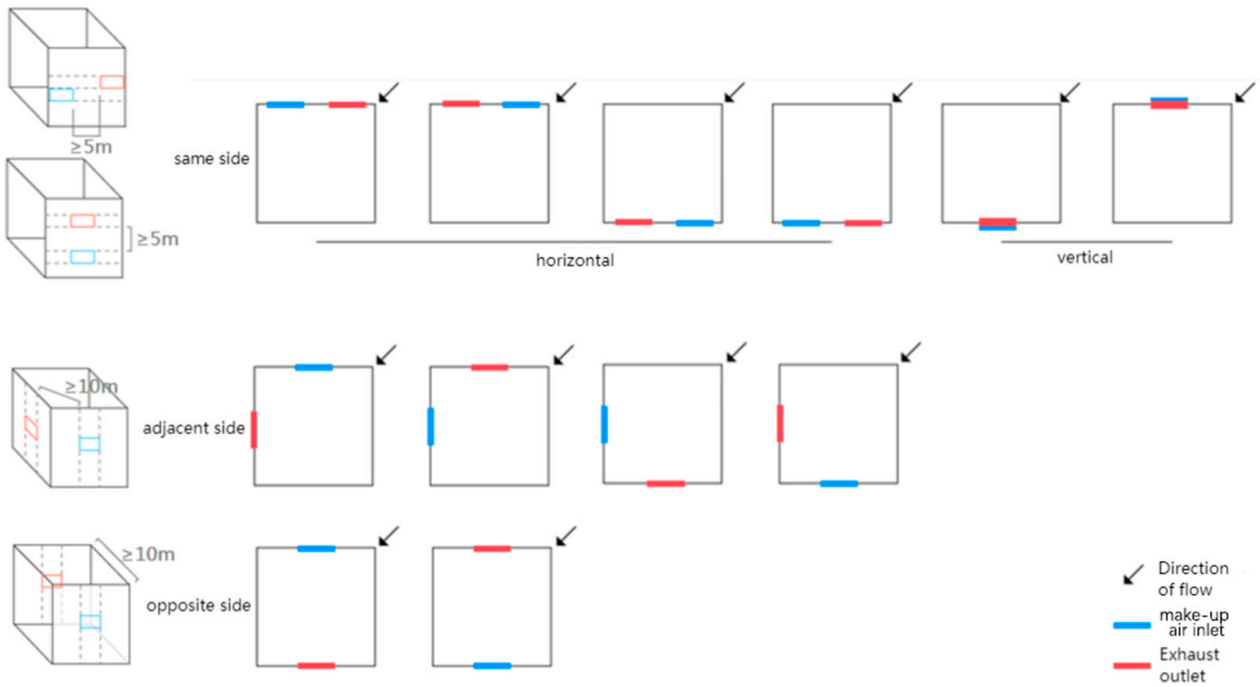


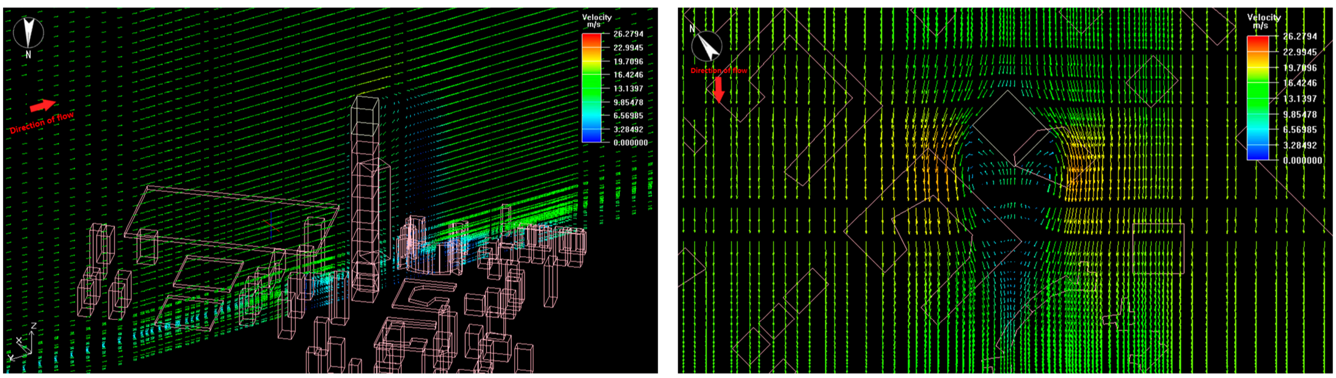
Figure 7. Schematic diagram of the simulation scene.

4. Results

4.1. External Wind Environment of Tower Crown Space

4.1.1. Outdoor Airflow Field

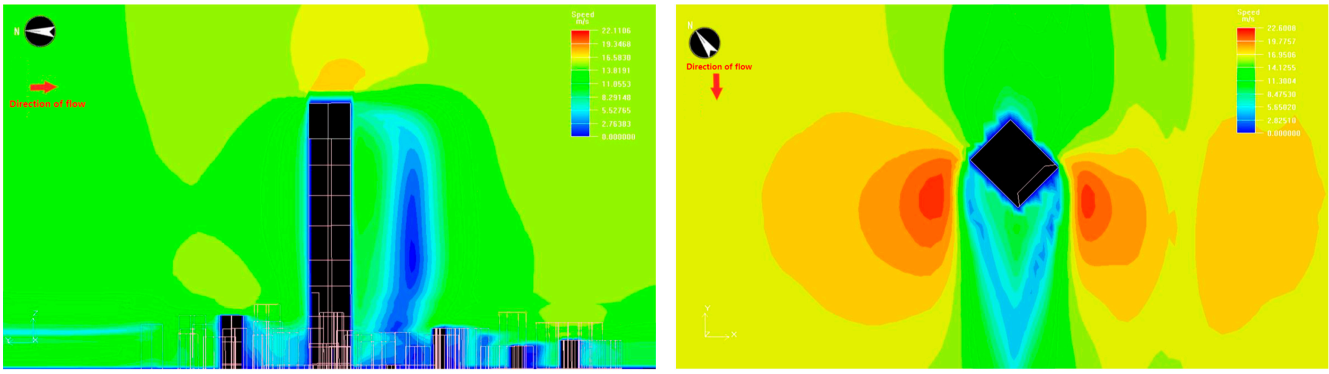
Figure 8 shows the distribution of flow field. The airflow at a height of 500 m had obvious three-dimensional properties. In the vertical direction, air flowing through buildings ascended approximately 400 m and formed a downward reflux after crossing the top of the tower crown. Another part of the airflow moved downward due to obstruction by the building at a height of about 200 m. In the horizontal direction, the windward surface at the northeast corner of the building formed a 45-degree included angle with the airflow, which then bypassed both sides of the building and traveled to the southwest and converged 100 m southwest of the building. The airflow in contact with the building generated two vortices with different directions of rotation at the northwest and southeast corners, and an airflow opposed to the incoming flow on the leeward side of the building.



(a)Distribution of vertical airflow field (b)Distribution of horizontal airflow field at Z=500 m

Figure 8. Distribution of flow field.

Figure 9 demonstrates the distribution of wind velocity. On the windward side, the airflow diverged upward, downward, and to the sides, leading to higher wind velocity at the top and sides. The wind velocity on the windward side of the building was 11 m/s in the vertical direction at a height of 400 m. The wind velocity reached 19 m/s at the top of the tower crown, increased from 8 m/s to 12 m/s between 550 and 400 m, and then fell to 3 m/s at a height of 2 m from the ground. The tower crown split the airflow on the windward side into west and south in the horizontal direction. At the northwest and southeast corners, two vortices took form with opposite rotations. The wind velocity rose from 12 m/s to 20 m/s. The vortex at a velocity of 10 m/s was on the building's leeward side (southwest corner) in the opposite direction of the incoming flow.



(a)Distribution of wind velocity in the vertical direction (b)Distribution of wind velocity in the horizontal direction at Z=500 m

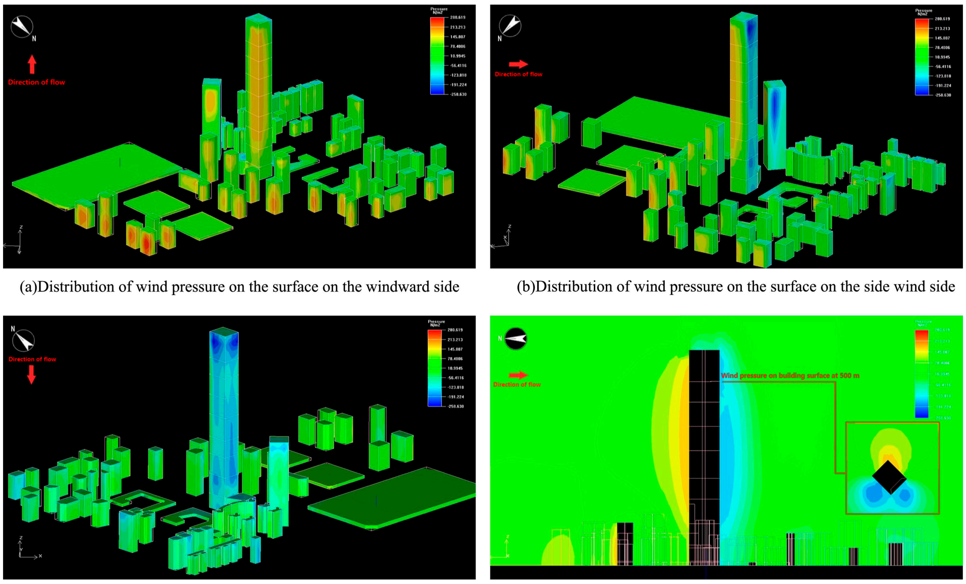
Figure 9. Distribution of wind velocity.

4.1.2. Pressure on Building Surface

Figure 10 shows the distribution of wind pressure for buildings within 500 m of Ping An Financial Center, with the wind pressure distribution on the building surface wind northeasterly downward in winter. Figure 10a demonstrates that, under this climatic wind velocity condition, the windward side of the building was not obstructed by tall buildings, and the majority of places on the windward side were subject to positive pressure, with a maximum value between 300 m and 400 m in height. The highest wind pressure was 170 Pa, although the wind pressure coefficient value near the edge and bottom of the side was miniscule, with a 150 Pa difference. As seen in Figure 10b, there was an obvious pressure difference on the sides (north and west facades), but the overall pressure difference did not increase positively with height due to the effect of the adjacent super-tall building to the south of the project building. Because of the super-high-rise building adjacent to the south of the project building, the pressure difference between the front and rear of the building at heights below 400 m increased with height, and above 400 m first decreased and then increased. As seen in Figure 10c, because the leeward side (west, south facade) was in the wind shadow area, the surface wind pressure was basically negative. Because of the influence of the adjacent buildings in the south direction, two opposite eddies were formed on the leeward side of the tower crown. As seen in Figure 10d, the leeward wind pressure reached a maximum of −258 Pa here and a minimum of −90 Pa at 270 m of the building, with a difference of 168 Pa.

4.2. Flowing Rules of Smoke under the Effect of Wind Environment

Table 4 shows the experimental results. There are a total of 12 plans, of which 6 plans have no smoke short-circuiting. According to the simulation results, plans 3, 4, and 6 with the same side arrangement of the vent on the leeward side were prone to smoke short-circuiting. There was a chance that smoke short-circuiting would occur in plans 1 and 7, where the same or adjacent side was situated on the windward side and the exhaust outlet was in the upwind direction. The other plans were less prone to smoke short-circuiting. Refer to Table 4 for details.



(a)Distribution of wind pressure on the surface on the windward side (b)Distribution of wind pressure on the surface on the side wind side

(c)Distribution of wind pressure on the surface on the leeward side (d)Distribution of wind pressure on the surface at Z=500 m

Figure 10. Distribution of wind pressure.

Table 4. Direction setting and smoke dispersion direction.

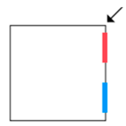
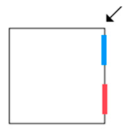
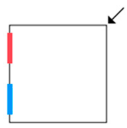
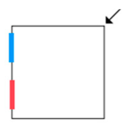
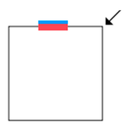
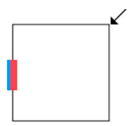
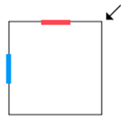
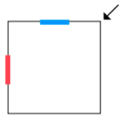
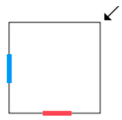
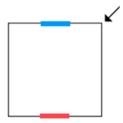
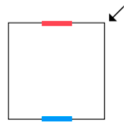
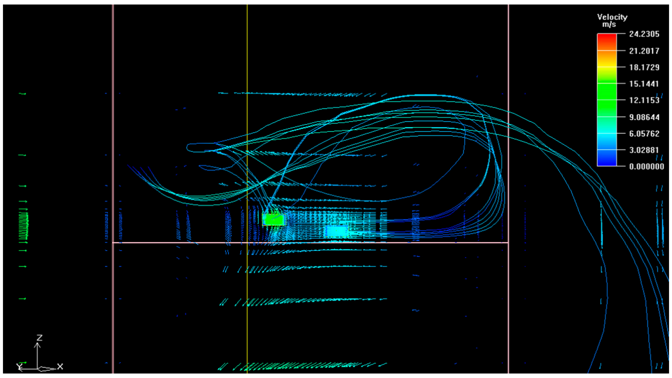
Position		No.	Diagram	Make-Up Air Inlet Direction	Exhaust Direction	Short-Circuiting
Same side	Horizontal	1		After touching the building, the incoming flow rises along the surface and is sucked into the make-up air inlet.	After being discharged, the smoke flows southward over the building surface while also moving upward due to the northeast flow. However, some of the smoke is likely to be sucked indoors.	Likely
		2		After the incoming flow touches the building, it moves upward along the surface and is sucked into the make-up air inlet.	The smoke flows westward along the building surface after being discharged, while also moving upward due to the effect of the northeast flow.	×
		3		A vortex is formed when the incoming flow passes through the building's corner, and the mixed component of the smoke is sucked into the make-up air inlet.	After being discharged, the smoke rises and is affected by horizontal and vertical eddy currents, with a portion of the smoke being sucked into the make-up air inlet.	√
		4		A vortex is formed as the incoming flow passes through the building's corner, and the smoke is rolled back to the make-up air inlet.	After being discharged, the smoke flows to the south, where it is affected by the horizontal vortex, and a portion of it is rolled back and sucked into the make-up air inlet.	√
	Vertical	5		After the incoming flow touches the building, it moves upward along the surface and is sucked into the make-up air inlet.	The smoke flows westward along the building surface after being discharged, while also moving upward due to the impact of the northeast flow.	×
		6		A vertical vortex is formed once the incoming flow passes through the top of the tower crown, the airflow continues downward, and the smoke is sucked into the make-up air inlet.	After being discharged, the smoke travels southwest along the building surface, where it is affected by the vertical eddy current and sucked into the make-up air inlet.	√

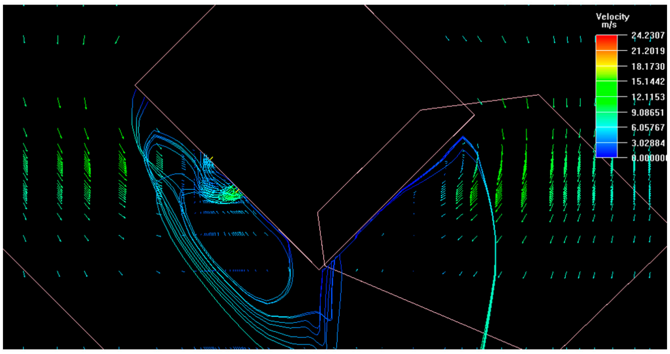
Table 4. *Cont.*

Position	No.	Diagram	Make-Up Air Inlet Direction	Exhaust Direction	Short-Circuiting
Adjacent side	7		A vertical vortex is formed once the incoming flow passes through the top of the tower crown, the airflow continues downward, and the smoke is sucked into the make-up air inlet.	Smoke flows westward when it is released. Some of the smoke is rolled back as a result of the horizontal and vertical eddy currents. It is likely to be sucked up by the make-up air inlet, despite moving downward on the leeward side.	Likely
	8		After the incoming flow touches the building, it moves upward along the surface and is sucked into the make-up air inlet.	After the smoke is discharged, it flows southward over the building surface, while the wind moves downward under the effect of the vertical vortex.	×
	9		A vertical vortex is formed once the incoming flow passes through the top of the tower crown, the airflow continues downward, and the smoke is sucked into the make-up air inlet,	After the smoke is discharged, it flows southward over the building surface, while the wind moves downward under the effect of the vertical vortex.	×
	10		Same as plan 9.	Same as plan 9.	×
Opposite side	11		After the incoming flow touches the building, it moves upward along the surface and is sucked into the make-up air inlet.	After the smoke is discharged, it flows southward over the building surface, while the wind moves downward under the effect of the vertical vortex.	×
	12		A vertical vortex is formed once the incoming flow passes through the top of the tower crown, the airflow continues downward, and the smoke is sucked into the make-up air inlet.	The smoke travels westward after it is discharged. Part of the smoke is rolled back and flows downward on the leeward side as a result of the horizontal and vertical eddies.	×

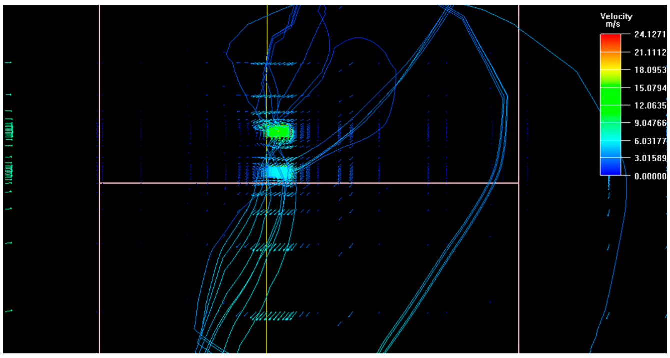
In plan 3, the incoming flow formed a vertical vortex by passing through the tower crown top, and the airflow then traveled downward after crossing the tower crown. The smoke was discharged and it formed a reflux with the downward flow above the exhaust outlet. Additionally, the horizontal vortex generated by the incoming flow passing through the building's corner allowed some of the smoke to be sucked into the make-up air inlet (see Figure 11a). When the incoming flow passed through the corner of the building in plan 4, a horizontal vortex formed, and the smoke traveled southward after being discharged. Part of the smoke was rolled back and sucked into the make-up air inlet as a result of the horizontal vortex (see Figure 11b). After the smoke was exhausted, it flowed southwestward along the building surface, and some of it was blown down by the air flow over the tower crown to the make-up air inlet, where it was sucked indoors again (see Figure 11c). Plans 3, 4, and 6 had their make-up air inlet and exhaust outlets on the leeward side; due to the effect of horizontal or vertical eddies, the make-up air inlet was in the downwind direction. Part of the exhaust gas rolled back to the vicinity of the make-up air inlet by the airflow due to the close distance between edges of the two vents before being sucked indoors again.



(a)Plan 3 Vertical airflow field and particle trajectories at the tuyere



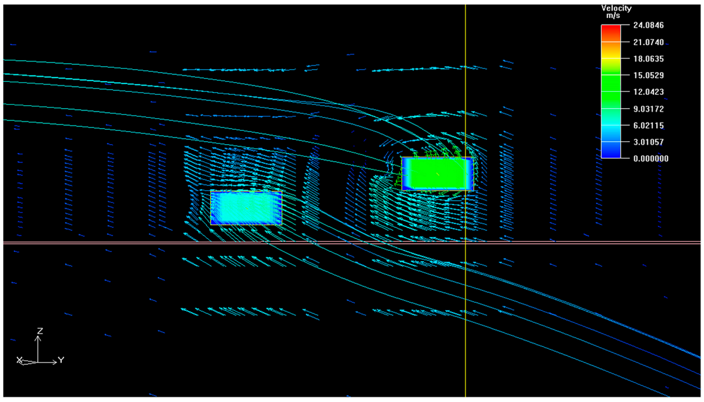
(b)Plan 4 Horizontal airflow field and particle trajectories at the tuyere



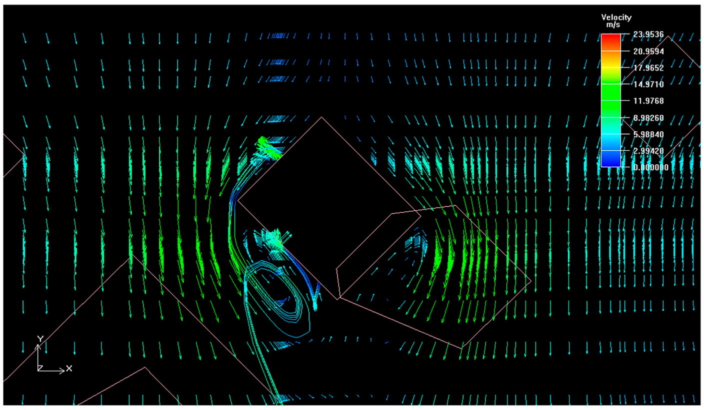
(c)Plan 6 Vertical airflow field and particle trajectories at the tuyere

Figure 11. Airflow field of plans with smoke short-circuiting.

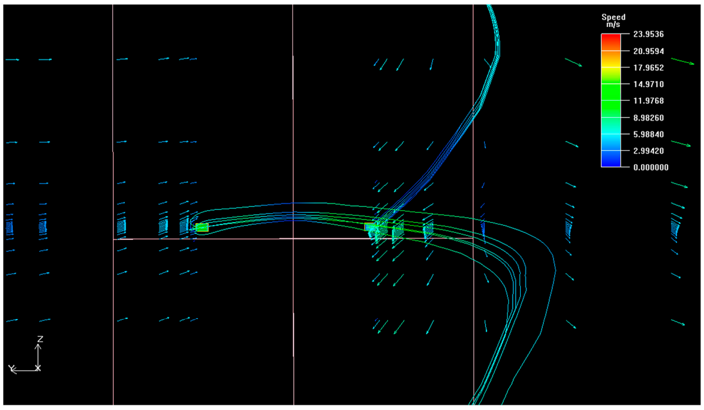
In plan 1, the northeast incoming flow was blocked by the building; it flowed upward along the surface of the tower crown, sucking fresh air into the make-up air inlet. The smoke that escaped from the exhaust outlet on the right side of the building went southward along the building surface, while the incoming flow influenced the smoke and caused it to move only slightly upward along the surface of the building. Because the two vents were on the same side of the room, there was a good chance that some smoke would be sucked into the room if they were too close together (see Figure 12a). The make-up air inlet was on the leeward side in plan 7, and the incoming flow moved downward beyond the top of the tower canopy, delivering air into the make-up air inlet. The exhaust outlet was on the windward side and, after being discharged, the smoke moved westward. The smoke rolled back horizontally on the leeward side (see Figure 12b) and moved downward vertically under the effect of the horizontal and vertical vortexes (see Figure 12c). The smoke was likely sucked into the make-up air inlet.



(a)Plan 1 Vertical airflow field and particle trajectories at the tuyere



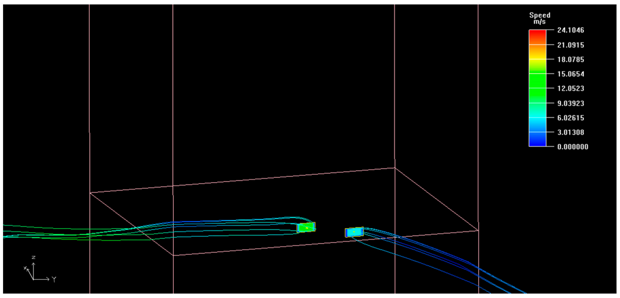
(b)Plan 7 Horizontal airflow field and particle trajectories at the tuyere



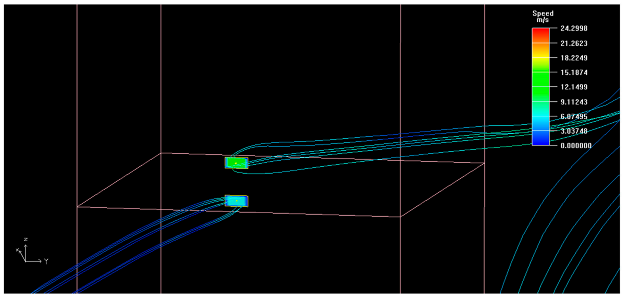
(c)Plan 7 Horizontal airflow field and particle trajectories at the tuyere

Figure 12. Airflow field of plans with possibility of smoke short-circuiting.

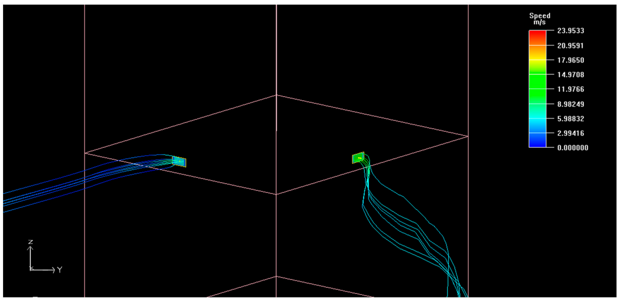
Plans 2, 5, 8, 9, 11, and 12 did not exhibit smoke short-circuiting, and the flow direction of the make-up air inlet and the exhaust outlet was clear (see Figure 13).



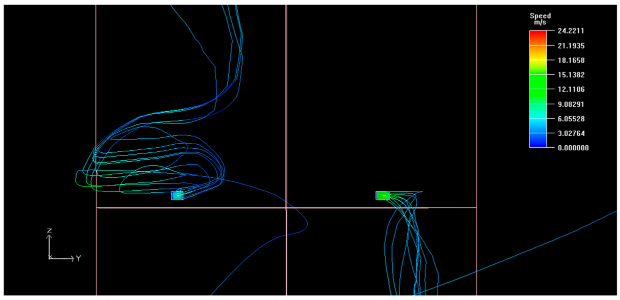
(a)Particle trajectory at the tuyere in plan 2



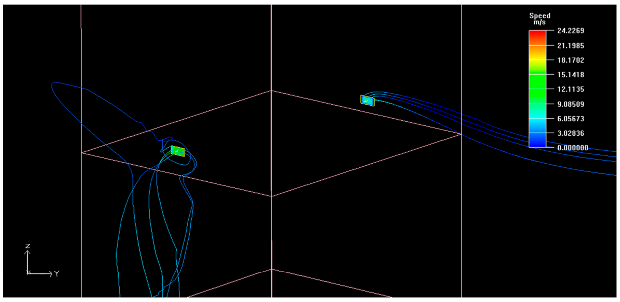
(b)Particle trajectory at the tuyere in plan 5



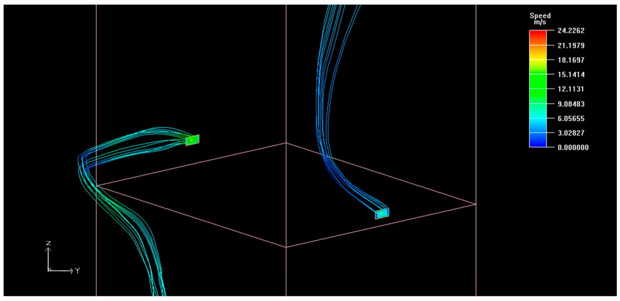
(c)Particle trajectory at the tuyere in plan 8



(d)Particle trajectory at the tuyere in plan 9



(e)Particle trajectory at the tuyere in plan 11



(f)Particle trajectory at the tuyere in plan 12

Figure 13. Particle trajectory.

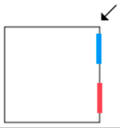
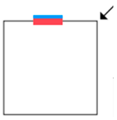
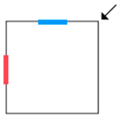
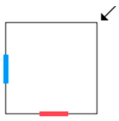
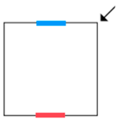
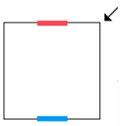
4.3. Effect of Pressure on Velocity at Make-up Air Inlet and Exhaust Outlet

4.3.1. Airflow and Corrected Velocity of Make-up Air Inlet and Exhaust Outlet under the Effect of Air Pressure

On the basis of the simulation findings, we screened six types of setup plans for the exhaust outlet and make-up air inlet that were unlikely to produce smoke short-circuiting. Table 5 shows the direction, inside and outside differential pressure, and flow rate of the exhaust outlet and make-up air inlet, and the flow rate and velocity of the exhaust outlet and make-up air inlet were calculated under the effect of their wind pressure.

The maximum difference between the correction velocity of the make-up air inlet and the original wind velocity occurred when the internal and external pressure difference was −70 Pa, and the maximum difference between the correction velocity of the exhaust outlet and the original wind velocity occurred when the internal and external pressure difference was 70 Pa.

Table 5. Parameters of air outlets.

Position		No.	Graphics	Type	Inside and Outside Pressure Difference (pa)	Air Flow (m^3/s)	Original Speed(m/s)	Revised Velocity (m/s)
Same side	Horizontal	1		Make-up air inlet	−150	6.469	5	3.531
				Exhaust outlet	150	8.844	10	11.156
	Vertical	2		Make-up air inlet	−150	6.469	5	3.531
				Exhaust outlet	150	8.844	10	11.156
Adjacent side		3		Make-up air inlet	−150	6.469	5	3.531
				Exhaust outlet	70	9.654	10	10.346
		4		Make-up air inlet	−70	5.722	5	4.278
				Exhaust outlet	70	9.654	10	10.346
Opposite side		5		Make-up air inlet	−150	6.469	5	3.531
				Exhaust outlet	70	9.654	10	10.346
		6		Make-up air inlet	150	4.343	5	5.657
				Exhaust outlet	−70	11.495	10	8.505

4.3.2. Simulation of Each Plan after Revising Velocity

We repeated the simulations after substituting the revised vent velocity values into the aforesaid six plans (Table 6). From the vent particle trajectory graphic, the vent flow direction of each plan was clear, there was no intersection, and the plans were conducive for smoke exhaust. The distribution of vent pressure indicated that, when the smoke exhaust system was running, most vent pressures were unevenly distributed. Because of the effect of the external airflow field, the local pressure was too high. After we revised the wind velocity of each vent, the appropriate smoke exhaust volume was achieved.

Table 6. Revised vent pressures and airflow fields.

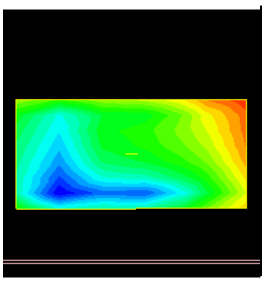
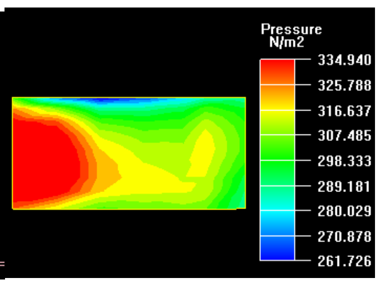
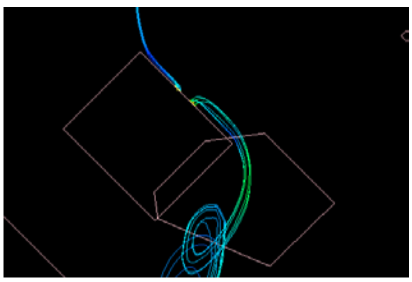
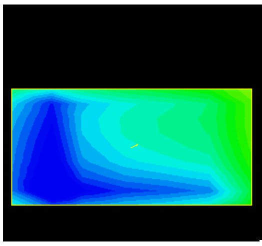
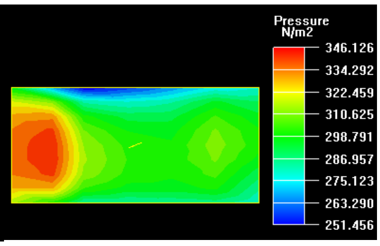
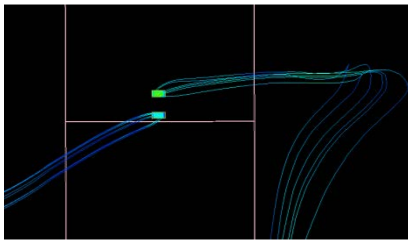
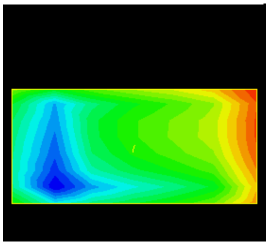
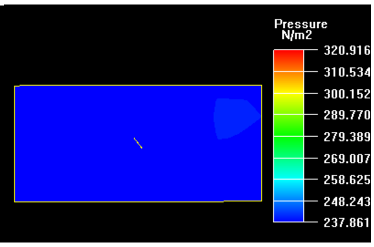
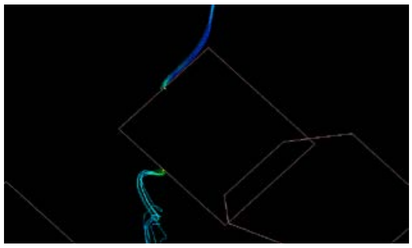
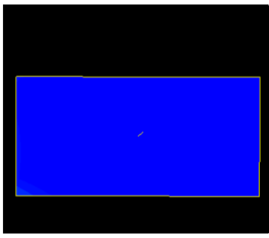
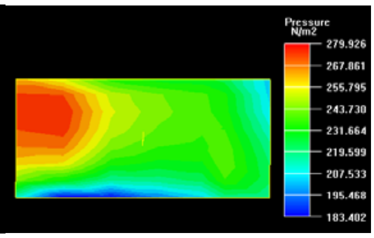
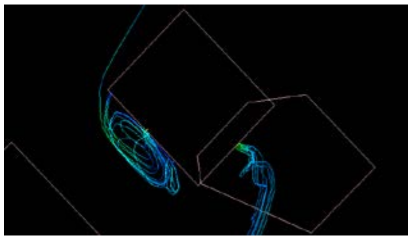
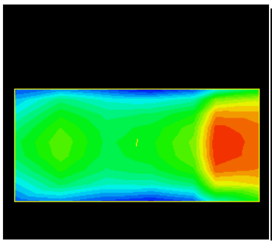
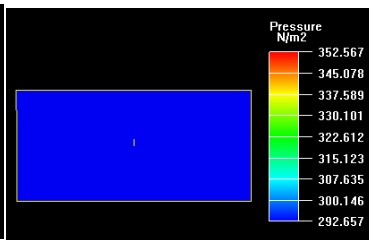
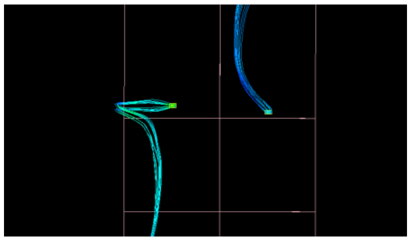
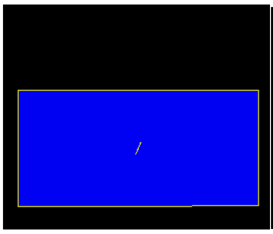
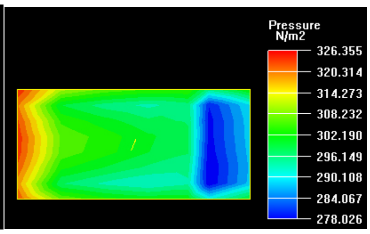
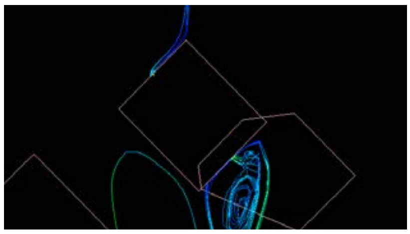
No.	Pressure Distribution at the Vent	Pressure Distribution at the Exhaust Outlet	Particle Trajectory at the Vent
1			

Table 6. *Cont.*

No.	Pressure Distribution at the Vent	Pressure Distribution at the Exhaust Outlet	Particle Trajectory at the Vent
2			
3			
4			
5			
6			

5. Discussion

We determined the effect of external wind direction and wind pressure in the high-rise area on smoke exhaust in the super-high-rise tower crown space. In this section, we discuss the short-circuiting of outdoor smoke flow caused by different wind directions or the relative positions of the exhaust outlet and the make-up air inlet and the high wind velocity. Excessive wind pressure on the surface of the vent affects smoke exhaust efficiency. First, we used Airpak simulation of plans of smoke exhaust outlet and supplementary air outlets with different orientations. We analyzed the direction, velocity, and wind pressure of the external airflow field. We clarified the setting orientation of the smoke exhaust outlet and supplementary air outlet. Second, we used Airpak to simulate the wind pressure on the building surface, the corrected velocity of the fans at the air outlets in all directions were calculated, and we obtained the azimuths and velocity ranges of the air supply outlets and smoke exhaust outlets in the tower crown space.

5.1. Mechanism of Smoke Flow and Effect of Wind Pressure on Vent Velocity

From the simulation results, the plans without smoke short-circuiting can be divided into one of two categories based on their airflow field. The supplementary air outlet was located in the upwind direction of the windward side, in contact with the incoming flow before the exhaust outlet. There was no backflow around the exhaust outlet, and it spread along the downwind direction after exhausting (plans 2, 5, 8, and 11 fit this category). Then, the incoming flow was at a 45-degree angle to the buildings and was dispersed at the northeast corner to form two complementary interfering flows; the make-up air inlet and the exhaust outlets in the two flows did not interfere with each other (plans 9, 11, and 12 fit this category). The make-up air inlet and the exhaust outlet of the three plans that were prone to smoke short-circuiting were located on the leeward side. Because of the horizontal or vertical eddy currents, the air supply port was in the downwind direction. Smoke rolls back to the vicinity of the supplementary air outlet and inhales the room for the second time.

In the plans without smoke short-circuiting, the exhaust volume of each vent met the requirements of the specification after the velocity was corrected. However, because of the effect of external airflow, when the exhaust system is running, the local pressure of most vents is too high, and local windproof components need to be used to reduce the effect of external wind. In addition, because the fan characteristic curve was not a linear function, the fan pressure and flow rate did not change in a gradient manner; thus, the modified vent speed was greater than the actual situation.

5.2. Recommendations for Optimized Setting of Exhaust Outlet and Make-Up Air Inlet under the Effect of External Wind Environment

(1) The exhaust outlet and make-up air inlet should be set on opposite sides, with restrictions when set on the same and adjacent sides.

Simulation findings showed that when the exhaust outlet and make-up air inlet were arranged on opposite sides, no smoke short-circuiting occurred; when arranged on adjacent sides and the exhaust was upstream of the airflow, there was a probability of smoke short-circuiting; when arranged on the same side and on the leeward side, smoke short-circuiting occurred; and on the windward side, when the exhaust was upstream of the airflow, there was a probability of smoke short-circuiting. Therefore, we suggest arranging the exhaust outlet and make-up air inlet on the opposite side. If the adjacent side arrangement is used, the exhaust outlet cannot be upstream of the airflow. If the same side arrangement is used, the exhaust outlet cannot be set on the leeward side and the exhaust outlet cannot be set upstream of the airflow. If the vertical arrangement on the same side is used, the distance between the exhaust outlet and the make-up air inlet should be as large as possible to ensure that the make-up air inlet is not within the range of smoke dispersion when reflux occurs around the make-up air inlet.

(2) Partial windproof components set up at exhaust outlet and make-up air inlet in the tower crown space make-up air inlet.

After revising the velocities of the exhaust outlet and make-up air inlet, we found that the flow rate of each air outlet satisfied the specification criteria. Nevertheless, the air outlet velocity exceeded the specification requirements, and the air outlet area expanded if the air volume remained the same. The pressure distribution at the air outlet indicated that the fan's operation was affected by the external airflow field. Most of the air outlet pressure distribution was uneven, and local pressure was high. Local wind-resistant components can be used to mitigate the effects of external wind.

5.3. Limitations and Prospects

Although simulation techniques are effective means of optimizing smoke extraction systems, they are not fully accurate due to the simplification of the parameters in the experiments. In a fire, the spread of smoke can also be affected by the thermal environment. This factor introduces uncertainty when setting boundary conditions in software simulations, thereby making the simulation difficult to control. The smoke texture deviates to some extent from actual fires. In addition, we did not conduct field experiments because of the limited conditions. In future work, it will be necessary to couple building thermal environment simulations with actual measurement data to obtain more accurate results.

6. Conclusions

On the basis of the spatial characteristics of super-high-rise building tower crowns and the difficulty of smoke prevention and exhaust, we examined the serious short-circuiting of smoke flow in the external environment and the effect of surface wind pressure on smoke exhaust equipment. The location and velocity of the smoke exhaust outlet and the air supply outlet in the crown space were set, and smoke texture simulations were conducted on the configurations. We found that the smoke exhaust outlet and the air supply outlet in the tower crown space should be arranged vertically on the same side. This conclusion can assist fire protection. Our specifications can guide the setting height, orientation, and equipment power of the vents in the smoke prevention and exhaust system of the tower crown space and provide a reference for the design of crown space smoke prevention and exhaust design. Our specific conclusions are the following:

1. Considering the short-circuiting of outdoor smoke flow caused by the external wind direction or improper setting of the relative position of the make-up air inlet and the exhaust outlet, we used Airpak simulations to analyze the airflow direction of the outdoor airflow by setting up smoke exhaust vents and supplementary air vents in different directions in the crown space with regard to velocity and particle trajectory. We concluded that the exhaust outlet and make-up air inlet should be set on opposite sides, with restrictions when set on the same and adjacent sides. The setting and orientation plan of a smoke-free short-circuiting was established.
2. Because excessive wind pressure on the surface of the vents caused by high wind velocity affects smoke exhaust efficiency, we analyzed a wind gradient with Airpak. We simulated the surface wind pressure of the smoke exhaust outlet and the make-up air inlet in each direction. The velocity of the vents and the surface wind pressure were analyzed, the velocity correction of the fan was performed via calculation, corrected 29.38%, 14.44%, and 11.34% for the make-up air inlet, and corrected 11.5%, 3.46%, 14.95% for the exhaust outlet. We obtained the set velocity ranges of the make-up air inlet and exhaust outlet in the tower crown space.
3. The corrected vents were simulated under the external airflow field. We found that most of the vent pressure was uneven under the influence of the airflow field during the operation of the smoke exhaust system, and the local pressure was too high. It is necessary to use local windproof components to reduce the effect of external wind.

Author Contributions: Conceptualization, T.Z.; methodology, T.Z.; software, Z.Z.; validation, X.Z. and Z.Z.; formal analysis, X.Z. and Z.Z.; investigation, T.Z., X.Z. and Z.Z.; resources, T.Z. and F.Q.; data curation, F.Q.; writing—original draft preparation, T.Z.; writing—review and editing, X.Z; visualization, Z.Z.; supervision, T.Z.; project administration, F.Q.; funding acquisition, T.Z. All authors have read and agreed to the published version of the manuscript.

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References

1. Zheng, C.; Li, Y.; Wu, Y. Pedestrian-level wind environment on outdoor platforms of a thousand-meter-scale megatall building: Sub-configuration experiment and wind comfort assessment. *Build. Environ.* **2016**, *106*, 313–326. [CrossRef]
2. Liu, K.; Wang, Q.; Zhang, W. Analysis of the current situation and common problems of our national defense smoke extraction system. *Fire Sci. Technol.* **2018**, *37*, 331–333+336.
3. Cheng, L. Exploring the maximum allowable smoke exhaust volume of a single smoke vent. *HVAC* **2020**, *50*, 82–85+102.
4. Xin, J. Analysis of the problem of fire smoke exhaust system design and fan selection. *HVAC* **2017**, *47*, 27–31+66.
5. Li, B.; Yang, H.; Zhang, J. Characteristics of smoke exhaust system and selection of smoke exhaust fan. *HVAC* **2014**, *44*, 8–12+17.
6. Tang, S.; Lu, G.; Hu, Z.; Gan, Z. Study on the "short circuit" phenomenon of outdoor smoke flow in buildings. *Fire Sci. Technol.* **2014**, *33*, 1019–1021.6.
7. Fang, Q. Study on the Influence of External Wind Environment on the Design of Smoke Evacuation in Super High-Rise Buildings. Master's Thesis, Jilin University of Architecture, Changchun, China, 2018.
8. Li, L. A study on the performance of smoke extraction system in ultra-high atrium based on numerical simulation. *Fire Sci. Technol.* **2015**, *34*, 1587–1589.
9. Hadjisophocleous, G.; Zhou, J. Evaluation of Atrium Smoke Exhaust Make-Up Air Velocity. *ASHRAE Trans.* **2008**, *114*, 147–155.
10. Li, X.F. Influence of make-up air methods on the effectiveness of mechanical smoke extraction in atrium-type large-space buildings. *Fire Sci. Technol.* **2016**, *35*, 193–197.
11. Sun, G. The effect of mechanical make-up air outlet setting height on smoke exhaust effect. *Fire Sci. Technol.* **2019**, *38*, 812–814.
12. Zhou, D.; Wang, J.; He, Y. Numerical Simulation Study of Smoke Exhaust Efficiency in an Atrium. *J. Fire Prot. Eng.* **2010**, *20*, 117–142. [CrossRef]
13. Huang, D.; Zhu, J.; Xia, R.; Li, J. Numerical simulation of the effect of outdoor wind on the smoke motion in the shaft of a high-rise building. *Fire Sci. Technol.* **2007**, *26*, 595–598.
14. Zhang, H.; Chen, J.; Wang, H.; Li, H. Simulation of the effect of natural wind pressure on fire smoke extraction in super high-rise buildings. *Fire Sci. Technol.* **2018**, *37*, 180–184.
15. Song, X. Analysis of design points of tower crown part of super high-rise public buildings below 250 m. *Real Estate Guide* **2019**, *15*, 37–38. [CrossRef]
16. Qu, H. Study on Building Energy Consumption and Thermal Comfort of Ice Rink. Master's Thesis, North China University of Science and Technology, Tangshan, China, 2021.
17. Ye, X.; Jiang, X.Y.; Shen, G. Application of Airpak software in the field of airflow organization. *Appl. Energy Technol.* **2006**, *10*, 45–47.
18. Zhang, F.; Ryu, Y. Simulation Study on Indoor Air Distribution and Indoor Humidity Distribution of Three Ventilation Patterns Using Computational Fluid Dynamics. *Sustainability* **2021**, *13*, 3630. [CrossRef]
19. Meteorological Data Room; Meteorological Information Center; China Meteorological Administration. *China Building Thermal Environment Analysis Specialized Meteorological Data Set*; China Building Industry Press: Beijing, China, 2005; ISBN 7-112-07274-3.
20. *SZJG 30-2009*; Shenzhen Green Building Evaluation Code. Shenzhen Bureau of Quality and Technical Supervision: Shenzhen, China; China Construction Industry Press: Shenzhen, China, 2009.
21. Hussain, S.; Oosthuizen, P.H.; Kalendar, A. Evaluation of Various Turbulence Models for the Prediction of the Airflow and Temperature Distributions in Atria. *Energy Build.* **2012**, *48*, 18–28. [CrossRef]
22. Lu, C.; Li, Q.; Huang, S.; Zhi, L.; Fu, X. Simulation analysis of wind response of Ping An International Finance Building in Shenzhen. *J. Build. Struct.* **2012**, *33*, 1–11.
23. *GB51251-2017*; Technical Standards for Smoke Prevention and Exhaust Systems in Buildings (2018 Edition). Ministry of Public Security of the People's Republic of China: Beijing, China; China Planning Press: Beijing, China, 2018.
24. *JG/T 14-2010*; Development of the People's Republic of China Ventilation and Air Conditioning Vent. Ministry of Housing and Urban-Rural: Beijing, China; China Standard Publishing House: Beijing, China, 2010.