Article

Ventilation Characteristics and Performance Evaluation of Different Window-Opening Forms in a Typical Office Room

Yuanyuan Wang ¹, Yanzhe Yu ¹ , Tianzhen Ye ^{1,2,*} and Quan Bo ¹

¹ School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, China; yuanyuan16336@tju.edu.cn (Y.W.); yuyanzhe@tju.edu.cn (Y.Y.); tjboq@cohl.com (Q.B.)

² National Engineering Laboratory for Digital Construction and Evaluation Technology of Urban Rail Transit, Tianjin 300350, China

* Correspondence: tzhye@tju.edu.cn

Abstract: As most existing office buildings in China lack fresh air systems for ventilation, natural ventilation with windows remains the main means of improving indoor air quality and adjusting indoor thermal comfort. However, knowledge of the ventilation characteristics of various window-opening forms in actual buildings is limited and current methods for evaluating ventilation performance lack a comprehensive consideration of ventilation rate and thermal comfort. In this study, the ventilation characteristics of different window-opening forms were systematically compared by conducting computational fluid dynamics (CFD) simulations. A full-scale experiment was conducted in a typical office room in a university in Tianjin to validate the CFD simulation. Two ventilation modes (wind-driven cross-ventilation and temperature-driven single-sided ventilation), three window-opening angles, and seven window types were investigated. Additionally, the ratio of the ventilation rate to the absolute value of thermal sensation was used to quantify the indoor natural-ventilation performance. The results showed that a sliding window with a full opening has the highest discharge coefficients of 0.68 and 0.52 under wind-driven cross-ventilation and temperature-driven single-sided ventilation, respectively, and top-hung windows opening both inwards and outwards have better ventilation performance than other window types under the two ventilation modes. This study is applicable to the design and practice of natural ventilation.

Keywords: natural ventilation; window-opening forms; ventilation performance; CFD

Citation: Wang, Y.; Yu, Y.; Ye, T.; Bo, Q. Ventilation Characteristics and Performance Evaluation of Different Window-Opening Forms in a Typical Office Room. *Appl. Sci.* **2021**, *11*, 8966. <https://doi.org/10.3390/app11198966>

Academic Editor: Cesare Biserni

Received: 11 September 2021

Accepted: 21 September 2021

Published: 26 September 2021

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1. Introduction

Natural ventilation can help adjust indoor thermal comfort [1–3], improve indoor air quality [4,5], and reduce the energy consumption of mechanical ventilation systems [6–8]. Due to the pulsating characteristics of natural ventilation, natural ventilation can provide a comfortable indoor environment [9], which is conducive to people's physical and mental health. Thus, it is important to promote the adoption of natural ventilation in buildings.

One of the important methods of realising natural ventilation is window ventilation. The design [10–12], practice, and assessment of window ventilation [13–15] have received increasing research attention. In the design and practice of window ventilation, the window configuration, window-opening form, and opening angle are three important influencing factors [16]. Window configurations are usually categorised as cross-ventilation, where openings are on opposite sides of a building; and single-sided ventilation, where the openings are on only one side of a building [17]. There are three common window-opening forms—casement, hung, and sliding windows [18]—which can be subdivided according to the axis position and type of opening (inner and outer). Thus, various specific application forms can be obtained. The occupants usually control the window-opening angle to adjust the ventilation rate [19].

The influence of these three factors on the discharge coefficient and ventilation performance has been studied by the research community. Favaro et al. [20] analysed the

effects of the position of a large rectangular opening on the discharge coefficient under single-sided ventilation and concluded that the vertical position of the opening is the most important influencing factor. Heiselberg et al. [21] investigated the ventilation performance of side-hung windows and bottom-hung windows under single-sided ventilation and cross-ventilation and confirmed that the discharge coefficient varies with both the opening area and window type. Yang et al. [22] conducted computational fluid dynamics (CFD) simulations to identify a positive correlation between the discharge coefficient and the opening angles. However, the aforementioned studies are limited in terms of certain window-opening forms or window configurations. In addition, there have been few studies on the window-opening angle [23].

To evaluate the performance of natural ventilation, indices such as air change per hour [24,25] and age of air [26] are commonly used. The air change per hour is the ratio of ventilation rate per hour to room volume. The age of air refers to the time required for air from entering the room to reaching a certain point in the room, which reflects the freshness of indoor air. However, under unsteady conditions, the advantages and disadvantages of natural ventilation cannot be determined based on only the ventilation rate; the indoor thermal comfort should also be considered. For the evaluation of thermal comfort under natural ventilation, the commonly used indices are the predicted mean vote–predicted percentage dissatisfied (PMV-PPD) [27,28] and the thermal comfort adaptability model [29]. PMV represents the average cold and heat felt by most people in the same environment. PPD represents the percentage of people dissatisfied with the thermal environment. Yu et al. [30] discussed the advantages and disadvantages of the PMV and adaptive comfort models in evaluating the thermal comfort of natural ventilation and proposed that attention should be paid to their combination. In general, occupants open windows for ventilation for two main purposes: one is to meet the needs of indoor ventilation, and the other is to adjust the indoor thermal comfort. However, the current evaluation index considers only one aspect, that is, either the ventilation rate or indoor thermal comfort, and lacks a comprehensive consideration of both.

Although many studies have been conducted on the design, practice, and assessment of window ventilation, the ventilation characteristics of various window-opening forms and opening angles in actual buildings are rarely systematically and quantitatively compared. Moreover, there is a lack of comprehensive consideration of the ventilation rate and thermal comfort in the evaluation of ventilation performance. To address this research gap, in this study, natural ventilation characteristics and performance were quantified and assessed under different window-opening forms and ventilation modes. A natural ventilation experiment was conducted in an office room in a university in Tianjin to validate the CFD simulation. The natural ventilation flow under seven window types, three opening angles, and two ventilation modes was simulated by using the CFD method. The window ventilation performance was comprehensively evaluated by combining the ventilation rate and thermal comfort.

2. Evaluation Model of Ventilation Performance

There are two main purposes for which occupants open windows for ventilation: one is to meet the needs of indoor ventilation, and for this purpose, the greater the ventilation rate is, the better. The other purpose is to adjust the indoor thermal comfort, and for this purpose, the closer the thermal sensation of the human body to the neutral temperature is, the better. To determine thermal comfort, the modified adaptive comfort model proposed by Su [31] was used in this study to calculate the human thermal sensation neutral temperature, t_c , and the expression is given as

$$t_c = 19.7 + 0.30t_0 + \frac{0.55v_{in}}{0.15} \quad (1)$$

where t_0 is the outdoor monthly average temperature (°C), and v_{in} is the indoor air velocity (m/s).

The difference between the thermal neutral temperature and the actual temperature is defined as the thermal sensation (the thermal sensation here is different from the predicted average thermal sensation of the PMV-PPD method owing to the different calculation methods). To comprehensively consider the indoor ventilation rate and the thermal comfort, the ratio of the ventilation rate to the absolute value of thermal sensation can be used as an index to evaluate the natural ventilation performance: the larger the ratio is, the better the ventilation performance.

3. Full-Scale Experiments

3.1. Experimental Site and Test Instruments

The experiment was conducted in an office building in a university in Tianjin. The university is located in the suburbs, with flat and open surrounding terrain, and there are no other buildings around the experimental building. The experimental building has five floors, and the maximum number of building floors in the school is five, which reduces the influence of the complex building layout on the natural wind field. The experimental room is on the fourth floor of the office building, and the internal size of the room is $8.1\text{ m} \times 4.8\text{ m} \times 2.7\text{ m}$ ($L \times W \times H$). The orientation of the north wall is 13° north by east. The north wall of the office is an exterior wall having a window with two sheets, which is the casement window opening outwards. There are offices in both the east and west sides and in the floors above and below the experimental room. The south side, which has an inner door, is adjacent to the inner corridor, and the elevator hall is connected to the corridor. There is a glass window on the south side of the waiting hall, which is open and is equal to the window in the room. There are four sets of desks and chairs, and two sets of lockers in the experimental room. The dimensions of the experimental room and exterior window are shown in Figure 1, and the area and volume parameters are listed in Tables 1 and 2, respectively.

Figure 1. Dimensions of (a) experimental room and (b) exterior window.

Table 1. Building area parameters of experimental room.

Exterior Wall Area (m ²)	Exterior Window Area (m ²)	Sheet Area of the Exterior Window (m ²)	Interior Wall Area (m ²)	Door Area (m ²)	Room Area (m ²)
5.67	2.43	1.08	52.48	2.11	38.88

Table 2. Building volume parameters of experimental room.

Total Volume (m ³)	Furniture Volume (m ³)	Net Volume (m ³)
104.98	16.64	88.34

The indoor ventilation rate was measured using a tracer gas concentration attenuation method. CO₂ was selected as the tracer gas in this experiment, and a dry ice fire extinguisher was selected to release CO₂ gas. The instruments used in the test included a small weather station, temperature and humidity recorder, miniature wind pressure gauge, infrared thermometer, warm air blower, CO₂ detection recorder, and carbon dioxide fire extinguisher. The instruments used are shown in Figure 2. The measuring range, resolution, accuracy, model, and supplier of the instruments are listed in Table 3.

Figure 2. Experimental instruments: (a) small weather station; (b) temperature and humidity recorder; (c) miniature wind pressure gauge; (d) dry ice fire extinguisher; (e) CO₂ detection recorder; (f) warm air blower; and (g) infrared thermometer.

Prior to the experiment, each instrument was calibrated to ensure test accuracy. For the small weather station installed on the experimental building roof, the installation height of the wind speed and direction sensor from the roof was at least 1.2 m according to the instructions. The wind vane of the wind speed and direction sensor was pointed north. The CO₂ concentration sensors were placed in a well-ventilated outdoor environment without crowd interference, and the data acquisition host was connected. The sensors operated stably for more than 20 min at an outdoor concentration of 400 ppm, and a manual

calibration operation was performed. The indoor temperature and humidity recorder was calibrated before leaving the factory. The miniature wind pressure gauge was placed in a windless room, and it was ensured that no person directly breathed to the instrument. The manual zero-point calibration was conducted after the wind pressure difference was stable.

Table 3. Test parameters of instruments.

Instrument	Parameter Category	Measuring Range	Resolution	Precision	Model	Supplier
Small weather station	Wind speed	1–68 m/s	0.1 m/s	±5% (1.5 m/s)	Vantage pro2	DAVIS
	Wind direction	0°–360°	1°	±3°		
	Air temperature	−40–65 °C	0.1 °C	±0.5 °C		
	Relative humidity	0–100%	1%	±3%		
Temperature and humidity recorder	Air temperature	20–70 °C	0.1 °C	±0.5 °C	U10-003	Onset HOBO
	Relative humidity	25–95%	1%	±3.5–5%		
Miniature wind pressure gauge	Wind pressure	−3735–+3735 Pa	0.1 Pa	±1.5%	DP-CALC5815	TSI
CO ₂ detection recorder	CO ₂ concentration	0–5000 ppm	1 ppm	±50 ppm	MH-Z14A	WINSEN
Infrared thermometer	Wall temperature	−40–800 °C	0.1 °C	±1% or ±1.0 °C	FLUKE568	FLUKE

3.2. Data Acquisition

The sampling interval of the small weather station was set as the shortest sampling interval, i.e., 5 min. The sampling interval of the CO₂ detection recorder and the temperature and humidity recorder were set to 1 min. The sampling interval of the miniature wind pressure gauge was set to 10 s.

The arrangement of measurement points and instruments was as follows: the height of the outdoor temperature, wind speed, wind direction, and CO₂ concentration measurement points from the ground was approximately 20 m, and the horizontal distance to the test room was within 5 m. For the indoor CO₂ concentration measurement points, according to the provisions of the Indoor Air Quality Standard [32], 1–3 points should be set for rooms less than 50 m². To prevent the calculation error of the ventilation rate caused by the uneven distribution of indoor CO₂, the five CO₂ concentration measurement points were arranged in a quincunx shape. The arrangement of the temperature and humidity measurement points was the same as that of the CO₂ concentration measurement points. Based on relevant research [33], the wind pressure measurement points were symmetrically arranged, indoors and outdoors, at a distance of 30 mm from the window. All indoor measurement points were arranged at a height of 1.2 m above the ground, which is consistent with the breathing height of humans. As the warm air blower can affect the uniformity of the indoor temperature and CO₂ distribution, it was placed on the south side of the room, near the interior wall. The warm air blower blows along the surface of the interior wall, thus reducing interference with the indoor air flow. Figure 3 shows the layout of the measurement points of wind-driven cross-ventilation (CV) and temperature-driven single-sided ventilation (SV).

Figure 3. Layout of the measurement points of (a) CV and (b) SV.

3.3. Experimental Conditions and Procedures

The experiment involved two ventilation modes: CV and SV. For CV, the windows in the room and on the south side and the door in the room were open. For SV, only the window in the room was open. Each mode was divided into four window states according to the number of open sheets of the window and the angle of the window opening—totalling eight conditions, as listed in Table 4.

Table 4. Experimental conditions.

Ventilation Mode	Condition Number	Door Status	Number of Open Sheets of the Window	Window Opening
CV	1-1	Open	1	30°
	1-2		2	30°
	1-3		1	45°
	1-4		2	45°
SV	2-1	Closed	1	30°
	2-2		2	30°
	2-3		1	45°
	2-4		2	45°

Before each experiment, to eliminate the influence of CO₂ produced by the experimenters' respiration on the measurement of tracer gas concentration, the rate of the CO₂ production of the experimenters was measured. There were four experimenters in the room. The experimental procedures were as follows: all gaps except the door and window were well sealed. A dry ice fire extinguisher was used to spray CO₂ into the test room. The initial concentration was not significantly high or low; an excessively high concentration can harm the health of the experimenters, whereas if it is too low, it can affect test accuracy. According to the literature [34], 1800 ppm was set as the lower limit of the initial concentration of CO₂. For the upper limit, when the CO₂ concentration in the air is 2000–4000 ppm,

people will breathe faster. Therefore, the upper limit of the initial concentration was set to 2000 ppm. In the test, the initial concentration of CO₂ was controlled at 1800–2000 ppm by multiple releases. The fan coil was turned on for the indoor circulation mode to accelerate air mixing in the room. When the indoor CO₂ concentration reached 1800–2000 ppm, the release of CO₂ was stopped, and the fan coil continued to operate to accelerate mixing. When the difference between the measurement points was less than 10% [35], the indoor CO₂ concentrations were considered uniform, and the fan coil was closed. For the SV condition, the warm air blower was turned on to heat the indoor air at this time. When the required air temperature was reached and the difference between the indoor measurement points was within ± 0.5 °C [9], the warm air blower was turned off. Then, the door and window were opened for ventilation according to the required conditions.

4. CFD Simulation

4.1. Geometrical Models and Numerical Methods

Seven typical window types that are widely used in buildings were selected in this study: casement window opening inwards (CWI), casement window opening outwards (CWO), top-hung window opening inwards (THWI), top-hung window opening outwards (THWO), bottom-hung window opening inwards (BHWI), bottom-hung window opening outwards (BHOW), and sliding window (SW). Figure 4 presents diagrams of the seven windows.

Figure 4. Diagrams of the seven windows: (a) CWI; (b) CWO; (c) THWI; (d) THWO; (e) BHWI; (f) BHOW; and (g) SW.

At present, room models established by researchers in CFD simulations of natural ventilation are mostly classified into two types: the single-opening model and the double-opening model with windows on opposite walls. The first model is suitable for SV in this study, whereas the latter model is relatively rare in actual buildings. When the influence of wind direction on natural ventilation is considered, the windward and leeward sides cannot be distinguished because of the geometric symmetry. Therefore, a room model with a corridor was proposed for CV in this study. The layout of the model room was the same as that of the experimental room. As the wall thickness had a minor effect on the discharge coefficient of windows [20], and when the upper, lower, left, and right adjacent rooms open the windows, it has little impact on the indoor ventilation [36]. Therefore, according to the above similar studies, the wall thickness and adjacent rooms were not considered in the CFD models. The model conforms to a common office structure. It can distinguish the windward and leeward sides, and it avoids setting a complex model, which simplifies

the simulation process. Figure 5 shows the models of the two ventilation modes. The size of the model room is $8.1 \text{ m} \times 4.8 \text{ m} \times 2.7 \text{ m}$ ($L \times W \times H$). The window-opening size of the room is $0.45 \text{ m} \times 1.18 \text{ m}$ ($W \times H$). In the CV model, the corridor size is $4.8 \text{ m} \times 1.6 \text{ m}$ ($L \times W$), the window-opening size of the corridor is the same as that of the room, and the door size is $0.9 \text{ m} \times 2.34 \text{ m}$ ($W \times H$). The outfield area was set outside the room. Referring to the relevant research [37], the distances from the left, right, front, rear, and top sides of the outfield to the corresponding surfaces of the room model were set as $6H$, $6H$, $3H$, $3H$, and $3H$, respectively (H is the height of the model room).

Figure 5. Geometric models: (a) CV and (b) SV.

In this study, an industry-leading fluid simulation software, ANSYS Fluent [38], was used, which can accurately solve the widest range of CFD problems. Three-dimensional steady-state Reynolds-averaged Navier–Stokes models [39] were used because of their low requirements for computer memory space and computing speed. As the natural ventilation problem in this study belonged to a flow with a high Reynolds number and high shear rate, it was suitable to adopt the realisable $k-\epsilon$ turbulence model [40,41]. A pressure-based solver, which is applicable to the low-speed incompressible flow problem in this study and has a fast convergence speed, was adopted, and the SIMPLE algorithm was employed for the coupling of the pressure and velocity fields.

4.2. Numerical Grids and Boundary Conditions

A hybrid grid was established, including a tetrahedral unstructured mesh between the model room and outfield boundary and a hexahedral structured grid inside the model room. To ensure the accuracy of the numerical simulation and simplify the complexity of the simulation calculation, the grid spacing in the model room was 0.1 m , and the grid spacing from the model room to the outfield changed from 0.1 m to 1 m at a rate of 1.1 . As the high Reynolds number $k-\epsilon$ model and standard wall function method were used in

this study, the grid near the wall was not encrypted, but the first node was arranged in the region where turbulence was fully developed [38]. The total numbers of cells in the CV and SV grids were approximately 1,910,000 and 1,610,000, respectively. A grid independence analysis was carried out by increasing the numbers of cells to 4.77 million and 4.01 million for the CV and SV grids when the window is the CWO, respectively. Simulation results based on the two numbers of cells in the grids showed that there were negligible differences in the ventilation rate, confirming that the grid independence test was satisfactory.

The boundary conditions are shown in Figure 6. For the CV model, the velocity-inlet boundary condition was applied to the inlet surface of the outfield. The velocity of the outfield was fixed at 2.2 m/s according to the average wind speed in the transition season in Tianjin. The outflow boundary condition was applied to the outlet surface of the outfield. A symmetrical boundary condition was applied to the sides and top of the outfield. The bottom of the outfield and the wall of the room were set as the wall boundary condition. For the SV model, the boundary conditions of the outlet surface, sides, and top of the outfield were the same as those of the CV model. The bottom of the outfield and the wall and floor of the room were assigned a wall boundary condition with a fixed temperature. The velocity of the outfield was set to be 0.1 m/s to form a flow and realise the ventilation process. In the simulation validation, the measured value of the average outdoor air temperature was taken as the outfield inflow temperature boundary condition, and the measured values of the wall temperature of the room under different conditions were taken as the wall temperature boundary condition. According to the relevant research, when the outdoor air temperature was higher than 10 °C and the indoor temperature was higher than 22 °C, the window opening probability of occupants began to increase significantly [42]. Therefore, in further simulations, the temperature of the outfield inflow and the bottom of outfield was set to 10 °C, and the wall and floor temperatures of the room were set to 22 °C. For the velocity-inlet boundary condition, the method of turbulent intensity and viscosity ratio was specified. The turbulent intensity was 5%, and the turbulent viscosity ratio was 10.

Figure 6. Boundary conditions: (a) CV and (b) SV.

4.3. CFD Validation

4.3.1. Validation of Wind Pressure Difference and Discharge Coefficient for CV Model

Owing to the limitation of the indoor CO₂ release concentration, the duration of the CO₂ attenuation process needed to calculate the ventilation rate in the experiment is short; therefore, for the validation of the discharge coefficient, the simulated values can be directly compared with the measured value. However, the validation of the wind pressure coefficient (C_p) was different. First, the measurement of the wind pressure difference does not depend on the tracer gas method, and it can be carried out independently. Second, the instrument measurement interval of the wind pressure difference can be smaller than that of the outdoor wind speed and direction. Therefore, the method of the combination

of mean comparison and sequence correlation comparison was used to validate the wind pressure difference.

In the process of the wind pressure difference test, 50 min was taken as the length of each sequence, and 10 sequences were compared. The time interval of the simulated values in each sequence was 5 min, with a total of 10 values, and the time interval of the measured values was 10 s, with a total of 300 values. The mean values and Pearson correlation coefficients between the simulated value sequence and the measured value sequence are listed in Table 5, in which the minimum correlation coefficient is 0.746.

Table 5. Comparison of mean values and Pearson correlation coefficients of wind pressure difference.

Serial Number	Mean Wind Speed (m/s)	Dominant Wind Direction	Mean Value		Pearson Correlation Coefficient
			Simulated Value (Pa)	Measured Value (Pa)	
1	4.0	67.5°	2.53	2.19	0.868
2	2.2	315°	1.20	1.55	0.746
3	2.5	112.5°	0.51	0.40	0.774
4	2.1	112.5°	0.38	0.33	0.769
5	3.3	67.5°	0.58	0.46	0.832
6	1.2	45°	1.12	1.40	0.809
7	1.7	247.5°	0.47	0.31	0.798
8	2.4	270°	0.32	0.41	0.755
9	3.8	225°	1.91	2.26	0.817
10	2.1	112.5°	0.38	0.33	0.769

A comparison between the CFD simulation values and experimental values of the discharge coefficient for CV (C_d) is presented in Table 6.

Table 6. Comparison between simulated and experimental values of the discharge coefficient under CV.

Condition Number	Outdoor Mean Wind Speed (m/s)	Dominant Wind Direction	Average Temperature Difference between Indoor and Outdoor (°C)	C_d		
				Simulated Value	Experimental Value	Relative Error
1–1	0.2	112.5°	3.9	0.319	0.335	4.8%
1–2	3.0	22.5°	3.3	0.457	0.474	3.6%
1–3	3.0	202.5°	1.1	0.413	0.404	−2.2%
1–4	2.6	337.5°	1.4	0.270	0.261	−3.4%

4.3.2. Validation of the Discharge Coefficient for SV Model

A comparison between the CFD simulation values and the experimental values of the discharge coefficient for SV (C_d') is presented in Table 7.

Table 7. Comparison between simulated and experimental values of the discharge coefficient under SV.

Condition Number	Outdoor Mean Wind Speed (m/s)	Indoor and Outdoor Average Temperature Difference			C_d'		
		Simulated Value	Experimental Value	Relative Error	Simulated Value	Experimental Value	Relative Error
2–1	2.0	15.5	16.6	6.6%	0.360	0.371	3.0%
2–2	1.2	17.5	18.7	6.4%	0.363	0.356	−2.0%
2–3	1.0	18.3	19.8	7.6%	0.408	0.395	−3.3%
2–4	1.2	8.3	9.0	7.8%	0.426	0.430	0.9%

From Tables 6 and 7, it can be observed that the agreement between the CFD results and the experimental data is acceptable, and the CFD model can be used for subsequent simulations.

5. Results and Discussion

5.1. Comparison of Ventilation Characteristics of Seven Window Types with Different Wind Directions under CV

In CV, the window-opening angle was 30° , and the window-opening area was equal. The simulated conditions of CV were divided according to the angle between the incoming wind direction and the plane of the window based on the 16-wind direction interval method, where 0° (360°) was condition 1, each increase of 22.5° was a condition, and 337.5° was condition 16. According to the left and right symmetry, the seven window types were divided into two types: symmetrical windows, namely THWI, THWO, BHWI, BHWO, and SW, and asymmetric windows, namely CWI and CWO. Figure 7 depicts the simulated wind pressure and discharge coefficients for different window types in different wind directions.

Figure 7. C_p and C_d of the (a) symmetrical window and (b) asymmetrical window.

As shown in Figure 7, the overall changing trend of the wind pressure coefficient of the symmetrical windows is similar. It is worth noting that on the windward side, the maximum value of the wind pressure coefficient does not appear at 0° (360°), but under the symmetrical condition of 22.5° (337.5°); there is a similar situation on the leeward side, where the minimum value of the coefficient appears in the symmetrical conditions of 157.5° (202.5°). For the asymmetrical window, the wind pressure coefficient is higher on one side for the left and right directions of the windward window, and the high and low directions of the CWI and CWO are opposite, and the trend is similar on the leeward side. The maximum and minimum values of the wind pressure coefficient still deviate from 0° (360°) and 180° . The discharge coefficient of symmetrical windows fluctuates in a

small range under different wind directions, and there is no obvious distinction between the windward and leeward sides. The discharge coefficient of the asymmetric window fluctuates considerably on the windward side and gently on the leeward side.

5.2. Comparison of Ventilation Characteristics of Seven Window Types with Three Opening Angles under CV and SV

In CV, the wind direction was fixed to the plane of the window. Three opening angles of each window type were simulated, in which the window opening state of the sliding window was set as one-third, two-thirds, and fully open, and the window-opening states of other window types were set as 15°, 30°, and 45°, respectively. The three types of openings were defined as small, medium, and large openings, respectively.

The discharge coefficients of the three opening angles for the seven window types under the two ventilation modes were simulated, as shown in Figure 8. The discharge coefficient for each window type under CV is generally larger than that under SV, and the difference in discharge coefficient of each window type of the three openings under SV is less obvious than that under CV, which is due to the different mechanisms of wind pressure ventilation and thermal pressure ventilation, resulting in different airflow characteristics at the openings. In addition, for CV and SV, the discharge coefficient increases with the increase in window opening, and the SW has the highest discharge coefficient under a large opening, which is 0.68, and 0.52, respectively. For medium and small openings, the discharge coefficient of BHWI is the highest under CV, and the discharge coefficient of THWI is the highest under SV.

Figure 8. C_d' of three openings for seven window types: (a) CV and (b) SV.

5.3. Comprehensive Evaluation of Ventilation Performance of Different Window Types

According to the description of the temperature and wind sensitive area of ANSI/ASHRAE Standard 55-2013, a 1.1 m height plane (head height of a human when sitting) in the room was selected for ventilation comfort analysis [43]. Figure 9 shows the velocity field and velocity vector of each window under the two ventilation modes. In the plan of the room, the exterior window of the room is located on the left. For CV, the influence range of the airflow is small under the three opening angles for CWO and BHWI, whereas the influence range for SW, THWI, and BHOW is large. The airflow influence range for CWI and THWO is small only under a small opening.

Figure 9. Velocity field and velocity vector diagram of seven window types under (a) CV and (b) SV.

Furthermore, the neutral temperature, average thermal sensation, and the proportion of thermal sensation interval of different window-opening forms of the $z = 1.1$ m plane of the room were calculated according to the method described in Section 3.3. For CV,

the outdoor temperature was set to 25 °C according to the outdoor monthly average temperature during the experiment. For SV, the outdoor temperature was 10 °C, the same as that set in the simulation process. The average thermal sensation and proportion of thermal sensation intervals under the three opening angles of the two ventilation modes are shown in Figure 10.

Figure 10. Average thermal sensation and proportion of thermal sensation interval: (a) small opening for CV; (b) medium opening for CV; (c) large opening for CV; (d) small opening for SV; (e) medium opening for SV; and (f) large opening for SV.

It can be observed that, for CV, the average thermal sensation of the seven window types is within the comfort zone under the three opening degrees. The comfort of the THWO is the best under a small opening, and the comfort of the seven window types is similar under the medium opening. The comfort of the SW is the best under a large opening. For SV, the average thermal sensation of the seven window types is beyond the range of the thermal comfort zone under medium opening and large opening. The comfort of the SW is best under a small opening.

To evaluate the ventilation performance of the different window-opening forms comprehensively, the ventilation rate for CV (Q) and SV (Q') of each window type was obtained by CFD simulation. Figure 11 presents a comprehensive comparison of the ventilation rate and thermal comfort of the $z = 1.1$ m plane under different conditions. As can be observed from Figure 11, SW-1 (the full opening of the sliding window) has the maximum ventilation rate under the two ventilation modes. The thermal sensations of the two ventilation modes are not close to 0 or equal to 0. The thermal sensations of the seven window types are similar under CV, and the thermal sensations of windows with large openings are worse than those with small openings under SV.

Figure 11. Comprehensive comparison of ventilation rate and comfort: (a) CV and (b) SV.

The ratios of the ventilation rate to the absolute value of the thermal sensation for different window types are listed in Table 8. It can be seen that SW-1 has the best ventilation performance under CV, with a ratio of 1293.26, and THWI-45° has the best ventilation performance under SV, with a ratio of 51.97. In summary, THWI and THWO have better ventilation performance under the two ventilation modes.

Table 8. Ratios of the ventilation rate to the absolute value of the thermal sensation for different window-opening forms.

Window Types	CV			SV		
	Ventilation Rate (m ³ /h)	Thermal Sensation (°C)	Ratio	Ventilation Rate (m ³ /h)	Thermal Sensation (°C)	Ratio
SW-1/3	858.12	1.85	464.40	71.52	−1.64	43.69
CWI-15°	952.16	1.90	501.14	86.31	−2.03	42.52
CWO-15°	814.04	2.01	405.00	98.56	−2.45	40.23
THWI-15°	1428.25	1.93	740.03	133.86	−2.78	48.15
THWO-15°	1451.76	1.70	853.98	127.24	−2.77	45.94
BHWI-15°	1572.25	2.00	786.13	119.14	−3.00	39.71
BHWO-15°	1069.71	1.79	597.60	135.54	−3.09	43.86
SW-2/3	1472.33	1.71	861.87	138.90	−3.31	41.98
CWI-30°	1384.16	1.77	782.01	138.12	−2.88	47.96
CWO-30°	1378.29	1.79	769.99	143.16	−3.28	43.65
THWI-30°	1789.71	1.72	1040.53	172.01	−3.56	48.32
THWO-30°	1751.51	1.73	1012.43	162.48	−3.32	48.94
BHWI-30°	1901.39	1.84	1033.36	158.60	−3.72	42.63
BHWO-30°	1316.57	1.80	731.43	155.81	−3.60	43.28
SW-1	2004.25	1.55	1293.26	203.94	−4.17	48.93
CWI-45°	1613.39	1.80	896.33	167.76	−3.47	48.35
CWO-45°	1625.14	1.76	923.38	168.51	−3.80	44.34
THWI-45°	1822.04	1.76	1035.25	188.14	−3.62	51.97
THWO-45°	1895.51	1.63	1162.89	170.79	−3.32	51.44
BHWI-45°	1892.57	1.66	1140.10	179.72	−4.14	43.41
BHWO-45°	1498.78	1.76	851.58	173.79	−3.76	46.22

6. Conclusions

In this study, the ventilation characteristics of a typical office room with different window-opening forms under CV and SV were studied. The ratio of the ventilation rate to the absolute value of thermal sensation was used to evaluate the natural ventilation performance. The main conclusions drawn are as follows.

- (1) For CV, on the windward side, the maximum value of the wind pressure coefficient of different window types does not appear at 0° (360°), but under the symmetrical condition of 22.5° (337.5°); there is a similar situation on the leeward side, where the minimum value of the coefficient appears in the symmetrical conditions of 157.5° (202.5°).
- (2) For CV and SV, the discharge coefficient increases with the increase in window opening, and the full opening of the sliding window has the highest discharge coefficient, which is 0.68 and 0.52, respectively. For medium and small openings, the discharge coefficient of the bottom-hung window opening inwards is the highest under CV, whereas that of the top-hung window opening inwards is the highest under SV.
- (3) Based on the evaluation of the ventilation performance of different window-opening forms, it is concluded that the sliding window with a full opening has the best ventilation performance under CV, with a ratio of 1293.26, whereas the ventilation performance is the best under SV when the opening of the top-hung window opening inwards is 45°, with a ratio of 51.97. In general, the two types of top-hung windows have better ventilation performance under the two ventilation modes. The results of this study are useful for designers when selecting window types and designing windows with opening restrictors for office buildings.

Author Contributions: Conceptualization, Y.W., Y.Y., T.Y. and Q.B.; methodology, Y.W. and Y.Y.; software, Y.W. and Y.Y.; validation, Q.B.; formal analysis, Y.W., Y.Y., T.Y. and Q.B.; investigation, T.Y.; resources, Q.B.; data curation, Q.B.; writing—original draft preparation, Y.W. and Y.Y.; writing—review and editing, T.Y.; visualization, T.Y.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was founded by the Science and Technology Planning Project of Tianjin (No. 18ZXGDGX00080).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was accomplished in the National Engineering Laboratory for Digital Construction and Evaluation Technology of Urban Rail Transit.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BHWI	Bottom-hung window opening inwards
BHWI-15°	Bottom-hung window opening inwards at 15°
BHWI-30°	Bottom-hung window opening inwards at 30°
BHWI-45°	Bottom-hung window opening inwards at 45°
BHWO	Bottom-hung window opening outwards
BHWI	Bottom-hung window opening inwards
BHWI-15°	Bottom-hung window opening inwards at 15°
BHWI-30°	Bottom-hung window opening inwards at 30°
BHWI-45°	Bottom-hung window opening inwards at 45°
BHWO	Bottom-hung window opening outwards
BHWO-15°	Bottom-hung window opening outwards at 15°
BHWO-30°	Bottom-hung window opening outwards at 30°
BHWO-45°	Bottom-hung window opening outwards at 45°
CFD	Computational fluid dynamics
CV	Wind-driven cross-ventilation
BHWI	Bottom-hung window opening inwards
BHWI-15°	Bottom-hung window opening inwards at 15°
BHWI-30°	Bottom-hung window opening inwards at 30°
BHWI-45°	Bottom-hung window opening inwards at 45°
CWO-30°	Casement window opening outwards at 30°
CWO-45°	Casement window opening outwards at 45°
Q	Ventilation rate for wind-driven cross-ventilation (m^3/s)
Q'	Ventilation rate for temperature-driven single-sided ventilation (m^3/s)
SV	Temperature-driven single-sided ventilation
SW	Sliding window
SW-1/3	Sliding window with 1/3 opening
SW-2/3	Sliding window with 2/3 opening
SW-1	Sliding window with full opening
t_c	Human thermal sensation neutral temperature
THWI	Top-hung window opening inwards
THWI-15°	Top-hung window opening inwards at 15°
THWI-30°	Top-hung window opening inwards at 30°
THWI-45°	Top-hung window opening inwards at 45°
THWO	Top-hung window opening outwards
THWO-15°	Top-hung window opening outwards at 15°
THWO-30°	Top-hung window opening outwards at 30°
THWO-45°	Top-hung window opening outwards at 45°

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