

Article

CFD Analysis of Building Cross-Ventilation with Different Angled Gable Roofs and Opening Locations

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Abstract: The geometric shape of the roof and the opening position are important parameters influencing the internal cross-ventilation of buildings. Although there has been extensive research on natural ventilation, most of it has focused on flat or sloping roofs with the same opening positions. There is still limited research on the impact of different opening positions and sloping roofs on natural ventilation. In this study, computational fluid dynamics (CFD) was used to investigate the air exchange efficiency (AEE) in general isolated buildings. These buildings encompassed three distinct opening configurations (top–top, top–bottom, and bottom–top) and six varying slope angles for gable roofs (0°, 9°, 18°, 27°, 36°, and 45°). Computational simulations were carried out using the SST k-omega turbulence model, and validation was performed against experimental data supplied by the Japanese AIJ Wind Tunnel Laboratory. Grid independence validation was also conducted to ensure the reliability of the CFD simulation results. The study revealed that the highest AEE was 48.1%, achieved with the top–bottom opening configuration and a gable roof slope angle of 45°. Conversely, the lowest AEE was 31.4%, attained with the bottom–top opening configuration and a gable roof slope angle of 27°. Furthermore, it was observed that when the opening configuration was set to top–top and bottom–top, the slope angle of the gable roof had minimal influence on AEE, with an average AEE of only around 33%. When the opening configuration was top–bottom, it was found that there was a positive correlation between the gable roof slope angle and AEE.



Citation: Shi, J.; Zhao, C.; Liu, Y. CFD Analysis of Building Cross-Ventilation with Different Angled Gable Roofs and Opening Locations. *Buildings* **2023**, *13*, 2716. <https://doi.org/10.3390/buildings13112716>

Academic Editors: Adrian Pitts and Francesco Nocera

Received: 21 September 2023

Revised: 5 October 2023

Accepted: 26 October 2023

Published: 27 October 2023



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Keywords: gable roof; natural ventilation; computational fluid dynamics (CFD); air exchange efficiency (AEE)

1. Introduction

The global demand for energy has been continually increasing, with the construction industry playing a significant role. Therefore, enhancing its energy efficiency becomes especially important. An overreliance on mechanical and electrical equipment to provide a comfortable environment has led to a disproportionate energy consumption in buildings, particularly from heating, ventilation, and air conditioning (HVAC) systems [1]. In China, between 2005 and 2020, the national total energy consumption from buildings increased from 930 million tce to 2.233 billion tce, with an average annual growth rate of 6.0%. By the end of 2020, the building stock in China had reached 69.6 billion square meters [2]. With such an immense inventory, reduction in building energy consumption has remained a key concern for both the government and society. With mild weather conditions, it is highly recommended to use natural ventilation to replace air conditioning for cooling [3]. Compared with air conditioning systems, the cooling ability of natural ventilation seems to be limited and its performance is also not quite stable. Therefore, many researchers have moved to studying how to maximize the performance of natural ventilation in cooling buildings.

Regarding opening positions, natural ventilation can be generally categorized into three types: (1) SSV—single-sided ventilation (one or more vents are placed on one side

of the building); (2) CV—cross-ventilation (allowing natural airflow through the building by having windows positioned on opposite facades), and (3) SV—stack ventilation (utilizing temperature difference between indoor and outdoor environments, with vents located at different heights) [4]. Compared with SSV, CV generally gives higher ventilation efficiency [5], hence it was selected in this study.

In terms of opening positions in the vertical direction, according to Karava [6], apart from wall porosity, the relative locations of openings and exits on building facades are significant factors affecting cross-ventilation. Zhang [7] conducted a study on two different-sized external openings and found that the most effective configuration for enhancing cross-ventilation was to have a larger opening on the leeward side than on the windward side. The aforementioned studies primarily focused on the impact of opening size and position on cross-ventilation, with limited exploration of the building's form. However, as the roof is an integral component of the building's form, its significance is self-evident. Roof forms can be categorized into gable roofs [8–10], arched roofs [11], mono-pitched roofs [12], sawtooth roofs [13] and various other roof types [14,15]. Previous studies have focused on analyzing the surface wind-pressure coefficients of these different types of roofs and providing some information on the potential for natural ventilation, but they have lacked an analysis of airflow inside buildings.

In recent years, the effects of various types of roofs and openings on the natural ventilation of buildings have been studied. Vaishnani [16] conducted numerical simulations and used the PMV model to assess the impact of roof slope angles on cross-ventilation under winter, summer, and monsoon weather conditions in Delhi, India. The results showed that the PMV values decreased with increasing roof slope angles in winter, while in summer, the PMV values increased with greater roof slope angles. Esfeh [17] enhanced natural ventilation capacity by adjusting the geometric shape of a semi-circular arc-shaped roof. The research revealed that the ventilation performance of the arched roof is highly sensitive to the wind angle α , with the best performance at α equals 0 and the poorest performance at 75° and 90°. Kosutova [18] conducted a study on the impact of louvers with varying positions and fixed angles in buildings with flat roofs on natural ventilation. Building upon this foundation, Tai [19] conducted research on the impact of louvers with different positions and angles in buildings with flat roofs on air exchange efficiency. He also proposed optimization factors to measure the relationship between AEE and DFR. Starting from roof types and roof angles, Peren [20] conducted simulations using computational fluid dynamics (CFD) and found that, compared to buildings without eaves, the maximum increase in internal air volume flow occurred when the windward eave had a slope angle of 27°. Then Peren [21] investigated a single-sloped roof and several other concave and convex roofs, and the results showed that convex roofs could maximize the negative pressure of the wake near the building's exhaust vents, thereby enhancing cross-ventilation inside the building. Leite [22], on the other hand, combined the slope angle of a single-sloped roof with the window opening position and found that the roof slope angle had a significant impact on ventilation airflow, while the vertical position of the outlet opening had a minor effect. Atmaca [23] conducted wind-tunnel experiments and computational fluid dynamics (CFD) simulations on three differently sloped gable roofs, and found that the lowest negative pressure at all roof slopes occurred when the wind direction angle was 90 degrees. Tominaga [24] conducted numerical simulations (CFD) to study the airflow around isolated gable-roofed buildings with different roof slopes and found significant differences in the flow fields for slope ratios of 3:10 and 5:10. Additionally, there are also studies related to wind towers, wind catchers, Mansard roofs, and other structures on rooftops [25–34].

A review of the literature indicates that there is almost no research on the combination of the slope angle of gable roofs and the vertical position of outlet openings. Therefore, the innovation of this study was to analyze the effects of gable roof slope angle and vertical opening position on indoor air exchange efficiency (AEE), wind-pressure coefficient, and wind speed of independent houses by using CFD method. In the remaining part of this

paper, Section 2 introduces the research methods adopted in this study. Section 3 analyzes the results from the CFD simulation with relevant discussions. A conclusion can then be found in Section 4.

2. Methodology

2.1. Wind-Tunnel Experiment

To calibrate the CFD model used in this study, data of wind loads on low-rise buildings, which were collected by wind-tunnel experiments at the Tokyo Institute of Technology in Japan [35], were used. Due to the prevalence of low-rise buildings in suburban areas, we selected suburban terrain, categorized as Terrain Category III in accordance with AIJ (2004), as the test wind field [36]. This particular category features a mean wind velocity profile exponent of 0.20 and a gradient height of 450 m. To replicate it, we utilized turbulence-generating spires, roughness elements, and a carpet on the upstream floor of the wind tunnel's test section. The wind velocity profile and turbulence intensity profile of the simulated wind field are presented in Figure 1. At a height of 10 cm, the turbulence density measured approximately 0.25. The wind velocity during testing at this height reached approximately 7.4 m per second, which corresponds to roughly 22 m per second at a height of 10 m at full scale. The baseline model selected for this study was the flat-roof model retrieved from the database. Wind pressure measurement taps were uniformly distributed across the surfaces of the tested models, as illustrated in Figure 2. The spacing between the taps was set at 20 mm, equivalent to 2 m at full scale. However, due to limitations in the capacity of wind pressure measurement scanivalve to measure a large number of taps simultaneously, certain inner points on models with larger surfaces were not measured. Each tap was connected to a pressure measurement scanivalve via synthetic resin tubes, measuring 80 cm in length and 1.2 mm in internal diameter. These scanivalves were capable of synchronously recording fluctuating wind pressures at nearly 384 points.

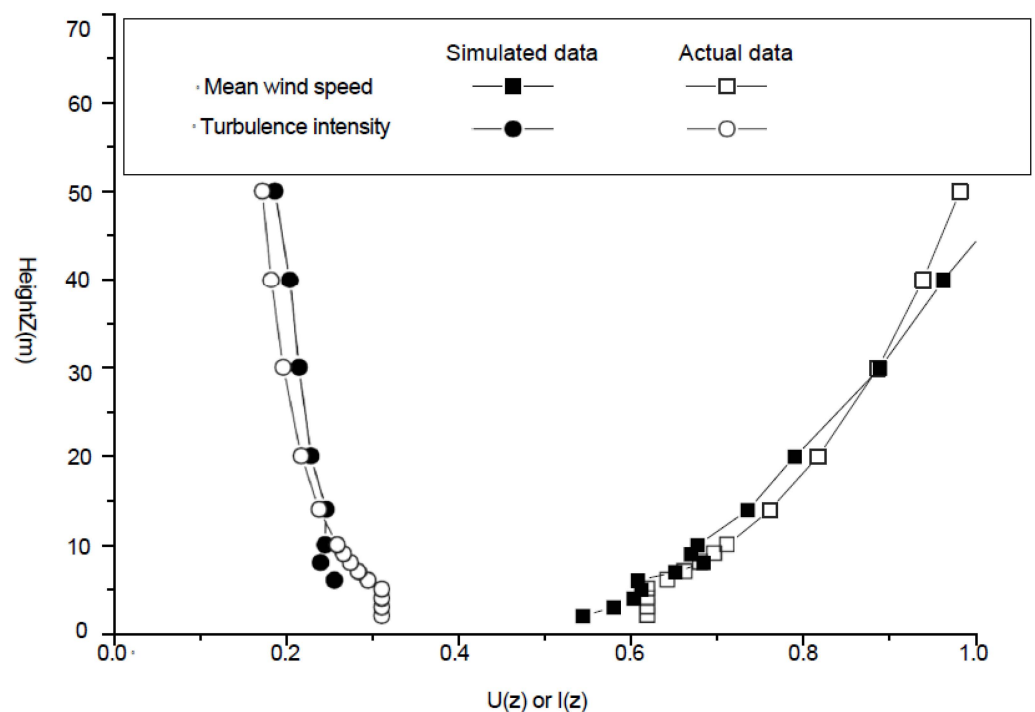
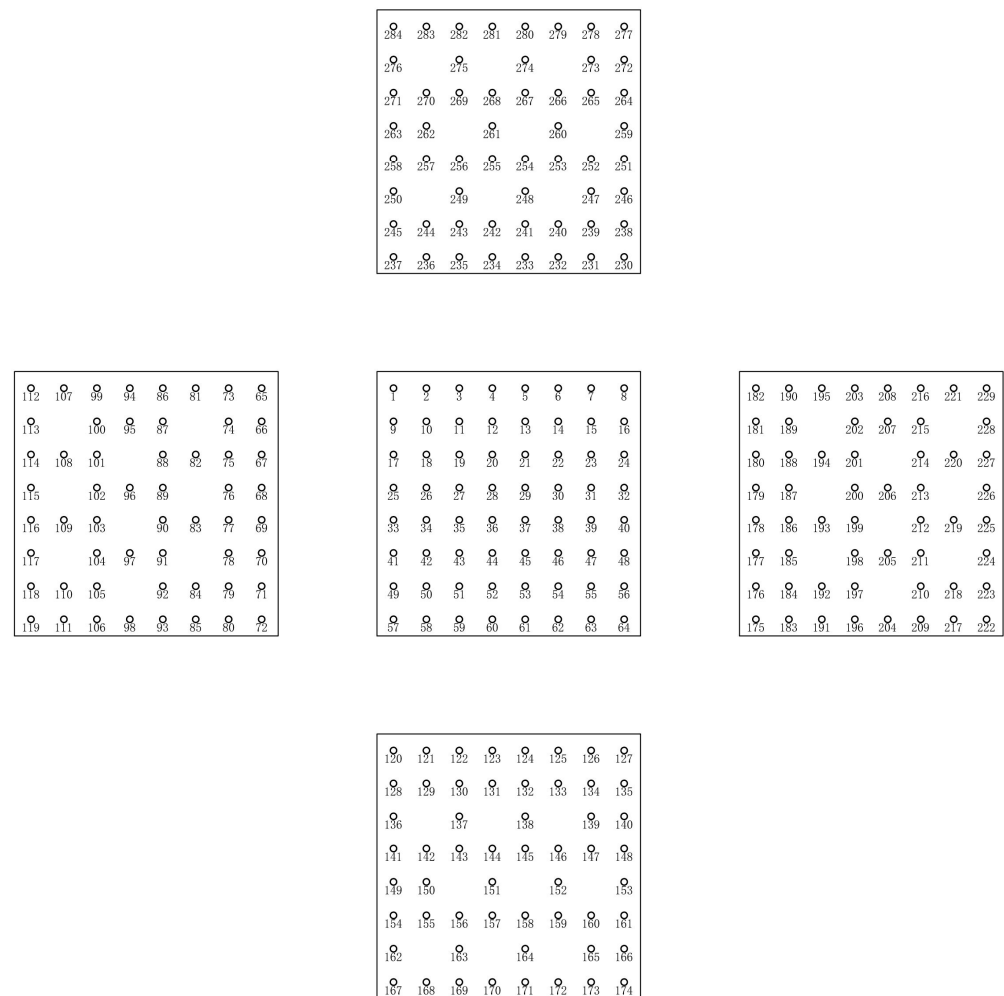


Figure 1. Simulated wind field of suburban terrain.



Position of measured points of a flat-roofed low-rise building

Building geometrical parameters: $H = 16.0$ m, $B = 16$ m, $D = 16$ m, $\beta = 0^\circ$

Figure 2. Arrangement of wind pressure measurement taps.

2.2. Model Geometry, Computational Domain, and Building Configuration

The dimensions of the building were $160 \text{ mm} \times 160 \text{ mm} \times 160 \text{ mm}$ ($L \times W \times H$). The distance from the front of the building model to the entrance was $3H$, from the side of the building model to the side and top wall of the fluid domain it was $5H$, and from the back of the building model to the exit it was $15H$, where H represents the height of the building model. The blockage ratio of the fluid domain was less than 3%. The above settings complied with the design specifications for the fluid domain [37].

The front view of the fluid domain is shown in Figure 3a, the longitudinal section in Figure 3b, and the transverse section in Figure 3c. ANSYS 2022 R1 was used for grid partitioning and CFD simulation, and local refinement of BOI was required, as shown in Figure 3b,c. The inlet and incident profile are shown in Figure 3e and the 3D mesh is shown in Figure 3f. Poly-hexcore cells were used in the meshing and 20 prism layers with a growth rate of 1.2 were applied on the ground and buildings, as shown in Figure 3d. The first cell height of the building was $35 \mu\text{m}$, with a corresponding Y^+ value of less than 0.60. Skewness of the grid was controlled to be no more than 0.65 in all numerical cases. Fine element sizes were applied at the model edges to achieve the desired grid quality and control the maximum Y^+ value. The final grid had a maximum Y^+ value of 1.26 for the walls and 1.13 for the ground. The respective average values of Y^+ for the walls and ground were 0.48235 and 0.41380.

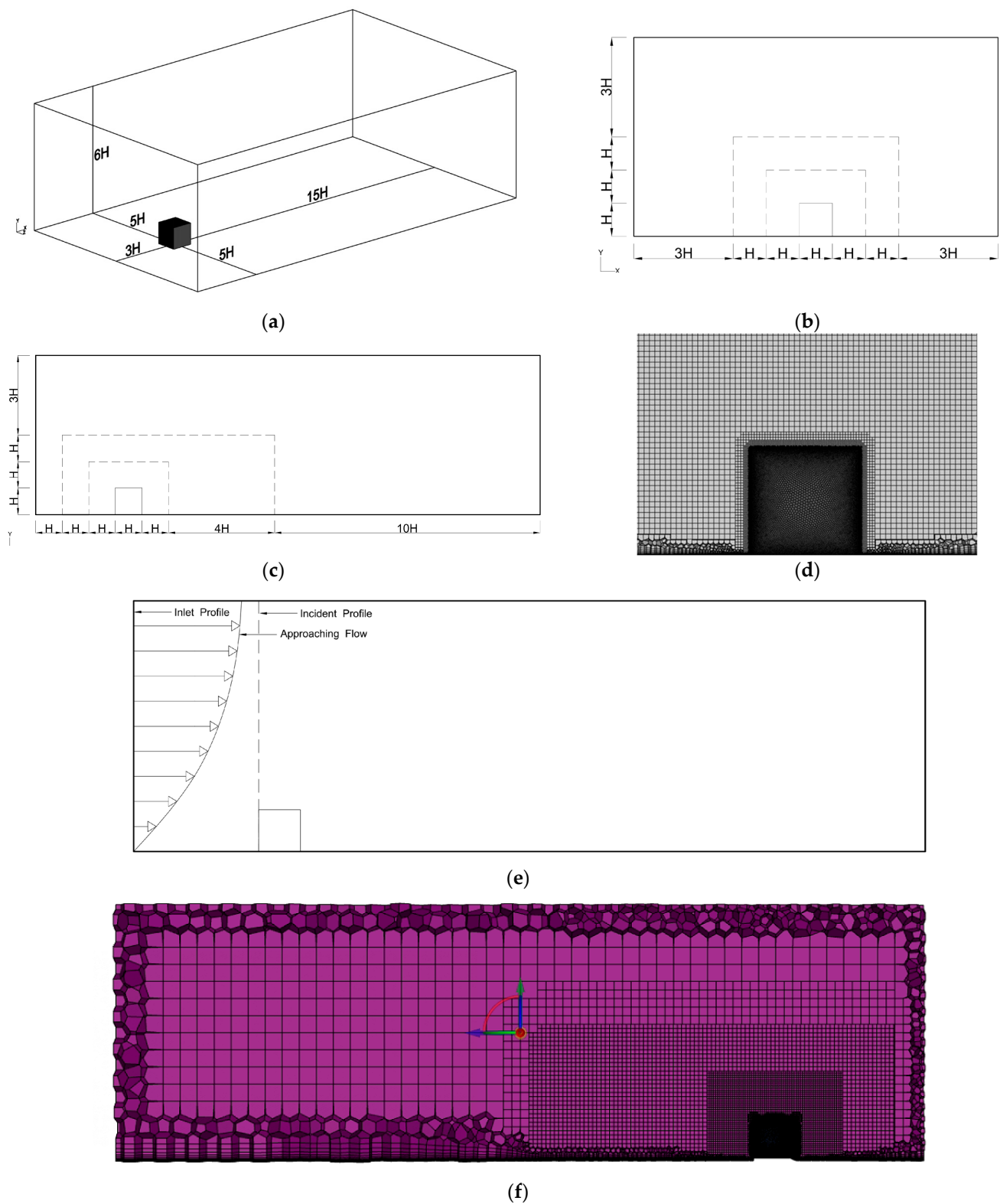


Figure 3. (a) The building in its computational domain, (b) longitudinal section, (c) transverse section, (d) prism layer around the house and ground, (e) inlet and incident profiles, and (f) 3D mesh.

2.3. Governing Equations

The shears-stress transport (SST) k - ω model transport equations are as follows:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\Gamma_k \frac{\partial k}{\partial x_j} \right] + G_k - Y_k + S_k \quad (1)$$

and

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_j} (\rho \omega u_j) = \frac{\partial}{\partial x_j} \left[\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega \quad (2)$$

where G_k represents the production of turbulence kinetic energy; G_ω represents the generation of ω ; Γ_k and Γ_ω represent the effective diffusivity of k and ω , respectively; Y_k and Y_ω represent the dissipation of k and ω due to turbulence; D_ω represents the cross-diffusion term; and S_k and S_ω are user-defined source terms. The calculation process is as follows:

2.3.1. Production of k

According to the exact equation of the transport of k , the term can be defined as

$$G_k = -\rho u_i' u_j' \frac{\partial u_j}{\partial x_i} \quad (3)$$

To evaluate G_k in a manner consistent with the Boussinesq hypothesis,

$$G_k = \mu_t S^2 \quad (4)$$

where S is the modulus of the mean rate-of-strain tensor, defined as

$$S \equiv \sqrt{2S_{ij}S_{ij}} \quad (5)$$

2.3.2. Production of ω

The production of ω is given by

$$G_\omega = \frac{\alpha \alpha^*}{V_t} G_k \quad (6)$$

where G_k is given by Equation (3) and α_∞ is given by

$$\alpha_\infty = F_1 \alpha_{\infty,1} + (1 - F_1) \alpha_{\infty,2} \quad (7)$$

$$\alpha_{\infty,1} = \frac{\beta_{i,1}}{\beta_\infty^*} - \frac{\kappa^2}{\sigma_{\omega,1} \sqrt{\beta_\infty^*}} \quad (8)$$

$$\alpha_{\infty,2} = \frac{\beta_{i,2}}{\beta_\infty^*} - \frac{\kappa^2}{\sigma_{\omega,2} \sqrt{\beta_\infty^*}} \quad (9)$$

$$\kappa = 0.41 \quad (10)$$

The coefficient is given by

$$\alpha = \frac{\alpha_\infty}{\alpha^*} \left[\frac{\alpha_0 + Re_t / R_\omega}{1 + Re_t / R_\omega} \right] \quad (11)$$

$$\alpha^* = \alpha_\infty^* \left[\frac{\alpha_0^* + Re_t / R_k}{1 + Re_t / R_k} \right] \quad (12)$$

$$Re_t = \frac{\rho k}{\mu \omega} \quad (13)$$

$$R_k = 6 \quad (14)$$

$$\alpha_0^* = \frac{\beta_i}{3} \quad (15)$$

$$\beta_i = 0.072 \quad (16)$$

2.3.3. Dissipation of k

The dissipation of k is given by

$$Y_k = \rho \beta^* f_{\beta^*} k \omega \quad (17)$$

where

$$f_{\beta^*} = 1 \quad (18)$$

and

$$\beta^* = \beta_i^* [1 + \zeta^* F(M_t)] \quad (19)$$

$$\beta_i^* = \beta_\infty^* \left[\frac{4/15 + (Re_t/R_\beta)^4}{1 + (Re_t/R_\beta)^4} \right] \quad (20)$$

$$\zeta^* = 1.5 \quad (21)$$

$$R_\beta = 8 \quad (22)$$

$$\beta_\infty^* = 0.09 \quad (23)$$

where Re_t is given by Equation (13).

2.3.4. Dissipation of ω

The dissipation of ω is given by

$$Y_\omega = \rho \beta f_\beta \omega^2 \quad (24)$$

where

$$f_\beta = 1 \quad (25)$$

$$\beta_i = F_1 \beta_{i,1} + (1 - F_1) \beta_{i,2} \quad (26)$$

$$\beta = \beta_i \left[1 - \frac{\beta_i^*}{\beta_i} \zeta^* F(M_t) \right] \quad (27)$$

F_1 is obtained from Equation (38), β_i^* is obtained from Equation (20), and $F(M_t)$ is obtained from Equation (29).

2.3.5. Cross-Diffusion Modification

D_ω is defined as

$$D_\omega = 2 (1 - F_1) \rho \frac{1}{\omega \sigma_{\omega,2}} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (28)$$

2.3.6. Compressibility Effects

The compressibility function, $F(M_t)$, is given by

$$F(M_t) = \begin{cases} 0 & M_t \leq M_{t0} \\ M_t^2 - M_{t0}^2 & M_t > M_{t0} \end{cases} \quad (29)$$

where

$$M_t^2 \equiv \frac{2k}{a^2} \quad (30)$$

$$M_{t0} = 0.25 \quad (31)$$

$$a = \sqrt{\gamma RT} \quad (32)$$

In the high-Reynolds number form of the k - ω model, $\beta_i^* = \beta_\infty^*$. In the incompressible form, $\beta^* = \beta_i^*$.

2.3.7. Modeling the Effective Diffusivity

The effective diffusivities for the SST k - ω model are given by

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \quad (33)$$

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \quad (34)$$

where σ_ω and μ_t are the turbulent Prandtl numbers for k and ω , respectively. The turbulent viscosity is μ_t .

$$\sigma_k = \frac{1}{F_1/\sigma_{k,1} + (1 - F_1)/\sigma_{k,2}} \quad (35)$$

$$\sigma_\omega = \frac{1}{F_1/\sigma_{\omega,1} + (1 - F_1)/\sigma_{\omega,2}} \quad (36)$$

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max\left[\frac{1}{\alpha^*}, \frac{SF_2}{a_1\omega}\right]} \quad (37)$$

where S is the strain rate magnitude and α^* is defined in Equation (12).

The blending function F_1 is given by

$$F_1 = \tanh(\phi_1^4) \quad (38)$$

$$\phi_1 = \min\left[\max\left[\frac{\sqrt{k}}{0.09\omega y}, \frac{500\mu}{\rho y^2\omega}\right], \frac{4\rho k}{\sigma_{\omega 2} D_\omega^+ y^2}\right] \quad (39)$$

$$D_\omega^+ = \max\left[2\rho \frac{1}{\sigma_{\omega 2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-10}\right] \quad (40)$$

The blending function F_2 is given by

$$F_2 = \tanh(\phi_2^2) \quad (41)$$

$$\phi_2 = \max\left[2 \frac{\sqrt{k}}{0.09\omega y}, \frac{500\mu}{\rho y^2\omega}\right] \quad (42)$$

where Y is the distance to the next surface.

2.3.8. Continuity Equation

$$\partial p / \partial t + \nabla \cdot (pu) = 0 \quad (43)$$

where p represents the pressure of the fluid and u represents the velocity of the fluid.

2.3.9. Momentum Equation

$$\partial (pu) / \partial t + \nabla \cdot (puu) = -\nabla p + \nabla \cdot (\mu_{eff} \nabla u) + \rho g + F \quad (44)$$

where ρ represents the density of the fluid, μ_{eff} represents the effective viscosity of the fluid, g represents the acceleration of gravity, and F represents the external force.

2.3.10. Turbulence Equation

$$\partial k / \partial t + \nabla \cdot (ku) = Pk - \varepsilon + \nabla \cdot (\mu_{eff} \nabla k) \quad (45)$$

$$\partial \omega / \partial t + \nabla \cdot (\omega u) = P\omega - \beta \omega \omega + \nabla \cdot (\mu_{eff} \nabla \omega) \quad (46)$$

where k represents turbulent flow energy, ω represents turbulent dissipation rate, Pk represents the generation term of turbulent flow energy, ε represents the dissipation term of turbulent flow energy, μ_{eff} represents the effective viscosity of turbulence, $P\omega$ represents the generation term of turbulent dissipation rate, and $\beta\omega$ represents the dissipation coefficient of turbulent dissipation rate. The constant values used in Equations (1)–(46) are shown in Table 1.

Table 1. Values of the constants used in Equations (1)–(46).

$\sigma_{k,1}$	$\sigma_{\omega,1}$	$\sigma_{k,2}$	$\sigma_{\omega,2}$	α_1	$\beta_{i,1}$	$\beta_{i,2}$	α_∞^*	α_∞	$\alpha_\circ$	β_∞^*	R_β	R_k	R_ω	ζ^*	M_{t0}
1.176	2.0	1.0	1.168	0.31	0.075	0.0828	1	0.52	1/9	0.09	8	6	2.95	1.5	0.25

2.4. Atmospheric Boundary Layer (ABL)

The ABL is the velocity profile that needs to be created from the inlet. The vertical velocity profile U on flat terrain is typically given by Equation (47), where U_{ref} is the wind speed at the reference height of 7.4 m/s, Y_{ref} is the reference height of 0.1m, and α is the roughness coefficient of 0.2 [36].

$$U = U_{ref} \left(\frac{y}{y_{ref}} \right)^\alpha \quad (47)$$

Turbulent kinetic energy K is determined by Equation (48), in which, I_u represents turbulent intensity, equal to 0.25, and A is equal to 1.

$$k = A \left(I_u U \right)^2 \quad (48)$$

The value of turbulent dissipation rate ε is typically estimated using the assumption of local equilibrium [38].

$$\varepsilon = C_\mu^{1/2} k \frac{dU}{dy} \quad (49)$$

where C_μ is the model constant equal to 0.09. Equation (50) can be obtained by rearranging the above equation.

$$\varepsilon = C_\mu^{1/2} k \frac{U_{ref}}{y_{ref}} \alpha \left(\frac{y}{y_{ref}} \right)^{\alpha-1} \quad (50)$$

Therefore, the specific turbulent dissipation rate ω is defined by Equation (51) [39]. The specific values of U , k , ε , ω are shown in Table 2.

$$\omega = \frac{\varepsilon}{C_\mu k} = C_\mu^{-1/2} \frac{U_{ref}}{y_{ref}} \alpha \left(\frac{y}{y_{ref}} \right)^{\alpha-1} \quad (51)$$

Table 2. U , k , ε , ω values at the inlet boundary.

Y (m)	U (m/s)	k (-)	ε (-)	ω (-)
0.02	5.363	1.798	28.924	178.799
0.04	6.160	2.371	21.917	102.682
0.06	8.816	4.858	32.455	74.237
0.08	9.338	5.440	28.927	58.975

2.5. Fluent Solver Settings

All CFD simulations were performed using ANSYS FLUENT 2022 R1. The SST K- ω turbulence model was employed, and a production limiter was chosen to obtain more accurate wind-pressure coefficients. The COUPLE scheme was used for pressure–velocity coupling. Pressure was selected with a second-order interpolation scheme, while momentum, turbulent kinetic energy, and turbulent dissipation rate were discretized using a second-order upwind scheme; user-defined scalars (UDS) were chosen as first-order upwind to generate more accurate results. Standard initialization was used in this numerical simulation. Convergence criteria for x , y , and z velocities; turbulent kinetic energy (k); and turbulent dissipation rate (ε) were set to 1×10^{-4} . For user-defined scalars (UDS), the convergence criteria were set to 1×10^{-5} . The computation method employed was pseudo-transient, with a time step of 0.02 s and 900 timesteps. All solutions converged after 500 iterations.

2.6. Grid Sensitivity Analysis

In the same computational domain, the grid sensitivity analysis was conducted using the aforementioned boundary conditions and solution methods. By varying the grid size of the computational domain, grid sensitivity analysis was performed on three different grid schemes with 707,430 cells (Grid 1); 1,913,049 cells (Grid 2); and 2,665,529 cells (Grid 3). Twelve points were placed on the windward, top, and leeward sides of the building to measure the wind-pressure coefficients. As shown in Figure 4, there was a significant deviation between mesh 1 and mesh 2, while there was a slight deviation between mesh 2 and mesh 3. The average percentage deviation of wind-pressure coefficients between mesh 1 and mesh 2 was 7.47%, while between mesh 2 and mesh 3, it was 0.96%. From the grid sensitivity analysis, the simulation results were not sensitive to mesh 2 and mesh 3. Therefore, mesh 2 was used for all other CFD simulations.

2.7. Model Calibration

The results from the CFD simulation were compared with data from the Japanese wind-tunnel laboratory. Twelve measurement points with a radius of 1.2 mm were selected on the windward, roof, and leeward sides of the building for comparing pressure coefficients. The pressure coefficients at various locations were calculated using Equation (6). Figure 5 compares the pressure coefficients on the building surfaces, showing overall good consistency despite some differences in negative pressure areas.

$$C_p = \frac{(P - P_0)}{(0.5\rho U_{ref}^2)} \quad (52)$$

where P represents static pressure, P_0 is the reference static pressure, ρ is the air density, and U_{ref} is the reference velocity.

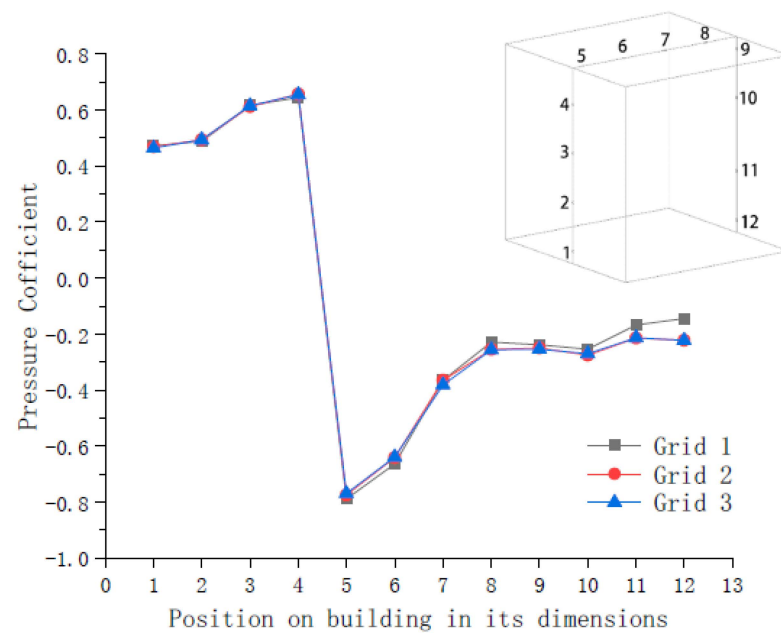


Figure 4. Results of grid sensitivity analysis.

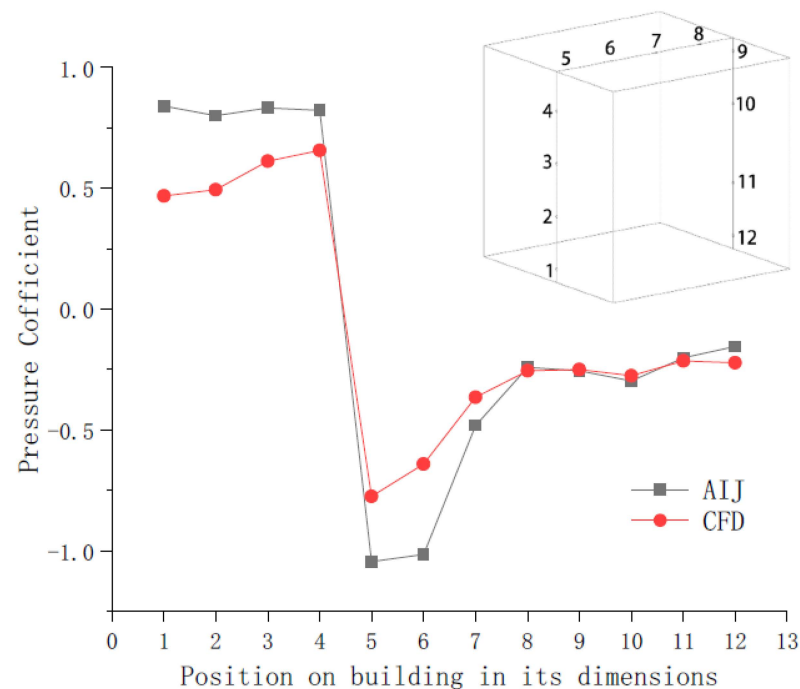


Figure 5. Comparison of CFD result with AIJ test.

3. Results and Discussion

To assess the impact of the roof inclination angle (RIA) and vertical opening position on ventilation airflow, a study was conducted on 18 different building models. These models encompassed three different opening positions (top–top, top–bottom, and bottom–top) and six different roof inclination angles (0° , 9° , 18° , 27° , 36° , and 45°). To facilitate a smooth comparison, the above models had the following characteristics: (1) identical internal volumes, (2) identical inlet and outlet opening sizes, and (3) different exit and entrance locations. Figures 6 and 7 illustrate three different opening positions and various angles of gable roofs.

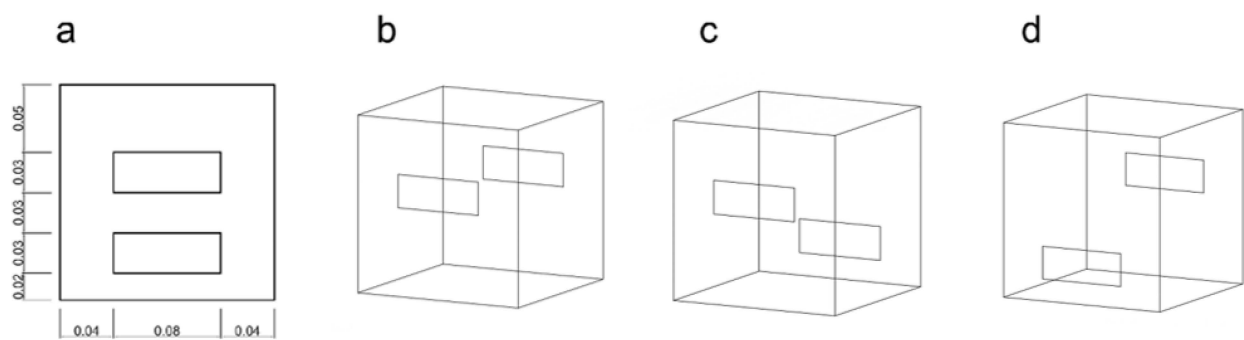


Figure 6. Opening positions and sizes. (a) The location and size of the top and bottom openings, (b) Top-Top opening configuration, (c) Top-Bottom opening configuration, (d) Bottom-Top opening configuration.

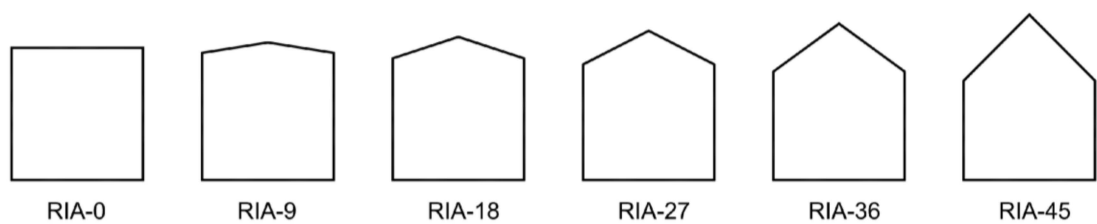


Figure 7. Gable roof inclination angles.

3.1. Pressure Coefficient, C_p

The pressure coefficient C_p is defined as the dimensionless ratio of static pressure at a specific location to the freestream static pressure, as shown in Equation (48). The contour lines of pressure coefficients are presented in Table 3. It can be observed that, with the same opening configuration, as the slope increased, the pressure stagnation region at the top of the building gradually shifted towards the highest point of the roof, and the leeward-side openings typically exhibited negative C_p values. In various building cases, the negative pressure difference at the building’s windward outlets was consistently greater than the positive pressure difference at the windward inlets, indicating that the roof slope angle is a crucial parameter for enhancing wind-driven natural cross-ventilation.

Table 3. Pressure coefficient, C_p , suitable for different open configurations with gable roofs.

Configuration	Legend	0	9	18	27	36	45
Top–Top	$\frac{U}{U_{ref}}$ $C_p[-]$ 						
Top–Bottom							
Bottom–Top							

3.2. Dimensionless U/U_{ref}

The dimensionless quantity U/U_{ref} was obtained by dividing the average streamwise velocity U by the reference velocity U_{ref} (7.4 m/s). The contour lines of the dimensionless quantity U/U_{ref} are depicted in Table 4. From Tables 4 and 5, it can be observed that there was a notable increase in flow velocity in the opening region, a phenomenon evident across all models. Through observation, it was noted that when the opening configuration was top–top or top–bottom, the flow velocity in the exhaust opening area increased with changes in the roof slope, reaching its maximum at 45° , with an acceleration rate 1.2 times that of a flat roof. Conversely, in the case of a bottom–top opening configuration, due to the Coanda effect, the airflow remained attached to the building's bottom, resulting in a lack of sensitivity of flow velocity in the exhaust opening area to changes in roof angle, with flow velocity remaining relatively constant at around 0.6. Overall, the airflow velocity in the exhaust opening area was more sensitive to the vertical opening position than to the slope angle of the gable roof.

Table 4. U/U_{ref} suitable for different open configurations with gable roofs.

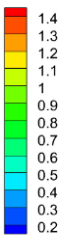
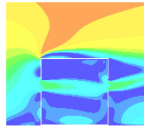
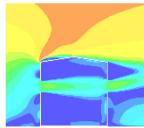
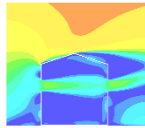
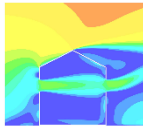
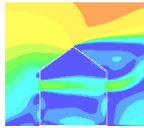
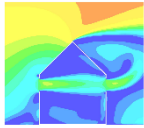
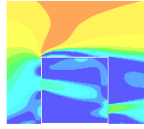
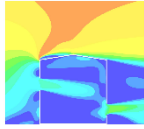
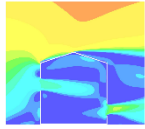
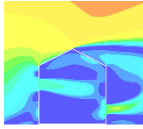
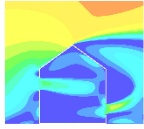
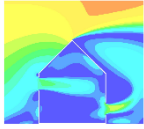
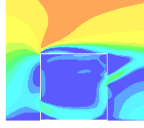
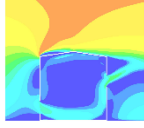
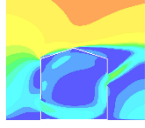
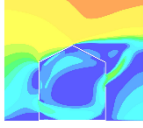
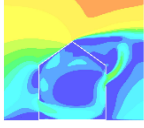
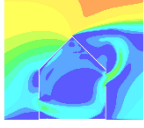
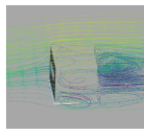
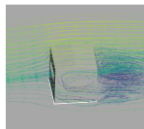
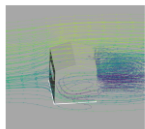
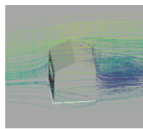
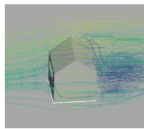
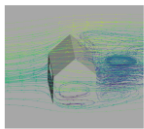
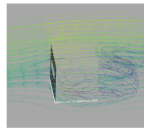
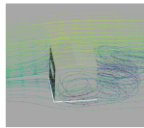
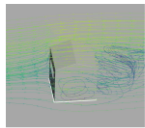
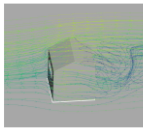
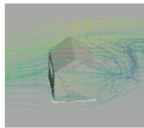
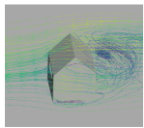
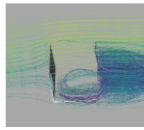
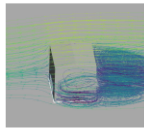
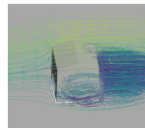
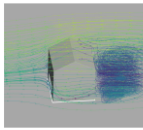
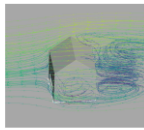
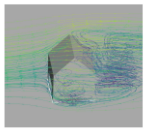
Configuration	Legend	0	9	18	27	36	45
Top–Top	$\xrightarrow{U/U_{ref}}$ $U/U_{ref}[-]$ 						
Top–Bottom							
Bottom–Top							

Table 5. U suitable for different open configurations with gable roofs.

Configuration	Legend	0	9	18	27	36	45
Top–Top	$\xrightarrow{U/U_{ref}}$ $U[m/s]$ 						
Top–Bottom							
Bottom–Top							

3.3. Air Exchange Efficiency (AEE)

Air exchange efficiency represents the efficiency of external air flushing the interior of a ventilated building [40]. The AEE is defined by Equation (53), where τ_r represents

the AOA at the leeward openings, and τ_{av} is the average volume-averaged AOA within the building.

$$\varepsilon_A = \frac{\bar{\tau}_r}{2\tau_{av}} \times 100[\%] \quad (53)$$

AOA is calculated using the following scalar transport equation [41].

$$\frac{\partial}{\partial t} \rho \varphi + \nabla \cdot (\rho U \varphi) - \nabla \cdot (\Gamma \nabla \varphi) = S_\varphi \quad (54)$$

where φ represents the scalar being solved for, i.e., AOA, with $S_\varphi = 1$ denoting the source term. The diffusion coefficient Γ is determined using a specific formula [41].

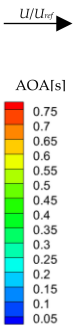
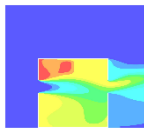
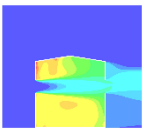
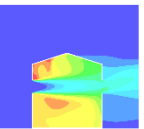
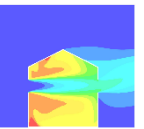
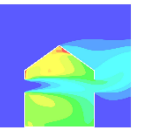
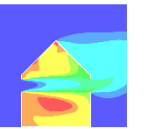
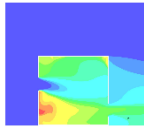
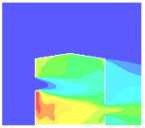
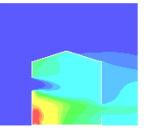
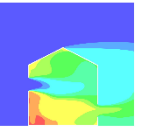
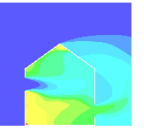
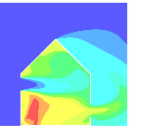
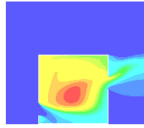
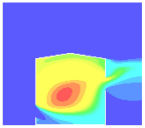
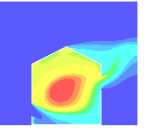
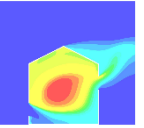
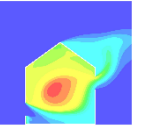
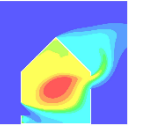
$$\Gamma = \rho D + \frac{\mu_t}{S_{ct}} \quad (55)$$

where $D = 2.88 \times 10^{-5} \text{m}^2/\text{s}$ represents the laminar viscosity of air at a working temperature of 20 °C, μ_t is the local turbulent viscosity, and $S_{ct} = 0.7$ is the turbulent Schmidt number.

Under steady-state conditions, the term $\partial (\rho \varphi) / \partial t$ in Equation (54) equals zero. The transport equation was implemented in FLUENT using user-defined scalars (UDS) to compute AOA within the building. Equation (55) was employed to determine boundary conditions, setting zero values at the inlet and zero gradients at the walls and exit surfaces.

Table 6 presents the AOA distribution for all operating conditions, Figure 8 illustrates the percentage of AEE for all conditions, and Figure 9 displays the average volume AOA within the building. From Table 4, it can be observed that in the top–top opening configuration, at 0°, the AOA between the windward-facing window and the roof was relatively high, gradually decreasing with an increase in roof angle, reaching an optimum at 36°. In the top–bottom configuration, the AOA between the windward-facing window and the roof was lower but higher than the ground as the roof angle increased, with the ground portion of AOA gradually decreasing. In the bottom–top configuration, the formation of eddies within the building led to excessively high AOA in the central region of the structure, and it was insensitive to changes in roof slope.

Table 6. Age of air (AOA) suitable for different open configurations with gable roofs.

Configuration	Legend	0	9	18	27	36	45
Top–Top							
Top–Bottom							
Bottom–Top							

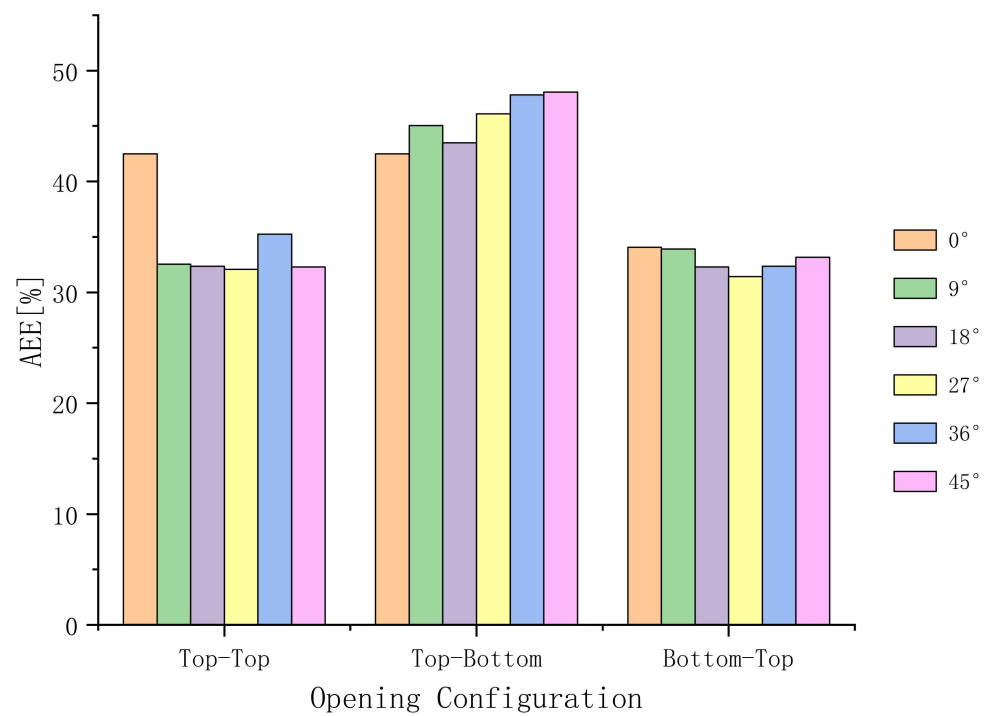


Figure 8. Air exchange efficiency (AEE) with different angles of gable roofs and different opening positions.

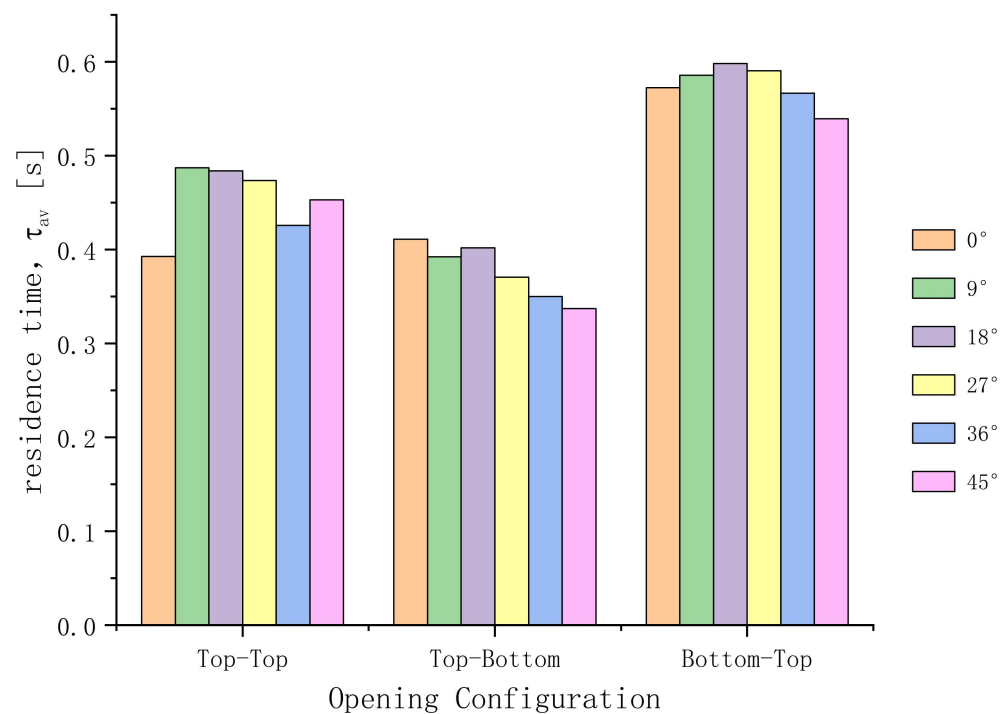


Figure 9. Average volume-averaged age of air (AOA) with different angles of gable roofs and different opening positions.

From Figure 8, it can be observed that the AEE was highest at 45° top-bottom, reaching 48.1%, and lowest at 27° bottom-top, at only 31.4%. In the top-top opening configuration, the AEE for the flat roof was highest at 42.5%, while the AEE for the other five angles was around 32%. This indicates that in this configuration, AEE is not highly sensitive to changes in the gable roof angle. In the top-bottom opening configuration, AEE increased

with an increase in roof slope angle, reaching its peak at 45° , at 48.1%. This suggests that in this configuration, the angle of the gable roof effectively promotes indoor airflow, thereby enhancing AEE.

In the bottom–top opening configuration, the AEE for roofs with different slope angles was quite similar, averaging around 32%. This suggests that AEE is not highly sensitive to changes in the gable roof angle in this configuration. Due to the presence of low–high windows, it is easy for vortices to form within the building, leading to a relatively low AEE.

Figure 9 reveals that in the top–bottom opening configuration with a gable roof slope angle of 45° , τ_{av} was at its lowest, measuring 0.33 s. In the bottom–top opening configuration with a roof slope angle of 18° , τ_{av} was highest, at 0.6 s. When considering Figures 8 and 9 together, it becomes evident that τ_{av} maintained a strong negative correlation with AEE. When τ_{av} was low, AEE tended to be high, and conversely, when AEE was high, τ_{av} was low.

4. Conclusions

The impact of gable roofs with varying slope angles and different vertical opening positions was investigated. The opening configurations included: (1) top–top, (2) top–bottom, and (3) bottom–top, with gable roof angles of 0° , 9° , 18° , 27° , 36° , and 45° , hence a total number of 18 combinations. The design of the computational domain adhered to best practices outlined in the literature and was simulated numerically with the inclusion of an atmospheric boundary layer (ABL). Reference grids underwent grid sensitivity analysis, and numerical simulations were carried out using the SST k- ω model, with results demonstrating good consistency. Subsequently, an analysis of internal velocities, pressure coefficients, AOA, AEE, and other parameters was conducted, contributing to the advancements made in this study.

- (1) In all configurations in this paper, the slope angle of the roof and the vertical opening positions did appear to have a significant impact on the wind-pressure coefficients.
- (2) In terms of flow velocity, favorable opening positions were more conducive to an acceleration in velocity. With the top–bottom opening configuration, the wind speed at the windward opening was greater than that in the other two opening configurations.
- (3) The highest AEE was 48.1%, obtained with the opening configuration of top–bottom and a roof slope angle of 45° , while the lowest AEE was 31.4%, achieved with the opening configuration of bottom–top and a roof slope angle of 27° .
- (4) When the opening configuration was top–bottom, the slope angle of gable roofs had a significant impact on AEE, with a 5.5% relative increase in AEE for a 45° gable roof compared to a flat roof. This configuration is encouraged for use in buildings.
- (5) When the opening configuration was bottom–top, the slope angle of the gable roof had a very limited impact on the profile wind speed and AEE. Therefore, it is not recommended to use this opening configuration in buildings.

In conclusion, this research has shown that in cross-ventilation, the slope angle of gable roofs and the vertical opening positions play crucial roles in internal airflow, pressure coefficients, AEE, AOA, and other parameters. It is hoped that through this study, buildings' reliance on mechanical cooling can be reduced. Future work should include, but not be limited to, researching wind speed profiles and pressure coefficients under different wind directions or introducing various types of guiding windows and more complex ventilated roofs on the basis of existing openings and studying their ventilation performance.

Author Contributions: Conceptualization, J.S., C.Z. and Y.L.; methodology, J.S.; software, C.Z.; validation, J.S.; formal analysis, J.S., C.Z. and Y.L.; investigation, C.Z.; resources, J.S.; data curation, C.Z.; writing—original draft preparation, J.S.; writing—review and editing, J.S., C.Z. and Y.L.; supervision J.S., C.Z. and Y.L.; project administration, J.S., C.Z. and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the support of the National Natural Science Foundation of China Youth Fund Project (52208095), the Chongqing Municipal Science and Technology Commission

“Doctoral Direct Train” Project (CSTB2022BSXM-JCX0162), the Chongqing Municipal Education Commission Science and Technology Project (KJQN202100736), and Research on the construction of Genetic Map of Traditional Villages in Chongqing Drievn by Digital Intelligence (23SKGH130).

Data Availability Statement: Not applicable.

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

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