



Parametric evaluation of a façade-integrated natural ventilation system for multi-storey buildings

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ABSTRACT

Single-sided ventilation (SSV) in multi-storey buildings often suffers from limited flow penetration, strong directional dependence, and floor-to-floor imbalance. This study investigates a façade-integrated Wall Windcatcher (WWC) system designed to overcome these limitations by combining a low-level supply inlet and a high-level exhaust outlet on the same façade, connected by an external vertical duct. A computational fluid dynamics (CFD) framework was first validated against atmospheric boundary layer wind-tunnel measurements using a baseline WWC geometry, which then served as the reference model for a systematic parametric analysis of geometric modifications and contextual factors based on a steady-state RANS ($k-\epsilon$ RNG) approach. Design variants were tested across wind angles from 0° to 180° to capture windward, oblique, parallel, and leeward exposures. For the $k-\epsilon$ RNG model, agreement in pressure coefficients (C_p) for WWC cases yielded MAPE values of 5.6% (0° wind angle), 4.6% (45°), and 6.8% (90°), providing a validated basis for parametric comparisons. Three design parameters were tested individually and in combination: (i) additional riser expansion transitions along the vertical exhaust duct, (ii) enlarged outlet size, and (iii) a thin inlet plane. The additional riser transition reduced internal back-pressure and improved vertical continuity, enlarged outlets strengthened upper-storey extraction but could suppress ground-floor intake at high obliquity, and the inlet plane provided the largest single improvement under oblique winds. The fully integrated design (COC2: inlet plane + transitions + enlarged outlet) achieved the highest and most uniform velocities, with up to $2-3\times$ higher performance than the baseline and measurable improvements even under leeward winds. Increasing building height (to four and five storeys) enhanced mid- and upper-floor ventilation without significantly penalising lower levels. Urban-canyon simulations showed that wider street-to-building ratios improved windward and side-zone performance, while leeward zones remained limited by wake shielding. The results demonstrate that a retrofit-focused WWC can outperform SSV when inlet capture (inlet plane), duct continuity (transitions), and outlet discharge are optimised together. The findings provide practical guidance for passive ventilation design, and the development of modular façade retrofit systems for multi-storey buildings.

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Nomenclature

Symbol/Term	Definition	Units
U	Local wind speed	m/s
U_{ref}	Reference wind speed at roof height z_{ref}	m/s
z	Height above ground/tunnel floor	m
z_{ref}	Reference height (roof level)	m
p	Static pressure	Pa
p_{ref}	Reference static pressure (upstream pitot-static)	Pa
ΔP	Pressure difference (e.g., pitot total-static)	Pa
$q_{ref} = 0.5\rho U_{ref}^2$	Reference dynamic pressure	Pa
$\mathbf{v} \rightarrow$	Velocity vector	m/s
v	Speed magnitude (indoor airflow)	m/s
$\dot{V}$	Volumetric flow rate	m ³ /s
A	Area (opening/section)	m ²
L, W, H	Length, width, height (geometry)	m
t	Time	s
e	Specific internal energy	J/kg
h_f	Specific enthalpy of mass (dry air)	J/kg
J_j	Diffusion flux of species j	kg/m ² s
S_h	Volumetric heat source	W/m ³
ρ	Air density	kg/m ³
μ	Dynamic viscosity	Pa·s
μ_{eff}	Effective viscosity	Pa·s
ν_t	Turbulent kinematic viscosity	m ² /s
κ_{eff}	Effective thermal conductivity	W/m·K
τ	Stress tensor	Pa
τ_{eff}	Effective stress tensor	Pa
k	Turbulence kinetic energy	m ² /s ²
ϵ	Turbulence dissipation rate (k- ϵ)	m ² /s ³
ω	Specific dissipation rate (k- ω)	1/s
α	Power-law exponent for ABL velocity profile	-
$\mathbf{g} \rightarrow$	Gravitational acceleration vector	m/s ²
C_p	Pressure coefficient	-
I or T_i	Turbulence intensity (σ_u/U)	-
MAPE	Mean Absolute Percentage Error	%
NMSE	Normalised Mean Square Error	-
FB	Fractional Bias	-
R, R ²	Pearson correlation, coefficient of determination	-
i, j	Spatial components/indexing	-
$\sim$	Spatial averaging operator	-
$\bar{}$	Time averaging operator	-

Acronym	Definition
ACH	Air Changes per Hour.
ABL	Atmospheric Boundary Layer
CFD	Computational Fluid Dynamics
RANS/URANS/LES	(Unsteady) Reynolds-Averaged Navier-Stokes/Large-Eddy Simulation
RNG/SST	Renormalization Group (k- ϵ)/Shear-Stress Transport (k- ω)
WWC	Wall Windcatcher (façade-integrated)
SSV/CV	Single-Sided Ventilation/Cross-Ventilation
COC1/COC2	Combined Optimised Cases
S/B	Street-to-Building height ratio
GF, 1F, 2F	Ground, First, Second Floor

1. Introduction

Rapid urbanisation and city-centre densification have increased the prevalence of multi-storey residential and office buildings [1], where achieving adequate indoor air quality [2–4] and thermal comfort [5] is challenging under variable winds and complex floor plans. While HVAC systems provide controllable ventilation, they carry high energy and carbon penalties and face growing scrutiny under decarbonisation targets and tightening efficiency standards [6,7]. This has renewed interest in robust, retrofit-friendly natural ventilation strategies that can deliver sufficient and more evenly distributed airflow in multi-storey buildings [8].

Conventional wind-driven ventilation typically relies on single-sided ventilation (SSV) through openings on one façade [9,10] or, where possible, cross ventilation (CV) between openings on opposite/adjacent façades [11,12]. SSV is simple but often provides limited airflow depth (Fig. 1a), is strongly wind-direction dependent, and tends to produce stagnant indoor zones, especially in multi-storey layouts with internal partitions and vertically stacked floors [9–13]. Because air enters and exits through the same façade, ventilation efficiency is reduced [14,15], particularly when wind approaches parallel to the opening, and is further weakened in dense urban environments by turbulence, pressure fluctuations, and sheltering from surrounding buildings [16]. Prior studies reflect these sensitivities: Zhong et al. [9] showed SSV is dominated by turbulent pulsations and eddy penetration unless openings are carefully designed, while Aflaki et al. [10] reported strong floor-to-floor imbalance in a 17-storey building, with upper windward units achieving 90% thermal acceptability (0.52 m/s) but air speeds up to eight times lower in lower leeward units; although “pumping

ventilation” between paired openings can help modestly [9], uneven distribution and stagnant zones remain common.

CV can, in principle, deliver much higher air exchange by establishing a clearer windward-to-leeward pathway [17,18]; for example, Chu [11] reported up to $20 \times$ higher airflow than SSV under identical wind speeds and opening areas, and Miše et al. [19] found ACH at least six times higher than SSV in wind-tunnel tests. However, real-building performance is often constrained by internal layout and external context: Pan et al. [20] showed that partitions and limited connectivity create substantial “internal resistance,” leading to non-unidirectional flow (consistency ratio = 50–98%) and ineffective recirculation when $\sigma < 70\%$, while Ai and Mak [13] found that floor-plan and door-position variations and external turbulence reduce uniformity and stability in multi-storey buildings. In dense urban settings, wake interference and shielding can reduce CV airflow by $>50\%$ when neighbouring buildings are closely aligned, recovering only when spacing exceeds five building widths ($W \approx 5B$) [21]; leeward units and shared circulation cores further limit effective CV pathways [22], and upstream vegetation can reduce cross-ventilation by 20–24% depending on canopy characteristics [23]. Collectively, these findings highlight that internal resistance, wake shielding, and wind-direction variability can severely limit the reliability of both SSV and CV in tall buildings.

Windcatchers are a well-established passive ventilation strategy: traditional roof-mounted systems, originating from Middle Eastern architecture, harness higher-elevation winds to drive indoor ventilation and cooling in hot, arid climates [24], and modern

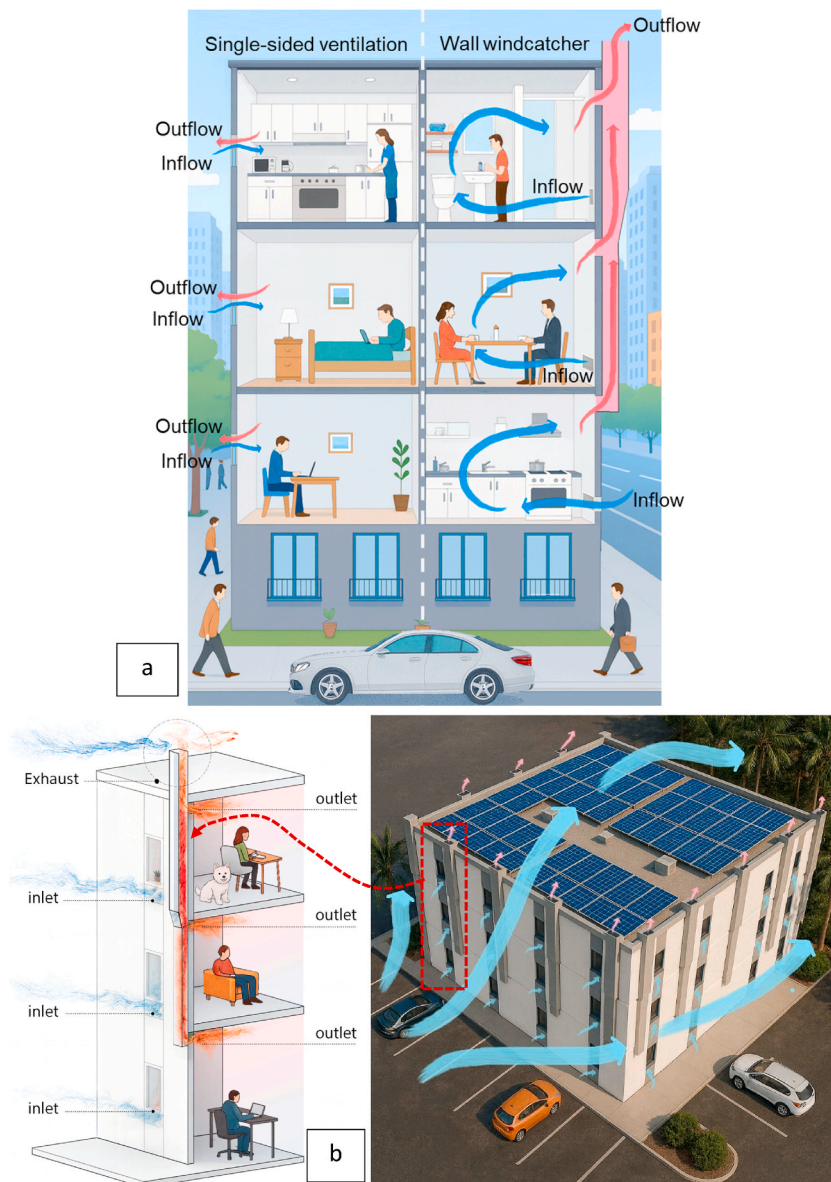


Fig. 1. Application of (a) single sided and WWC ventilation systems in a multi-story building. (b) Example of the installation of the WWC system into a multi-story, and the working principle.

designs incorporate aerodynamic refinements [25], internal partitions, and hybrid components such as heat exchangers [26] or evaporative cooling modules [27]. Although experiments and simulations show they can significantly enhance airflow and improve comfort under favourable conditions [28], conventional rooftop windcatchers mainly benefit upper storeys because airflow momentum decays with depth [29]; serving lower floors typically requires long internal ducting that adds friction and junction losses and is difficult to retrofit due to structural, fire-safety, and ceiling-space constraints, making installation in occupied multi-storey urban buildings costly and often impractical [30].

1.1. Research gap and motivation

Consequently, there remains a gap for a façade-integrated wind-driven system capable of delivering the benefits of roof windcatchers in a more compact, adaptable form. Such a system should (i) distribute airflow more evenly across multiple storeys, (ii) maintain performance across a wider range of wind directions including parallel (90°) and leeward (180°) cases where conventional strategies may be limited and (iii) be practical to retrofit with minimal disruption to occupants and building structure. This gap motivates façade-mounted solutions such as the wall windcatcher (WWC) previously introduced in Ref. [12,31], which combine wind-driven capture with integrated exhaust channels to deliver multi-storey ventilation in a compact, modular form (Fig. 1a).

In its basic form, the WWC places a low-level supply inlet and a high-level exhaust outlet on the same façade for each floor, linked via a shared, externally mounted vertical exhaust duct (Fig. 1b). The arrangement increases the pressure difference between inlet and outlet by combining local wind-induced effects at the façade with a Venturi-type suction at the duct head. By separating the supply and exhaust paths within the same wall, the configuration reduces short-circuiting risk and promotes deeper penetration and extraction compared with single openings. Crucially, because the main duct is external, the WWC is inherently retrofit-oriented and can be installed with minimal internal works, requiring only small façade accesses per floor. The external riser also simplifies maintenance and allows modular add-ons such as insect screens and filters without extensive reconfiguration, enabling scalable deployment.

Despite encouraging preliminary evidence that a baseline WWC can outperform SSV under several wind angles [31], its real-world value depends on design robustness across a wide range of operating scenarios that are known to degrade natural ventilation performance. In particular, ventilation effectiveness typically deteriorates as incident wind rotates from windward (0°) towards parallel (90°) and leeward (180°) orientations, where eddy penetration, separation, and fluctuating façade pressures dominate and where common modelling approaches show increased uncertainty. Furthermore, multi-storey retrofits must sustain performance when (i) building height increases the resistance of the shared exhaust duct and shifts floor-to-floor balance, and (ii) dense urban morphologies alter approach flows through sheltering and street-canyon effects.

These challenges motivate a focused, CFD-driven parametric study of the WWC geometry and operating envelope, supported by an atmospheric boundary layer wind-tunnel validation of the baseline WWC configuration. The aim is to identify design adjustments that strengthen the inlet–outlet pressure differential and reduce internal losses without changing the practical, retrofit-friendly placement of openings. Parameters of interest include (a) additional riser expansion transitions along the vertical exhaust duct (two-step enlargement) to reduce cumulative-flow losses, (b) outlet sizing to relieve back-pressure, (c) inlet plane features to improve wind capture and boundary-layer guidance, (d) coordinated combinations of these features, (e) scaling of the exhaust duct for taller buildings, and (f) sensitivity to surrounding-building layouts expressed via street-to-building (S/B) height ratios. By resolving how these parameters interact with wind direction and speed, the study seeks to produce evidence-based guidance for robust, scalable WWC designs that maintain or improve airflow even under oblique, parallel, and leeward winds and in constrained urban settings.

The motivation for this work is threefold: (1) address the persistent under-performance of SSV in multi-storey contexts through a façade-based alternative that is practical to retrofit; (2) quantify, via validated CFD, which geometric features most effectively convert available wind energy into stable, vertically distributed airflow under realistic wind directions; and (3) establish how building height and urban morphology modulate WWC performance so that design recommendations remain applicable to mid-rise retrofits and dense city blocks.

1.2. Contribution to knowledge, aims and objectives

This study advances façade-integrated, wind-driven ventilation by extending the WWC from a conceptual solution to a validated and advanced design framework for multi-storey buildings. Building on previous work [12,31], this research develops and experimentally validates a CFD model using steady-state Reynolds-Averaged Navier–Stokes (RANS) k – ϵ RNG model and ABL conditions, verified against wind-tunnel data for both pressure coefficients and airflow velocities. The validated framework is then applied to a structured parametric programme that isolates and quantifies the aerodynamic roles of three geometric features, an inlet plane, outlet transitions, and enlarged outlets, and their combined effects on airflow distribution and pressure differentials. Results identify how each parameter contributes to system performance across varying wind angles and demonstrate which configuration provides the most uniform and efficient multi-storey ventilation, as compared to single-sided ventilation (SSV) in particular under challenging parallel (90°) and leeward (180°) conditions. The study further examines the influence of building height on WWC performance, evaluating how airflow distribution evolves across multiple storeys and how transition geometry and duct sizing affect pressure balance in taller configurations.

Beyond individual design optimisation, the study introduces new insights into how urban morphology, multi-zone configurations, and street-to-building (S/B) ratios influence WWC performance. By simulating simplified canyon arrays, it quantifies the sensitivity of windward, side, and leeward façades to confinement and turbulence, demonstrating the WWC's superior resilience to sheltering compared with conventional SSV. These results are synthesised into practical design guidance that links geometric parameters,

building height, and urban form to performance outcomes, providing evidence-based strategies for retrofitting or designing mid-rise buildings in dense city environments. The novelty of this work lies in its integration of experimental validation, CFD-based parametric optimisation, and contextual sensitivity analysis within a single framework, establishing a comprehensive assessment of a façade-mounted WWC system. In doing so, it transforms the WWC from a proof-of-concept into a scalable, retrofit-ready natural ventilation technology with clearly defined aerodynamic principles and design recommendations for real-world application.

The primary aim of this study is to benchmark and refine the aerodynamic performance of the WWC system for multi-storey natural ventilation through a combined approach of CFD simulation and wind-tunnel validation. A baseline WWC configuration is first validated against atmospheric boundary layer wind-tunnel measurements and then retained as the reference model for all subsequent numerical investigations. The research compares baseline WWC and single-sided ventilation (SSV) performance across a range of wind angles, quantifies the effects of individual and combined geometric modifications on airflow distribution and extraction efficiency, and evaluates system robustness under oblique, parallel, and leeward wind conditions. It further examines the scalability of the WWC in four- and five-storey configurations, assesses performance in multi-zone layouts, and analyses sensitivity to urban morphology through variations in street-to-building (S/B) ratios and surrounding-building enclosures. The aerodynamic performance of the WWC is evaluated using validated CFD analysis based on steady-state RANS simulations with an atmospheric boundary layer (ABL) inlet profile, supported by concise validation against wind-tunnel measurements and a systematic series of parametric variations. Environmental conditions include wind angles from 0° to 180° at a reference roof-height velocity of 7.59 m s^{-1} , with key performance metrics comprising floor-averaged indoor velocity and pressure coefficients. Collectively, these objectives aim to generate evidence-based design recommendations for scalable, façade-integrated retrofit applications in multi-storey buildings.

The remainder of the paper is structured as follows. Section 2 outlines the research methodology, describing the overall workflow, the experimental wind-tunnel setup, the CFD modelling framework, and the validation process used to establish model reliability. Section 3 details the parametric study, presenting the baseline WWC configuration, geometric variations, height and urban-context scenarios, and the performance metrics adopted for comparison. Section 4 presents and discusses the results, including validation outcomes, the influence of each geometric modification, combined optimisation cases, height-scaling effects, and sensitivity to surrounding-building configurations. Section 5 synthesises the key findings, explaining the underlying aerodynamic mechanisms, design trade-offs, and implications for retrofit applications. It also outlines the study's limitations. Section 6 summarises the main conclusions and suggestions for future works.

2. Method and validation

2.1. Study workflow overview

The study followed a three-stage workflow. First, atmospheric boundary layer (ABL) wind tunnel tests were conducted on a three-storey acrylic model (Fig. 2) to obtain (i) internal pressure coefficients on room walls and (ii) air velocities at inlets and outlets for the baseline wall windcatcher (WWC) configuration. Second, a 3D steady-state RANS CFD model was developed to replicate the wind tunnel arrangement using the same baseline geometry, with the measured ABL velocity profile imposed as the inlet boundary condition and the $k-\epsilon$ RNG turbulence model employed. The CFD predictions were validated against the wind tunnel data using standard statistical metrics.

Third, the validated baseline CFD model was retained as the reference and extended to a parametric analysis of WWC design variants, including additional riser expansion transitions along the vertical exhaust duct, outlet sizing, inlet plane modifications, and combined optimised cases (COC1/COC2), as well as height scaling (four- and five-storey configurations) and urban context scenarios (enclosures with different street-to-building ratios). Simulations were performed across a range of wind angles representative of windward, oblique, parallel, and leeward exposures. The wind tunnel stage is presented concisely to support CFD validation, while the principal emphasis is placed on the CFD-based parametric exploration.

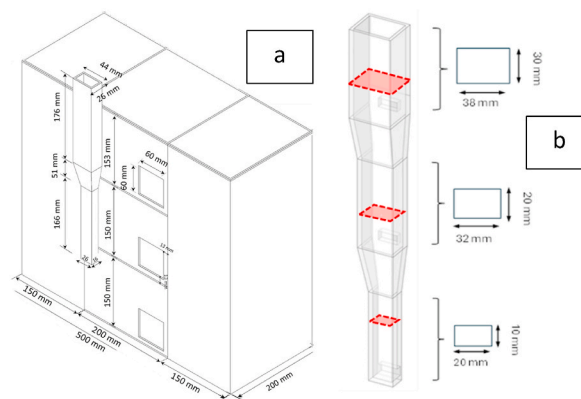


Fig. 2. Dimensions of the (a) multi-story building model and (b) WWC system.

2.2. Wind tunnel experiments

Experiments were performed in an ABL wind tunnel with a 3.1 m (L) $\times$ 2.4 m (W) $\times$ 1.9 m (H) test section and a 2 m diameter turntable to vary model orientation (Fig. 3a) [12,32,33]. An upstream fetch with Irwin spires and staggered roughness blocks generated a suburban-type boundary layer [34,35]. The building model (acrylic, 1:20 scale) measured 200 $\times$ 200 $\times$ 450 mm, with three 150 mm-high floors (Fig. 2). The WWC has a 60 $\times$ 60 mm low-level inlet and a 10 $\times$ 20 mm high-level outlet per floor, connected to an external vertical exhaust duct. In the baseline configuration, the duct consists of two rectangular segments (lower and upper) connected by a single riser expansion transition located near the first-floor outlet level, as described further in Section 3.1. Static pressures were recorded via 60 wall taps (20 per floor) routed to a Scanivalve MPS4264 (± 0.5 Pa accuracy) referenced to an upstream pitot-static tube (Fig. 3c). Air velocities at inlets/outlets were measured with Testo 405i hot-wire probes (Fig. 3b) [36].

The incoming ABL was characterised at the model centreline; the reference velocity at roof height ($z = 0.453$ m) was set to $U_{\text{ref}} = 7.59$ m/s for validation runs (additional low-speed checks at $U_{\text{ref}} = 3.82$ m/s were used to confirm scaling). The model was tested at 0° , 45° , and 90° . Pressure time series were sampled for 200 s at 50 Hz (three repeats); velocity series at inlets/outlets were recorded for 5 min (three repeats). Post-processing yielded time-averaged pressure coefficients (C_p) and mean air velocities at each monitored point.

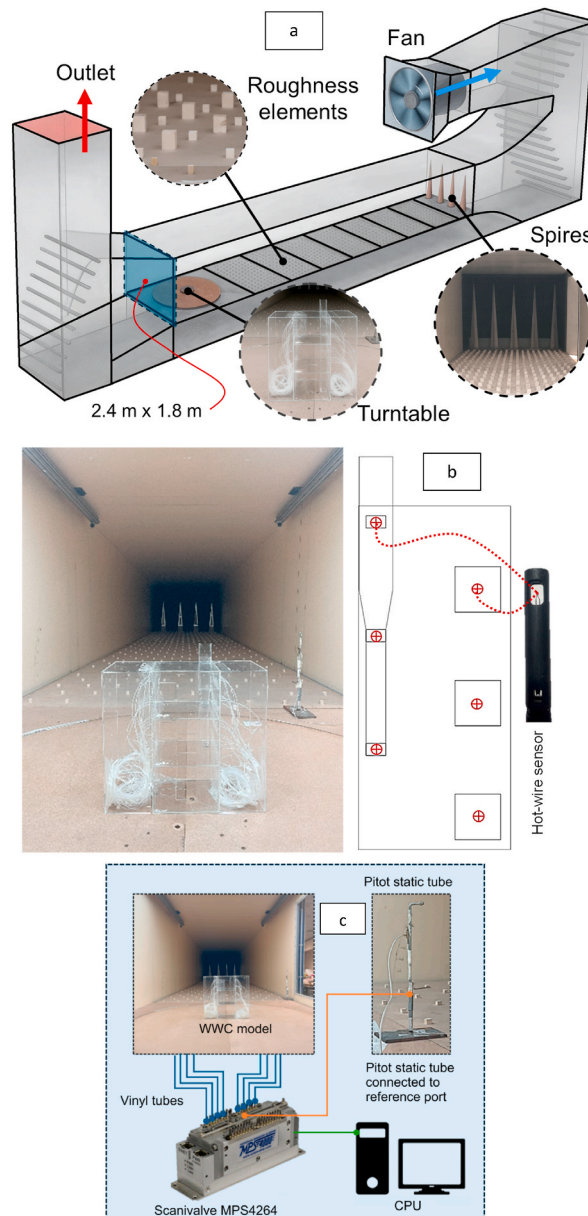


Fig. 3. (a) Roughness elements and spires in the ABL wind tunnel, (b) velocity and (c) pressure sensor setup and measurement.

2.3. CFD method

Simulations solved the incompressible Reynolds-Averaged Navier–Stokes (RANS) equations with the $k-\epsilon$ RNG turbulence model, selected for its documented robustness in building and ventilation aerodynamics and its demonstrated agreement with experimental ventilation measurements [37–40]. The governing equations for continuity, momentum, energy, turbulence kinetic energy, and dissipation rate are detailed in Ref. [31]. All transport equations were discretised using second-order accurate schemes, and pressure–velocity coupling was handled using the SIMPLE algorithm implemented in ANSYS Fluent 2022 R1 [41]. The computational domain was configured to match the wind-tunnel test section geometry and model placement, and to apply the same measured approach-flow profiles, allowing like-for-like validation of surface pressures and opening velocities against the wind-tunnel dataset (Fig. 4a). At the inlet, the measured atmospheric boundary layer (ABL) profiles of mean velocity and turbulence were imposed (Fig. 4b), represented by a power-law velocity profile with exponent $\alpha = 0.19$ and a turbulence intensity decreasing from approximately 4% near the floor to 1% at roof height. A pressure outlet boundary condition was applied at the downstream boundary.

All ground and model surfaces were treated as no-slip walls, while the top and lateral boundaries were defined as symmetry planes to minimise artificial confinement effects [42]. However, it should be noted that, although the wind tunnel dimensions were replicated, the actual boundary conditions of the tunnel walls and ceiling were simplified by applying symmetry conditions at the domain's top and side boundaries. Domain extents upstream and downstream of the model were selected to avoid blockage and flow recirculation effects, with the frontal area ratio maintained below 4.8%. The CFD geometry mirrored the wind-tunnel test model and included both the SSV and WWC baseline configurations, using an identical building envelope and explicitly representing the WWC's external vertical exhaust duct connecting the floor-level outlets.

An unstructured tetrahedral mesh was generated with local refinements at the façade openings, within the exhaust duct, and in near-wall regions (Fig. 5b). To assess mesh independence, five systematically refined meshes were employed, comprising 1.47 million (coarse), 1.72 million (moderately coarse), 2.11 million (medium), 2.54 million (moderately fine), and 3.30 million (fine) elements,

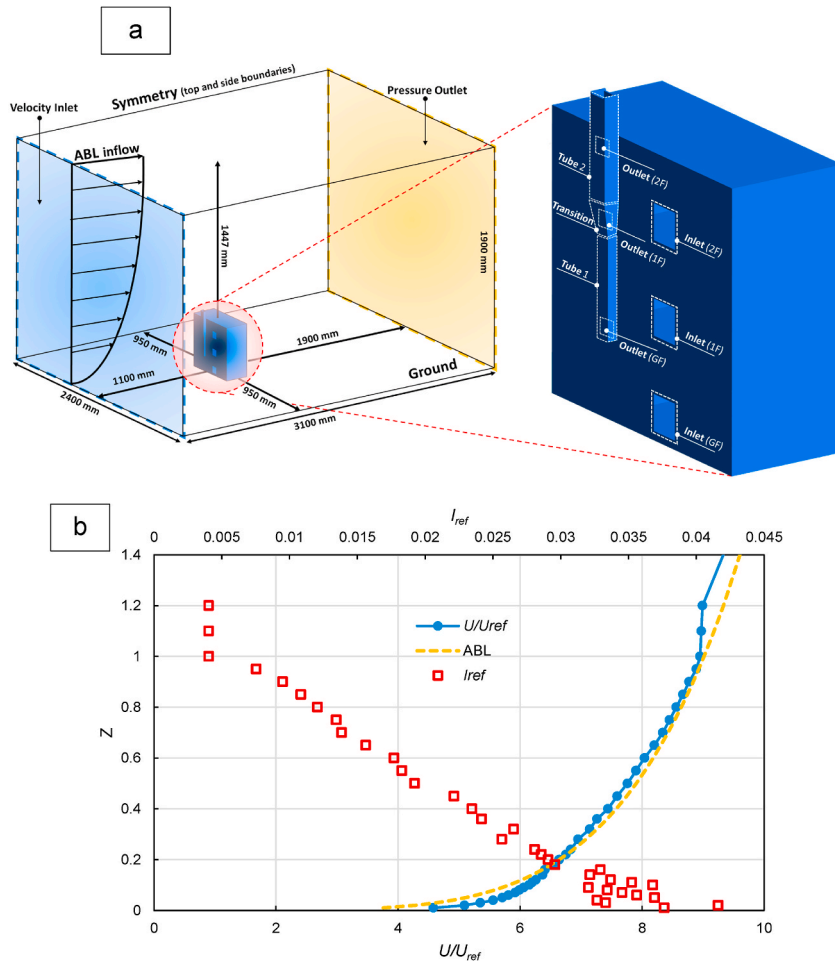


Fig. 4. Dimensions of the computational fluid domain and corresponding boundary conditions, and (b) atmospheric boundary layer (ABL) approach profile.

ensuring that the increase in element count between successive meshes remained well below 50%. Mesh refinement was achieved through uniform reductions in characteristic element size across all major subdomains (computational domain, building, openings, and exhaust duct), while maintaining consistent local refinement strategies near openings and within the exhaust riser to avoid abrupt or highly localised densification [43]. For the medium mesh, characteristic element sizes were 0.07 m in the domain, 0.02 m in the building, and 0.0011 m at the openings and within the exhaust duct, while the fine mesh employed corresponding sizes of 0.04 m, 0.008 m, and 0.001 m, respectively.

Grid sensitivity was evaluated by comparing velocity magnitude along representative sampling lines located in dynamically important flow regions. In the lower segment of the exhaust duct (Fig. 5a), where strong acceleration and flow turning occur, the coarse mesh generally underpredicted velocities, while progressively finer meshes captured higher and more stable values. The medium, moderately fine, and fine meshes showed similar velocity profiles, with an average difference of 8.3% between the medium and fine meshes and 4% between the moderately fine and fine meshes. In most of the duct, differences were below 5%, with larger local variations confined to the lower portion of the exhaust duct where sharp velocity gradients and intensified turbulence are present. These deviations were spatially limited and did not affect the overall velocity distribution or peak locations, indicating that the solution had stabilised by the medium mesh.

Additional grid sensitivity results are presented in Figure A5 (Appendix) for the second-floor region directly in front of the inlet opening, representing the indoor airflow field. The coarse and moderately coarse meshes exhibited greater scatter, while the medium, moderately fine, and fine meshes produced similar inlet-jet profiles. In the core of the inlet jet ($y = 0.36\text{--}0.40$ m), differences between the medium and fine meshes were mostly below 8%, with larger percentage differences again confined to near-zero velocity regions. Based on these results and the balance between numerical accuracy and computational cost, the medium mesh was adopted for all subsequent parametric simulations.

All cases used second-order spatial discretisation for momentum and turbulence quantities. Convergence was assessed by residuals $\leq 10^{-6}$ for continuity and momentum and by stabilised integral monitors (mass balance, area-averaged velocities at openings, and C_p on representative wall surface). Solutions were iterated until monitor plateaus corroborated residual criteria.

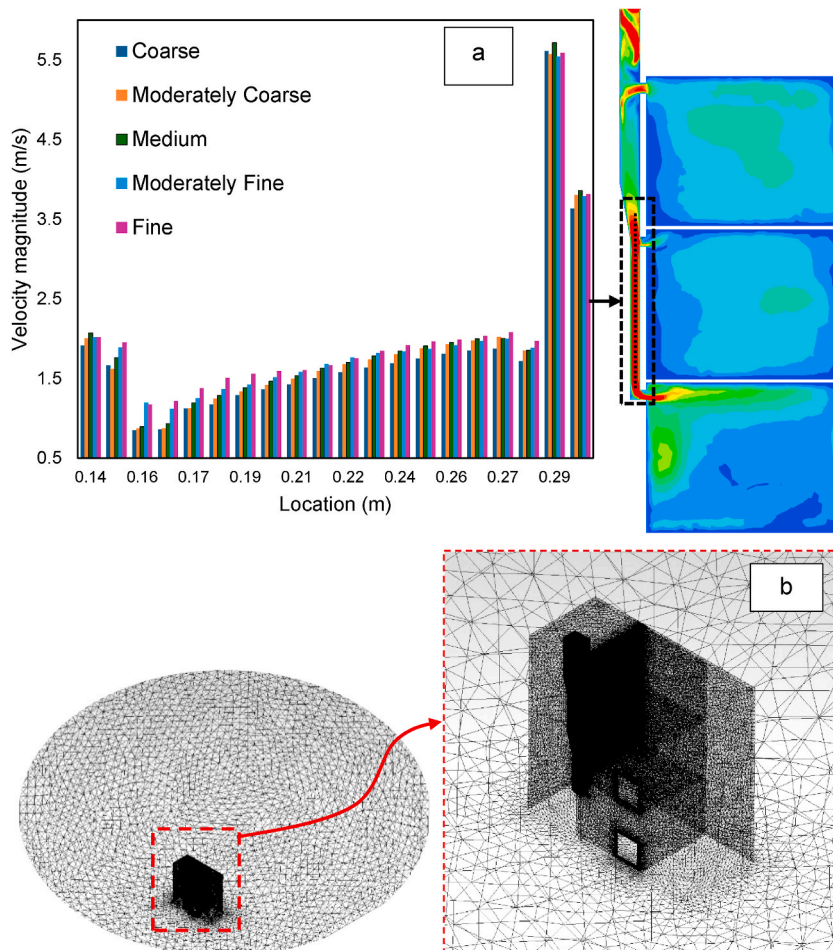


Fig. 5. (a) Grid sensitivity analysis, and (b) zoom in view of the computational grid.

2.4. CFD–experiment validation

Model performance was evaluated using standard statistical validation metrics applied to all measurement points within each scenario. These included the Mean Absolute Percentage Error (MAPE), Pearson correlation (R), coefficient of determination (R^2), Normalised Mean Square Error (NMSE), and Fractional Bias (FB). Each metric was calculated between CFD-predicted and experimentally measured values for both pressure coefficients (C_p) and airflow velocities at the WWC inlets and outlets, with the resulting validation statistics presented and discussed in Section 4.1.

For each wind direction, CFD data were extracted at the same spatial locations as the wind tunnel pressure taps and velocity probe points. The resulting datasets were compared to quantify deviations, correlation strength, and prediction bias. MAPE measured normalised error, R and R^2 assessed linear association, NMSE evaluated variance error, and FB indicated systematic over- or under-prediction. Together, these parameters provided a comprehensive measure of CFD accuracy across all flow variables and wind angles.

Validation was conducted separately for pressure and velocity using the same reference speed ($U_{\text{ref}} = 7.59 \text{ m/s}$) and normalisation procedures applied in the wind tunnel. This ensured consistent evaluation criteria across WWC configurations and established the accuracy range of the steady RANS ($k\text{--}\epsilon$ RNG) model before extending to the parametric analysis.

3. Parametric study setup

3.1. Baseline WWC configuration and constraints

The parametric analysis was developed from the three-storey baseline model of the WWC, based on the wind tunnel experiment described in Section 2.2. The model was designed to preserve retrofit practicality while maintaining consistent supply and exhaust positions across all floors. Each floor incorporated a pair of façade openings, a supply inlet and an exhaust outlet, located on the same wall (see Fig. 2a). The supply opening was fixed in the lower-right corner and measured $60 \text{ mm} \times 60 \text{ mm}$, while the exhaust opening was positioned diagonally opposite in the upper-left corner, sized $10 \text{ mm} \times 20 \text{ mm}$. This diagonal separation minimised the risk of short-circuiting and enhanced internal airflow circulation.

The exhaust outlets from each floor were connected externally to a vertical duct mounted on the façade (see Fig. 2b). In the baseline configuration, the duct comprised two rectangular riser segments: a lower segment ($20 \text{ mm} \times 10 \text{ mm}$, 166 mm height), an upper segment ($32 \text{ mm} \times 20 \text{ mm}$, 173 mm height), connected by a single expansion transition (53 mm in height) located near the first-floor outlet level. This single-step riser enlargement formed the baseline exhaust configuration, providing a continuous vertical discharge pathway while accommodating cumulative flow from the lower floors. The upward expansion of the riser cross-section contributes to reduced back-pressure and supports wind-induced suction at the duct head. The inclusion of the transition geometry was informed by preliminary simulations using a straight exhaust duct (see Appendix Figure A1), in which localised reverse flow was observed at the lower floors under certain wind conditions. Introducing transition sections at the room–duct junctions mitigated this behaviour by stabilising the pressure gradient along the riser, suppressing reverse flow and maintaining the intended upward exhaust direction.

Across the baseline and parametric cases, the overall system topology including the location of inlets and outlets, the unidirectional exhaust concept, and the external riser arrangement was held constant. Parametric variations were limited to geometric refinements such as outlet size and transition geometry, ensuring that observed performance differences arose from these controlled design modifications rather than changes in opening placement or flow-path configuration.

It should be noted that the WWC configuration evaluated in this study does not operate as a shared cross-ventilation duct between apartments. Each room (zone) is served by its own dedicated supply inlet and dedicated exhaust outlet, which connects to a common external vertical riser that functions exclusively as a unidirectional exhaust pathway. Airflow is intended to move from the façade inlet,

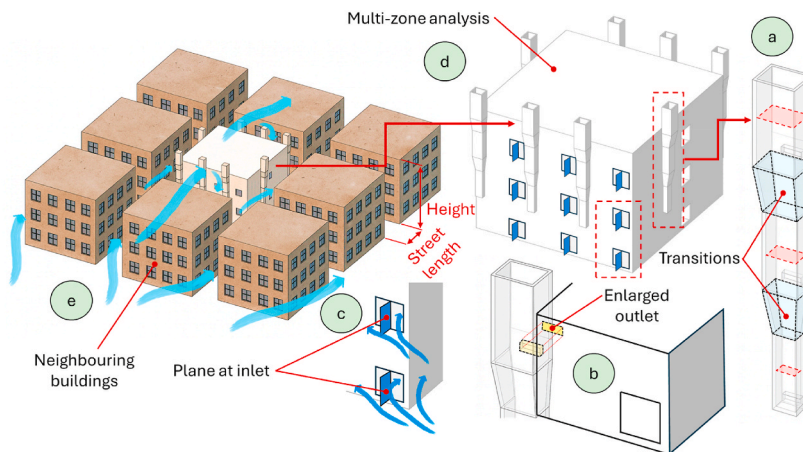


Fig. 6. Parametric analysis of the WWC system showing: (a) transition optimisation, (b) enlarged outlet configuration, and (c) inlet plane modification; (d) evaluation of multi-zone WWC installation, and (e) influence of neighbouring buildings.

through the room, into the exhaust branch, and upward to roof level.

3.2. Case definitions and design parameters

The parametric study introduced a series of design variations to the baseline WWC to reduce aerodynamic resistance, strengthen pressure differentials, and improve airflow distribution across floors. The first modification increased the number of riser expansion transitions along the external vertical duct. While the baseline configuration employed a single-step riser enlargement, this variant introduced an additional expansion transition near the second-floor outlet level (see Fig. 6a), creating a two-step progressive increase in duct cross-section with height. This staged enlargement was intended to better accommodate cumulative airflow from the lower floors, reduce back-pressure within the riser, and improve vertical flow continuity.

The second modification focused on outlet sizing, where the baseline 10 mm × 20 mm exhaust was enlarged to 20 mm × 20 mm (see Fig. 6b). This adjustment aimed to reduce back-pressure and facilitate a stronger discharge, particularly benefiting the upper floors. The third modification tested the inclusion of a thin inlet plane (30 mm × 60 mm, 3 mm thick) positioned at the supply opening (see Fig. 6c). This feature was designed to improve wind capture and guide incoming air under oblique or parallel wind conditions.

Two combined optimisation cases were also examined. Combined Optimised Case 1 (COC1) integrated the transition and enlarged outlet modifications to improve both flow continuity and exhaust capacity. Combined Optimised Case 2 (COC2) incorporated all three strategies, the transitions, enlarged outlets, and inlet plane, representing a fully optimised configuration of the system. By comparing the performance of the individual and combined cases, the study aimed to identify which modification or combination provided the most robust improvements across varying wind conditions.

3.3. Building height variants

Beyond the three-storey baseline, additional configurations were created to evaluate how WWC performance scales with vertical extension. A four-storey variant was generated by adding one additional floor and extending the vertical exhaust duct accordingly. The new segment followed the same dimensional scaling pattern, with duct cross-sections enlarged to accommodate increased airflow capacity (see Appendix Figure A2). Similarly, a five-storey model was constructed by adding two segments, again following the same transition and enlargement logic. Both taller models employed the COC1 optimisation as the baseline configuration to ensure that comparisons with the three-storey case isolated the influence of height rather than geometry. This approach allowed the study to assess whether increased height enhances or diminishes airflow distribution, particularly at lower floors where momentum losses could become more pronounced.

3.4. Urban context variants

To capture the influence of surrounding buildings, the WWC was also modelled within simplified enclosure scenarios representing dense urban blocks (see Fig. 6e). In this setup, the building was surrounded on all four sides by structures of equal height, width, and depth, forming a compact array that simulated a street-canyon environment. Within this arrangement, the building façades were divided into eight zones (A–H) according to orientation (see Fig. 6d and Appendix, Figure A3). Under a reference wind from 0°, zones A–C formed the windward façade, D represented the right side façade, E–G formed the leeward façade, and H represented the left façade. This zoning scheme was repeated across floors, enabling detailed examination of both horizontal and vertical airflow distributions.

The impact of urban canyon proportions was further explored using three street-to-building height (S/B) ratios: 0.5, 1.0, and 2.0 (see Appendix, Figure A4). These ratios corresponded to narrow, intermediate, and wide street canyons, respectively, with the building height fixed at 453 mm. This variation allowed the study to assess how confinement or openness influences façade pressure and system performance, and to identify which configurations best support natural ventilation under realistic urban conditions.

3.5. Flow conditions and performance metrics

The parametric analysis considered a range of wind directions and magnitudes to represent realistic atmospheric exposure. For the isolated-building cases, simulations were conducted at 0°, 20°, 30°, 45°, 60°, 70°, 90°, and 180°, covering windward, oblique, parallel, and leeward conditions. The reference velocity was defined at roof level ($z = 0.453$ m) and set to $U_{\text{ref}} = 7.59$ m/s, consistent with the wind tunnel characterisation of the baseline ABL profile.

Performance was assessed using several complementary metrics. The primary indicator was the floor-averaged indoor velocity, calculated as an area-weighted mean across multiple equally spaced planes within each room, providing a robust measure of airflow availability at the Ground Floor (GF), First Floor (1F), and Second Floor (2F). Pressure coefficients were extracted from selected internal wall patches and normalised against the dynamic pressure at reference velocity, enabling direct comparison with experimental data and between configurations. Additionally, qualitative insights into flow mechanisms were derived from two- and three-dimensional contour plots, which visualised airflow capture, acceleration, recirculation, and discharge patterns.

To provide a meaningful benchmark, an equivalent single-sided ventilation (SSV) configuration was modelled under identical conditions. The SSV geometry used the same building envelope and domain but included only one centrally placed opening (60 mm × 60 mm) per floor and no external exhaust duct. All other parameters, including wind conditions, boundary setups, and analysis metrics, were kept consistent. Comparisons were made using both absolute values and relative percentage improvements, focusing on floor-

averaged indoor velocities as well as velocity and pressure distributions. This ensured that the improvements attributed to the WWC and its parametric variants were evaluated fairly against the baseline SSV and helped identify conditions under which SSV could not deliver adequate ventilation performance.

4. Results

4.1. Validation of surface pressure coefficients, supply and exhaust airflow velocity

Fig. 7a compares the measured internal surface pressure coefficients from the ABL wind tunnel tests of the building model with WWC (base model) against the CFD-predicted values using the $k-\epsilon$ RNG turbulence model across 120 points at 0° , 45° , and 90° wind directions ($U_{\text{ref}} = 7.59$ m/s). The dashed line indicates perfect agreement. Overall, there is good correlation, with most points clustering near the 1:1 line. At 0° , both datasets fall in the positive range (0.65–0.85), with CFD slightly overpredicting pressures. At 45° , values group around 0.40–0.55, again with modest CFD overprediction but consistent trends. At 90° , negative coefficients (–0.6 to –0.9) indicate strong suction on the leeward façade; here, CFD slightly underpredicts suction magnitude compared to experiments.

The clustering of results within each wind angle group demonstrates that the $k-\epsilon$ RNG model reliably reproduces the variation in pressure distributions across façades under different wind exposures. Small deviations, particularly at oblique (45°) and parallel (90°)

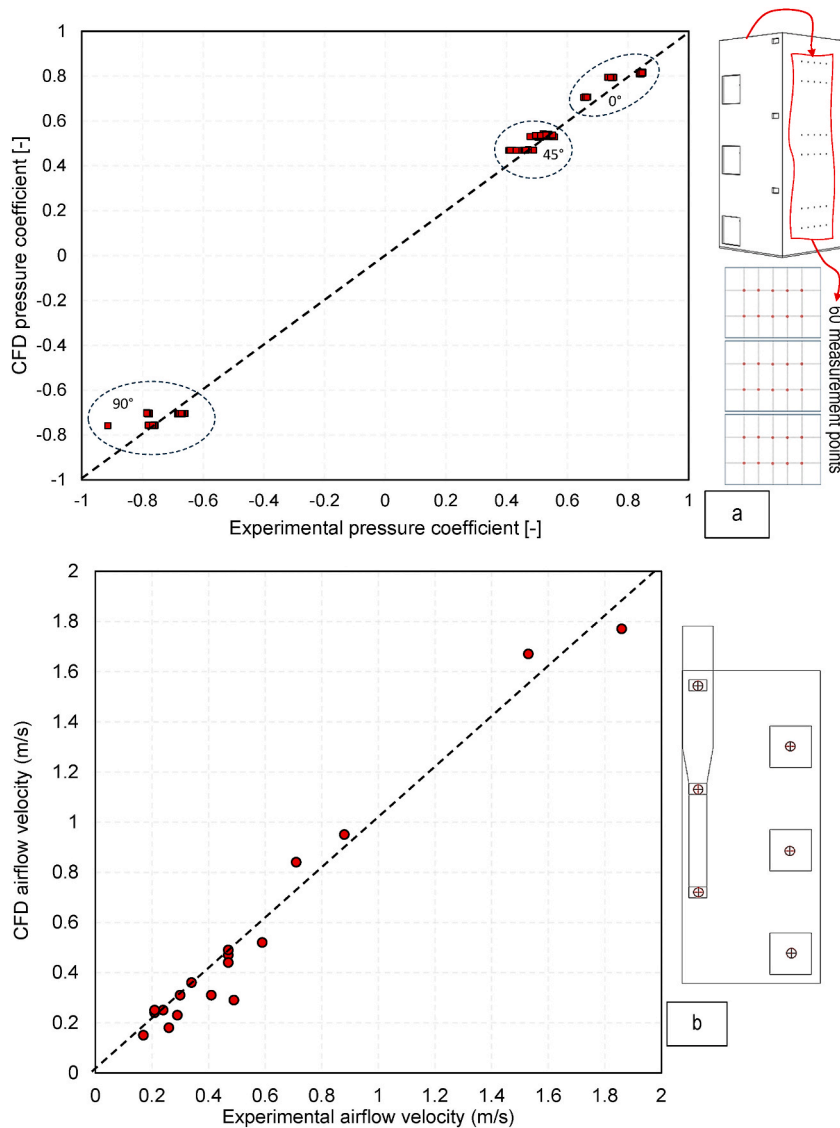


Fig. 7. Comparison between the CFD and experimental measurements of the (a) pressure coefficient (scatter plot) and (b) average air flow velocity in the WWC model (base case) at 0° , 45° , and 90° wind direction ($U_{\text{ref}} = 7.59$ m/s).

winds, likely arise from the steady-state RANS simplification, which cannot fully resolve unsteady vortex shedding and turbulent fluctuations captured in the wind tunnel. Nonetheless, the agreement confirms the suitability of the RNG model for predicting façade pressure coefficients in the WWC study, with errors remaining within acceptable limits.

Fig. 7b compares the supply and exhaust airflow velocities measured in the ABL wind tunnel for the WWC model with CFD predictions using the $k-\epsilon$ RNG model at 0° , 45° , and 90° wind directions ($U_{\text{ref}} = 7.59$ m/s). Overall, the CFD showed good agreement, with most points clustered near the 1:1 line. At 0° , supply flows were well captured (GF in 0.21 vs 0.24 m/s; 1F in 0.30 vs 0.31 m/s), while exhausts were predicted accurately but with a slight underestimation at 2F (1.86 vs 1.77 m/s). At 45° , ground-floor flows matched closely (0.24 vs 0.25 m/s; 0.21 vs 0.25 m/s), though deviations appeared at 1F inlets (0.26 vs 0.18 m/s); exhausts were slightly overpredicted (1F out 0.71 vs 0.84 m/s). At 90° , predictions were more variable: GF values remained consistent (e.g., 0.47 vs 0.49 m/s in), but CFD underpredicted 1F flows (in 0.41 vs 0.31 m/s; out 0.49 vs 0.29 m/s) and slightly reduced 2F exhaust (0.59 vs 0.52 m/s).

Quantitative validation metrics further confirm this performance. For the $k-\epsilon$ RNG model, agreement in pressure coefficients (C_p) for WWC cases yielded MAPE = 5.6% (0°), 4.6% (45°), and 6.8% (90°) with $R = 0.92$, 0.84, and 0.30, respectively. While the 90° case maintains a low average magnitude error, the low correlation indicates reduced point-by-point agreement in the spatial distribution of C_p under parallel wind conditions. NMSE remained small at 0° – 45° and increased at 90° , reflecting the added complexity of parallel wind conditions. For airflow velocity at WWC inlets and outlets, the RNG model achieved MAPE $\approx 6.5\%$ (0°), 16.8% (45°), and 16.5% (90°) with $R^2 = 0.996$, 0.990, and 0.713, and $|FB| \leq 0.041$ across angles. These statistics are consistent with expectations for steady RANS models in ventilation flows, good agreement under windward and oblique incidence, and reduced accuracy under parallel winds

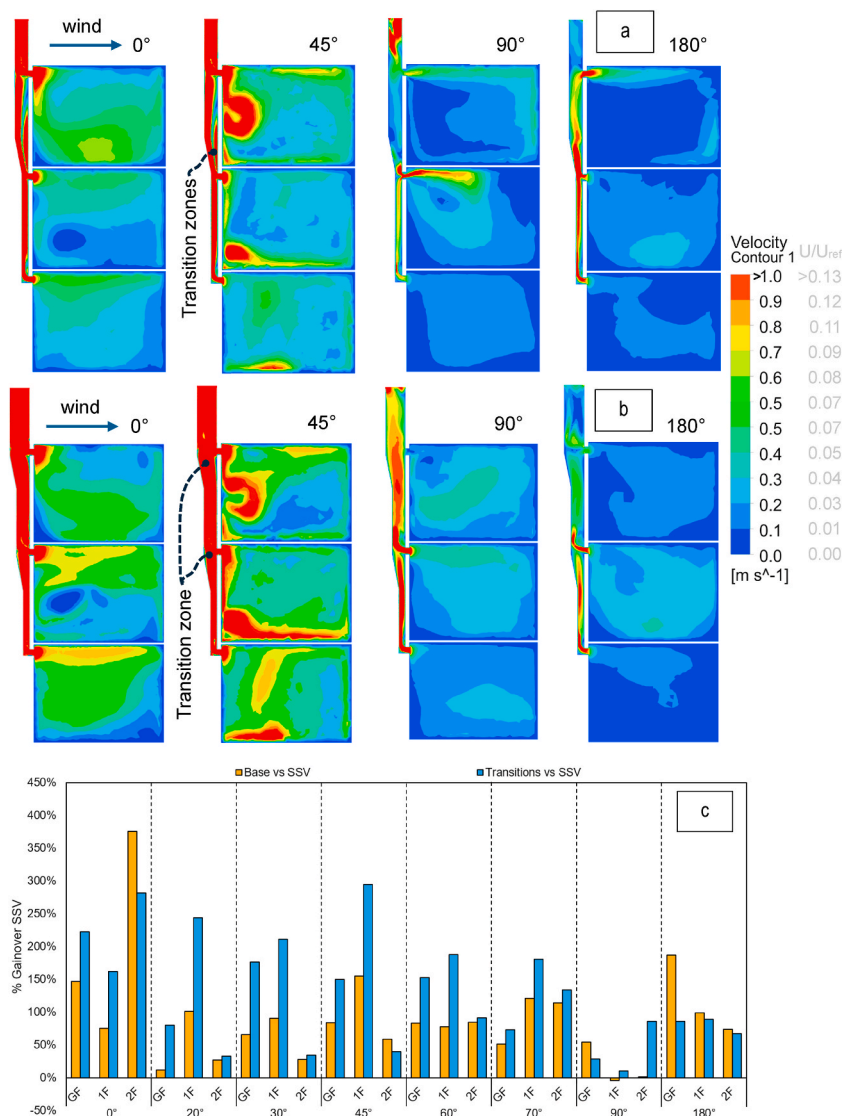


Fig. 8. Cross-sectional velocity contours at selected wind angles (0° , 45° , 90° , 180°) comparing the (a) baseline WWC and (b) transition-tube (two-step riser expansion) configuration ($U_{\text{ref}} = 7.59$ m/s). (c) Percentage gain in average airflow velocity over SSV.

where unsteady effects dominate [44].

Overall, the $k-\epsilon$ RNG model reproduced measured pressure and velocity fields with sufficient accuracy to support the subsequent parametric optimisation, while acknowledging increased uncertainty under parallel wind conditions [45].

Beyond validating the magnitude of pressures and airflow velocities, the baseline WWC results also reveal important trends in vertical exhaust distribution. Under windward and oblique winds, exhaust velocities increase strongly with height, while ground-floor exhaust velocities remain lower (e.g., GF out = 0.34 m/s, 1F out = 0.88 m/s, 2F out = 1.86 m/s at 0°). When converted to full-scale equivalent volumetric flow rates (using the geometric scale of the test model), this corresponds to exhaust flow rates of approximately 18 L/s at the ground floor, 51 L/s at the first floor, and 68 L/s at the second floor, demonstrating a strong overall extraction capacity but also indicating a pronounced vertical imbalance. For comparison, façade-integrated devices such as trickle ventilators typically provide ≤ 17 L/s [46], while single-sided window openings achieve approximately 23–45 L/s under comparable wind conditions [20]. While the WWC therefore can deliver greater total airflow than conventional façade ventilation strategies, the uneven distribution across floors highlights the need for targeted geometric optimisation, which motivates the parametric modifications investigated in the following section. At 90°, outlet velocities are substantially reduced and more uniform across floors (0.17–0.59 m/s), consistent with weaker façade driving pressure and a greater influence of cross-flow and recirculation on the supply–exhaust pathway.

4.2. Two-step riser expansion (additional duct transition)

The first modification increased the riser enlargement from a single-step expansion (baseline) to a two-step expansion by adding a second transition just below the second-floor outlet, producing a more gradual increase in riser cross-section with height. By enlarging duct cross-sections with height, the WWC could better handle cumulative airflow across floors. At 0°, the base configuration exhibited an uneven vertical distribution (standard deviation $\sigma = 0.077$ m/s), with relatively weak penetration at the ground floor (average indoor airflow speed of 0.28 m/s) and reduced velocities at the first floor (0.23 m/s on average), while the second floor experienced stronger airflow (0.41 m/s on average) driven by suction at the exhaust (Fig. 8a). This pattern is consistent with the static pressure contours and airflow vectors presented in Appendix Figure A6, which show a lower static pressure at the upper exhaust and an upward-directed flow path that preferentially enhances extraction at the second floor under windward conditions. The introduction of the additional riser expansion transition led to a more balanced vertical airflow distribution ($\sigma = 0.017$ m/s), with the average ground-floor velocity increasing to 0.37 m/s, improved penetration at the first floor (0.34 m/s on average), and the second-floor airflow remaining effective (0.33 m/s on average) but less dominant than in the base case. At 45°, the base model again showed patchy airflow, with pronounced spatial variability and low-velocity regions at the first floor, whereas the transition (two-step riser expansion) configuration produced deeper penetration at the ground and first floors and more uniform circulation across all floors, demonstrating a clear advantage under oblique wind conditions.

At 90°, ventilation performance was reduced in both configurations; however, the transition modification improved airflow capture and vertical continuity relative to the base case. In particular, the second floor showed deeper inflow penetration and a substantially higher average airflow (approximately 84% increase relative to the base configuration), while the first floor also exhibited modest increases in airflow intensity. Despite these improvements, overall ventilation remained limited under parallel wind conditions. Under leeward conditions (180°), both configurations exhibited weak ventilation, characterised by low but measurable indoor airflow across all floors, consistent with the wake-dominated pressure field. This behaviour is supported by the static pressure contours and airflow vectors in Appendix Figure A7, which show a weak pressure gradient and diffuse, low-momentum indoor circulation. The transition (two-step riser expansion) configuration showed performance broadly comparable to the base case, indicating that additional riser transitions does not provide a clear advantage under leeward exposure. These results confirm that, while transitions improve airflow distribution under windward and oblique conditions, ventilation remains constrained for both configurations when the available driving pressure is low.

Compared with single-sided ventilation (SSV), both base and transition (two-step riser expansion) WWCs performed substantially better across most wind angles (Fig. 8c). At 0°, ground-floor airflow increased from 0.114 m/s (SSV) to 0.281 m/s in the base case (+147%) and 0.368 m/s with the additional riser transitions (+223%), while first- and second-floor velocities also improved markedly (+75–162%). At 30° and 45°, transition-related gains exceeded 150% on multiple floors, reaching up to 294% at the first floor. At 20° and 60°, particularly strong improvements were again observed at the first floor, with velocities increasing by approximately 244% and 187% relative to SSV. At 70°, consistent gains were maintained across all floors, with the two-step riser expansion configuration achieving up to 181% improvement at the first floor. At 90°, improvements relative to SSV were more modest, with small gains at most floors and a slight reduction at the first floor for the base case, reflecting the limited driving pressure under parallel wind incidence. Under leeward conditions (180°), both WWC configurations continued to outperform SSV, although the two-step riser expansion case showed more moderate gains (67–89%) than the base configuration. Overall, the addition of the extra riser transition reduced internal losses and improved vertical airflow continuity under windward and oblique winds, while offering limited benefit under parallel and leeward exposure.

4.3. Enlarged outlet

The second modification enlarged the outlet from 10×20 mm to 20×20 mm to reduce back-pressure and strengthen discharge, particularly at upper floors. Fig. 9a shows velocity contours at 0°, 45°, 90°, and 180° ($U_{\text{ref}} = 7.59$ m/s), illustrating how the enlarged outlet primarily influences airflow at the mid and upper levels under windward and oblique wind conditions.

At 0°, the second floor exhibited stronger penetration compared with the base case while the first floor also benefitted and the

ground floor maintained moderate inflow. At 45° , locally intensified flow regions were observed near the enlarged outlets at the first and second floors, accompanied by improved penetration and circulation across all floors relative to the base configuration, although the strongest effect remained at the second floor. At 90° , overall inflow remained weak across all floors compared with the base configuration, with only slight improvements at the second floor; the enlarged outlet did not markedly alter the indoor flow structure, and ventilation remained dominated by low-momentum circulation and limited penetration depth. Under leeward conditions (180°), the enlarged outlet produced flow patterns broadly similar to the base configuration, characterised by weak but persistent extraction and diffuse indoor circulation. Overall, outlet enlargement primarily influenced the upper-storey flow structure under windward and oblique conditions, while offering little additional benefit under parallel and leeward exposure.

The quantitative results (Fig. 9c) support these observations. At 0° , the second-floor velocity increased from 0.409 m/s in the base case to 0.509 m/s with the enlarged outlet (24% increase in average airflow), while smaller increases were also observed at the first floor (16% increase in average airflow). At oblique wind angles (30° – 60°), the enlarged outlet produced consistent gains at the mid and upper floors, with an average increase of 23% relative to the base configuration. In contrast, ground-floor performance was more variable, with slight reductions at 20° – 60° and a pronounced decrease at 70° , where velocity dropped from 0.242 m/s to 0.123 m/s. At 90° , the enlarged outlet did not improve performance at the lower floors and produced only a small increase at the second floor. Under leeward conditions (180°), a slight increase was observed at the ground floor, while first- and second-floor velocities declined marginally relative to the base case. Overall, enlarging the outlet preferentially enhanced mid-to-upper floor extraction by reducing back-pressure, but introduced a trade-off in which ground-floor, parallel, and leeward performance became more variable, indicating that outlet enlargement alone can redistribute the pressure field unfavourably for the lowest storey unless combined with complementary inlet or transition measures.

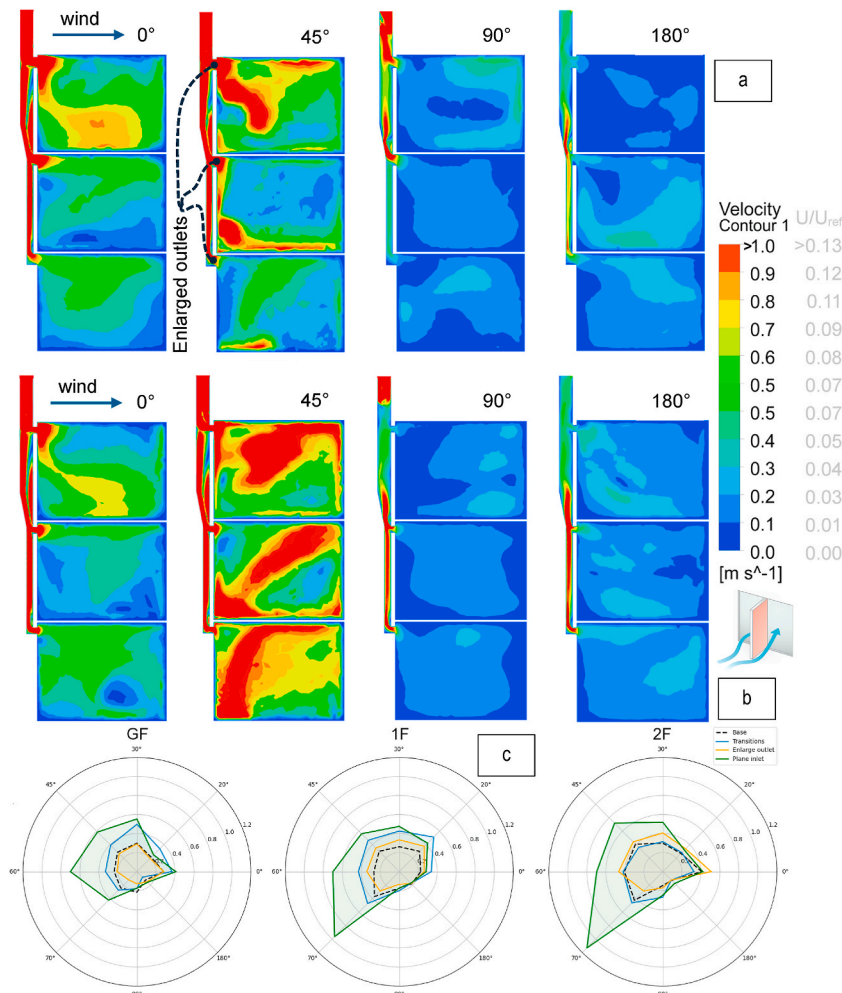


Fig. 9. Cross-sectional velocity contours at selected wind angles (0° , 45° , 90° , 180°) comparing the (a) enlarged outlet and (b) plane at inlet configuration ($U_{\text{ref}} = 7.59 \text{ m/s}$). A radar chart (c) comparison of the average indoor airflow velocity (m/s) across the floors for different configurations at different angles.

4.4. Plane at inlet

The third modification tested a thin inlet plane at the supply opening, intended to improve wind capture under oblique or near-parallel winds. Fig. 9b shows velocity contours at 0°, 45°, 90°, and 180° ($U_{ref} = 7.59$ m/s). At 0°, the inlet plane strengthened capture, raising ground- and first-floor velocities relative to the base configuration and slightly improving uniformity across floors. At 45°, the plane delivered the strongest qualitative improvement, with locally intensified flow regions (locally exceeding 1 m/s) extending across all floors, promoting deeper penetration and more active circulation. At 90°, improvements were modest, with a limited increase at the second floor while overall circulation remained constrained by parallel wind incidence. Under leeward conditions (180°), airflow increased at the ground and second floors, and overall circulation patterns were slightly improved relative to the base case.

The quantitative results (Fig. 9c) reinforce these observations. At 0°, the inlet plane produced clear gains at the lower levels, with ground- and first-floor velocities increasing by approximately 46% and 25%, respectively, while the second-floor velocity increased only slightly. Larger gains were observed at oblique angles; for example, at 30° the ground-floor velocity nearly doubled from 0.298 to 0.553 m/s, and the second-floor velocity increased to 0.518 m/s. At 45°, all floors experienced improvements, with the second-floor velocity reaching 0.720 m/s (+76%). The most pronounced gains occurred at 60°–70°, where first-floor velocities reached approximately 0.7–0.96 m/s and the second floor peaked at about 1.1 m/s compared with 0.424 m/s in the base case (+167%). At 90° and 180°, performance was mixed, showing modest second-floor gains but small reductions at the first floor. Overall, the inlet plane produced the highest velocities among all single modifications, substantially enhancing WWC performance under oblique winds, while providing moderate benefits under windward conditions and limited improvements under parallel and leeward exposure.

To further illustrate this, Fig. 10 compares the plan-view velocity contours for the base WWC and the WWC with an inlet plane at selected wind angles ($U_{ref} = 7.59$ m/s). At near-windward exposure (0°–20°), both configurations exhibit similar flow patterns, with relatively localised inflow confined to the region near the opening. Under oblique winds (30°–45°), the improvement associated with the inlet plane is most pronounced: large, high-velocity regions (locally exceeding 1 m/s) extend diagonally into the space, producing deeper penetration and stronger circulation, whereas the base configuration displays more extensive low-velocity regions. At 60°–70°, the inlet plane maintains broader regions of elevated velocity, confirming its role in sustaining inflow jets and enhancing ventilation performance under strongly oblique wind conditions. At 90° winds, gains are modest, with the inlet plane improving local capture near the opening but overall indoor velocities remaining low and penetration limited. Under 180° winds, both configurations exhibit weak inflow, although the inlet plane produces slightly greater local penetration near the supply opening.

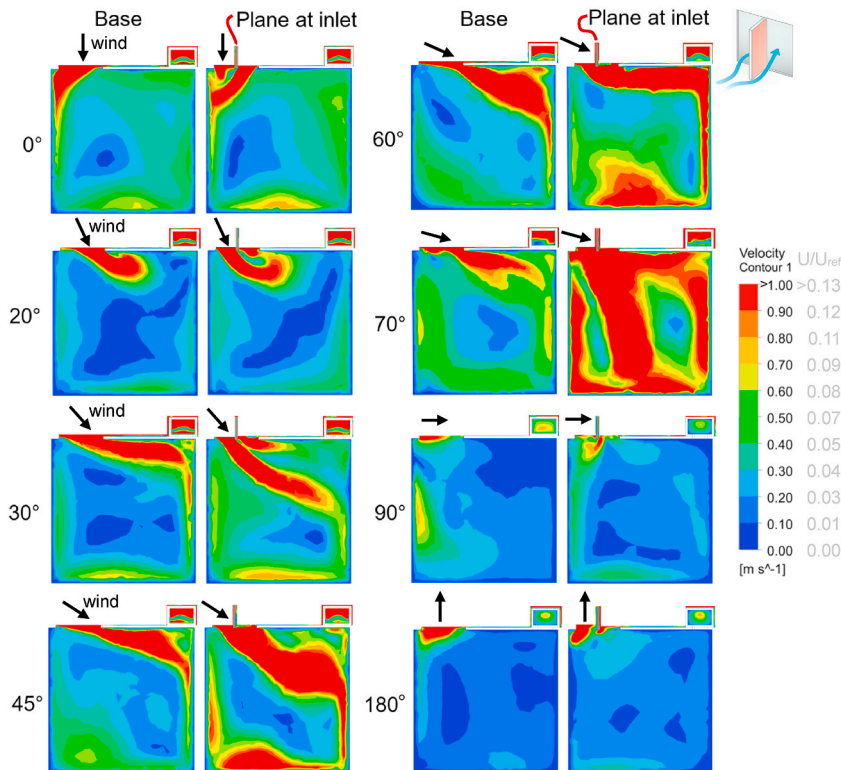


Fig. 10. Plan-view velocity contours comparing base WWC and WWC with inlet plane at selected wind angles ($U_{ref} = 7.59$ m/s).

4.5. Combined optimised case 1 (COC1) and 2 (COC2)

Two combined optimisation cases were tested to assess the effect of integrating multiple strategies. COC1 combined the additional exhaust-duct transition with enlarged outlets, while COC2 included all three modifications, adding the inlet plane. Fig. 11 shows cross-sectional velocity contours at selected wind angles (0° , 45° , 90° , 180°) for COC1 (Fig. 11a) and COC2 (Fig. 11b).

The results show that COC1 improves airflow distribution relative to the base configuration mainly under windward and oblique winds, while offering limited benefit under parallel and leeward exposure. At 0° , COC1 produces a more even vertical distribution, with higher and more continuous velocities at the ground and first floors and reduced dominance of second-floor extraction. At 45° , the improvement is more pronounced, with larger regions of elevated velocity extending deeper into the rooms and reduced low-velocity zones, indicating improved penetration and vertical continuity. At 90° , overall ventilation remains weak in both cases; however, COC1 produces a pronounced increase in second-floor airflow, while gains at the first floor remain modest. Under leeward conditions (180°), COC1 exhibits flow patterns broadly similar to the base case, with weak and diffuse indoor circulation across all floors.

By contrast, COC2 delivered a clear performance improvement relative to COC1 across most wind directions. At 0° , the ground and first floors exhibited higher penetration and more active circulation, reducing the strong upper-floor dominance seen in the base configuration. At 45° , extensive regions of elevated velocity (locally exceeding 1 m/s) developed across all floors, indicating deeper penetration and more coherent circulation throughout the spaces. At 90° , improvements remained modest overall but were more pronounced than in COC1, particularly at the second floor. Under leeward conditions (180°), COC2 exhibits more spatially distributed

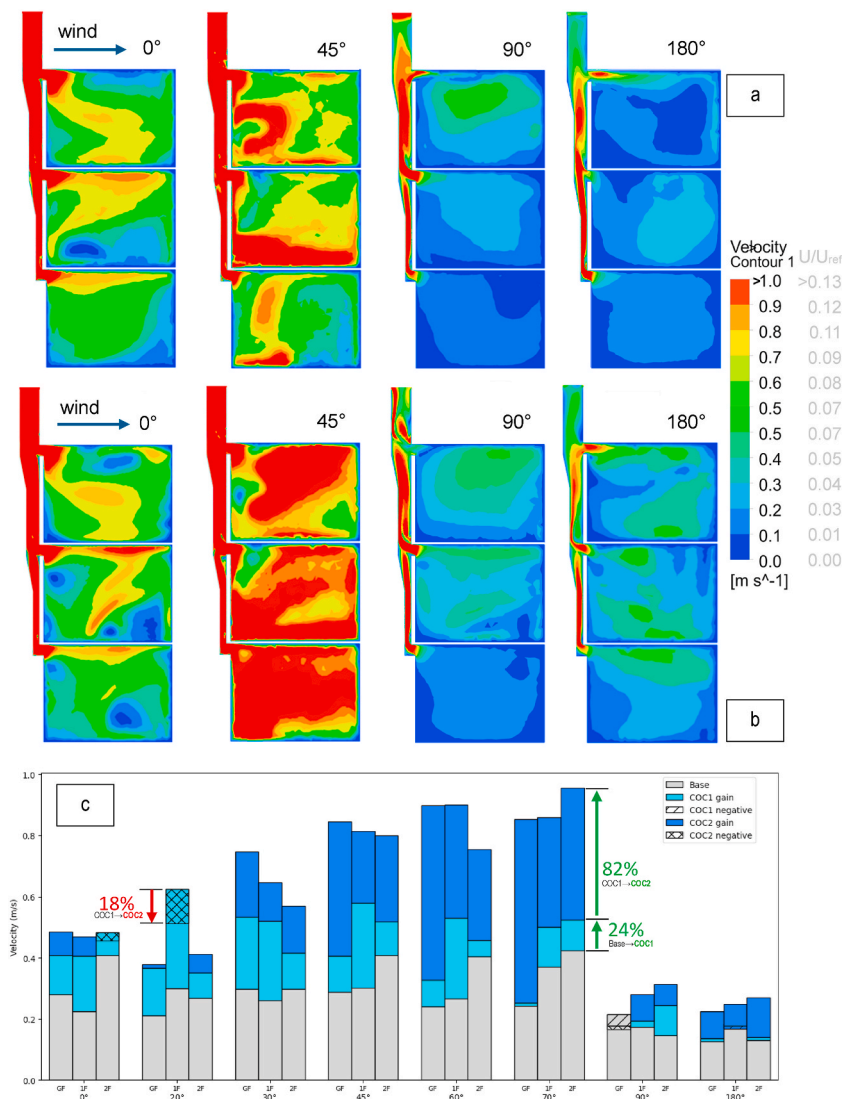


Fig. 11. Cross-sectional velocity contours at selected wind angles (0° , 45° , 90° , 180°) comparing the (a) COC1 and (b) COC2 ($U_{ref} = 7.59 \text{ m/s}$). A waterfall (c) chart showing the progression from Base to COC1 and to COC2 across wind angles (hatched represents reduction).

airflow and reduced low-velocity regions across all floors, indicating a modest improvement in penetration and circulation rather than a substantial increase in airflow magnitude. Overall, while COC1 enhanced flow continuity and outlet discharge, COC2 provided the most robust performance, particularly under oblique and leeward winds, confirming the value of integrating the inlet plane with other modifications. This is reflected, for example at 0°, in the effective outlet discharge coefficient (C_d), which increased from 0.67/0.55/0.66 (Base, GF/1F/2F) to 0.91/0.96/1.00 (COC2), indicating more efficient discharge across floors.

Under oblique winds (20°–70°), the benefits were greatest: at 30°, GF rose to 0.534 m/s (COC1) and 0.747 m/s (COC2), while at 45° 2F doubled from 0.408 to 0.800 m/s under COC2, and 1F rose from 0.301 to 0.814 m/s. At 90°, COC2 achieved measurable gains at 1F (0.293 m/s vs 0.174 base) and 2F (0.377 m/s vs 0.180 base). At 180°, COC2 more than doubled GF velocity from 0.102 to 0.226 m/s, while COC1 occasionally underperformed, particularly at 1F. In summary, the combined cases confirm strong synergy: COC1 provides robust but sometimes uneven gains, whereas COC2 delivers the highest and most uniform multi-storey ventilation across wind directions, with 90° remaining the most challenging condition.

Fig. 11c further quantifies the performance gains. At 0°, ground-floor velocity increased from 0.281 m/s in the base case to 0.409 m/s (COC1, +46% over base) and 0.485 m/s (COC2, +73% over base), with similarly strong improvements at the first floor, while changes at the second floor were more moderate (11–18%) due to the already strong baseline suction. Under oblique winds (30°–70°), average velocity increase of 21–73% achieved by COC1 and 130–199% achieved by COC2. At 60°–70°, COC2 consistently delivered the

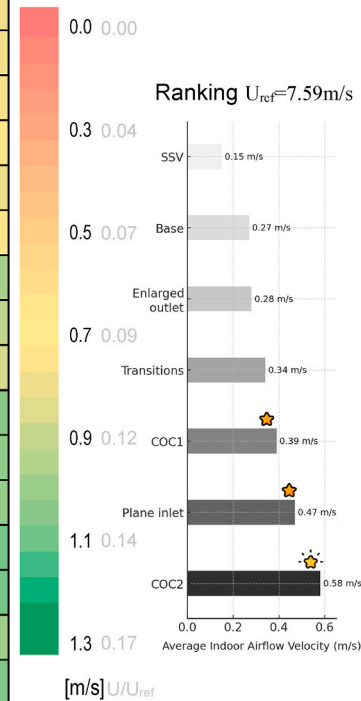
Table 1

Comparison of average indoor airflow velocity (m/s) across designs, floors, and wind angles.

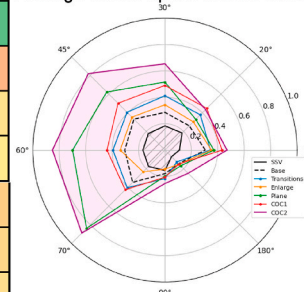
		SSV	Base	Transitions	Enlarge outlet	Plane inlet	COC1	COC2
0°	GF	0.114	0.281	0.368	0.282	0.409	0.409	0.485
	1F	0.129	0.226	0.338	0.263	0.283	0.407	0.469
	2F	0.086	0.409	0.328	0.509	0.42	0.483	0.455
20°	GF	0.189	0.212	0.34	0.195	0.247	0.366	0.379
	1F	0.149	0.3	0.512	0.375	0.422	0.624	0.512
	2F	0.212	0.269	0.282	0.339	0.32	0.352	0.413
30°	GF	0.18	0.298	0.497	0.291	0.553	0.534	0.747
	1F	0.137	0.261	0.426	0.334	0.475	0.52	0.646
	2F	0.233	0.298	0.314	0.406	0.518	0.417	0.57
45°	GF	0.157	0.288	0.392	0.266	0.587	0.407	0.846
	1F	0.118	0.301	0.465	0.351	0.562	0.58	0.814
	2F	0.257	0.408	0.36	0.442	0.72	0.519	0.8
60°	GF	0.131	0.24	0.331	0.209	0.701	0.328	0.899
	1F	0.15	0.267	0.431	0.342	0.699	0.53	0.9
	2F	0.219	0.405	0.419	0.466	0.697	0.458	0.755
70°	GF	0.16	0.242	0.277	0.123	0.422	0.252	0.853
	1F	0.168	0.371	0.472	0.288	0.963	0.501	0.86
	2F	0.198	0.424	0.463	0.288	1.131	0.524	0.956
90°	GF	0.139	0.215	0.179	0.128	0.173	0.178	0.167
	1F	0.181	0.174	0.200	0.133	0.172	0.193	0.280
	2F	0.144	0.146	0.268	0.170	0.247	0.245	0.313
180°	GF	0.044	0.126	0.082	0.151	0.158	0.137	0.226
	1F	0.092	0.183	0.174	0.179	0.172	0.169	0.249
	2F	0.075	0.130	0.125	0.125	0.175	0.141	0.271

Highlighted value indicates highest for each floor.

Highlighted value indicates highest for each floor.



Average airflow speed across floors



highest velocities across all floors, with particularly large gains at the ground and first floors and the second floor peaking at 0.956 m/s.

At 90°, overall performance remained constrained; COC2 produced clear gains at the first and second floors (61–115% relative to the base case), while the ground-floor velocity decreased slightly (–22%). Under leeward conditions (180°), COC2 improved airflow at all floors compared with the base configuration, most notably at the ground floor, whereas COC1 showed more variable performance, including slight reductions at the first floor. Overall, the combined cases confirm strong synergy: COC1 provides robust but sometimes uneven gains, while COC2 delivers the highest and most consistently distributed multi-storey ventilation across wind directions, with parallel winds (90°) remaining the most challenging condition.

4.6. Summary ranking of designs and key gains

When results are aggregated across all floors and wind angles (Table 1), the overall average airflow performance follows a clear hierarchy: COC2 achieves the highest velocities, followed by the plane inlet, COC1, transitions (two-step riser expansion), enlarged outlet, the base WWC, and finally SSV. COC2, which integrates the inlet plane with the two-step riser expansion transitions and enlarged outlets, ranks highest by delivering both the greatest airflow magnitudes and the most balanced vertical distribution. It remains robust at 90° and continues to provide measurable gains at 180°, where most other configurations struggle. The inlet plane emerges as the strongest single modification, producing the largest average improvements, particularly under oblique winds. COC1 ranks just below it, offering improved flow continuity and exhaust capacity, and demonstrating greater robustness at 0° and 20°, as well as slightly better performance than single-parameter cases under less favourable wind directions at 90° and 180°. The transition modification delivers consistent, moderate improvements across most wind angles, particularly windward/oblique, while the enlarged outlet enhances upper-floor extraction but can intermittently weaken ground-floor inflow under highly oblique wind conditions.

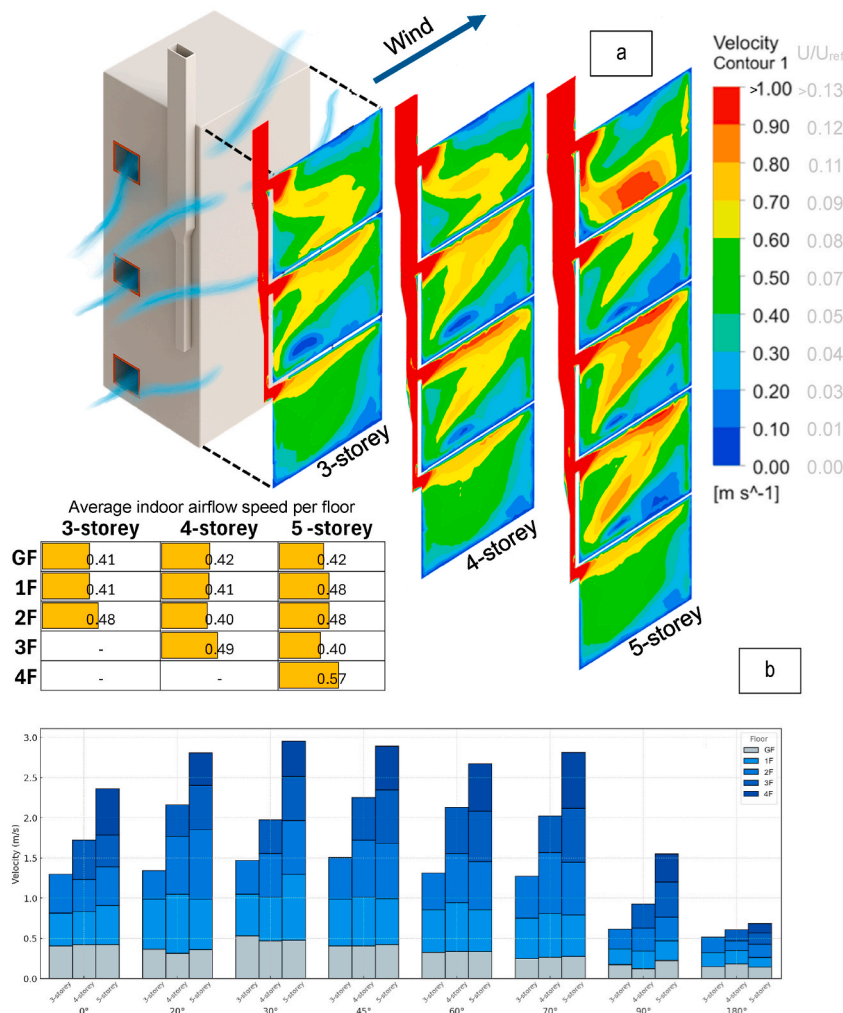


Fig. 12. (a) Cross-sectional velocity contours of WWC airflow at 0° wind angle ($U_{ref} = 7.59$ m/s) for 3-, 4-, and 5-storey COC1 configurations. Stacked distribution (b) of floor-level ventilation velocities by wind angle and building height.

To quantify the relative influence of each parameter and the extent of interaction effects, mean indoor velocity was also computed by aggregating Table 1 results across all floors and wind angles. The baseline WWC mean was 0.270 m/s. The single-parameter mean gains were +0.07 m/s for transitions (0.34 m/s), +0.008 m/s for enlarged outlet (0.277 m/s), and +0.198 m/s for the inlet plane (0.468 m/s). The combined case COC1 reached 0.386 m/s (total gain +0.117 m/s); compared with the additive expectation (baseline + transitions + enlarged outlet = 0.343 m/s), an additional +0.044 m/s is attributable to positive interaction beyond additive effects. The fully combined case COC2 reached 0.578 m/s (total gain +0.309 m/s); compared with the additive expectation from the three single modifications (0.541 m/s), an additional +0.037 m/s is attributable to interaction effects, confirming measurable synergy when capture, conveyance, and discharge are optimised together.

Across wind orientations, ventilation performance generally improves from windward (0°) toward oblique incidence (30° – 70°), where inlet capture and the upward draw of the exhaust riser act together to strengthen through-flow and improve penetration. This is most evident for the best-performing cases: COC2 peaks around 60° – 70° , reaching high and relatively even velocities across floors (e.g., at 70° : 0.853 m/s (GF), 0.860 m/s (1F), 0.956 m/s (2F)). The inlet plane is the strongest single modification in this oblique range; for instance, at 70° it increases the second-floor velocity from 0.424 to 1.131 m/s ($2.7\times$), indicating that improving aerodynamic capture can strongly amplify the benefit of favourable wind alignment. By contrast, at 0° the baseline already exhibits relatively strong upper-floor suction (2F = 0.409 m/s), so most modifications deliver their most noticeable gains at GF and 1F, while changes at 2F tend to be smaller in relative terms.

Under parallel (90°) and leeward (180°) winds, all configurations remain weaker because the available driving pressure across the inlet–exhaust pathway is reduced and the indoor flow is more dominated by low-momentum circulation. Even so, COC2 remains the most resilient: at 90° it produces clear improvements on the upper floors (e.g., 1F: 0.174 to 0.280 m/s; 2F: 0.146 to 0.313 m/s) although the ground floor does not benefit in the same way. At 180° , COC2 provides the largest gains across floors (e.g., GF: 0.126 to 0.226 m/s; 2F: 0.130 to 0.271 m/s), whereas COC1 is more variable and can show smaller or less consistent benefits. Overall, these results support COC2 as the most robust configuration, with the inlet plane providing the largest single-measure uplift (especially under oblique winds), transitions delivering reliable but more moderate improvements, and outlet enlargement mainly supporting upper-storey extraction while sometimes compromising ground-floor intake under strongly oblique exposure.

From a practical perspective, these results support incorporating inlet-plane features wherever façade geometry permits, combined with transitions and outlet resizing to achieve COC2-level performance. Where only limited modifications are possible, two-step riser expansion transitions remain a reliable standalone measure, providing consistent gains without significantly disturbing floor-to-floor balance. Design choices should be guided by site-specific wind roses: buildings dominated by oblique or near-parallel winds should prioritise inlet-plane features, while those experiencing frequent windward or leeward exposure may benefit more from COC1-type measures that reduce internal losses and strengthen discharge. Notably, integrated designs, particularly COC2, reduce sensitivity to wind direction by optimising both intake and exhaust, making them the most resilient overall solution.

4.7. Effect of building height

This analysis examines the effect of increasing building height on airflow distribution within the WWC system under a 0° wind angle ($U_{\text{ref}} = 7.59$ m/s) using the COC1 design as an example. At this condition, the velocity contours (Fig. 12a) show that the COC1 configuration maintains effective airflow distribution across the 3-, 4-, and 5-storey WWC cases, with performance shifting as building height increases. In the 3-storey model, ventilation is balanced with average velocities of 0.41 m/s at the ground and first floors and 0.48 m/s at the second floor, where suction effects are highest. Extending to four storeys slightly reduces velocities on the second floor, but the newly added third floor records 0.49 m/s, illustrating enhanced vertical continuity and extraction at higher levels.

In the 5-storey configuration, the ground (0.42 m/s) and first floor (0.48 m/s) remain stable, the second floor recovers to 0.48 m/s, while the third floor weakens slightly (0.40 m/s). Importantly, the new top floor achieves the highest airflow of 0.57 m/s, reflecting intensified suction at the uppermost outlet. These results show that the WWC system scales effectively under direct wind, with lower floors retaining consistent ventilation while additional height shifts airflow benefits upward, increasing extraction at mid and upper storeys without compromising performance at the base levels.

The stacked bar chart (Fig. 12b) provides a comparison of average indoor airflow velocities across the 3-storey, 4-storey, and 5-storey WWC configurations under varying wind directions for the COC1 design. At favourable wind directions (20° – 70°), increasing building height enhances airflow, particularly in the middle and upper floors. For example, at 20° the first and second floors in the 4-storey model reached 0.732 m/s and 0.723 m/s, significantly higher than the three-storey case (0.624 m/s and 0.352 m/s), while the five-storey model further improved second-floor airflow to 0.865 m/s. Similarly, at 30° the five-storey configuration achieved the highest values, with 1F rising to 0.816 m/s and 2F to 0.670 m/s. The pattern becomes more pronounced at 45° – 70° , where additional height improved vertical continuity, generating velocities above 0.6–0.7 m/s on the second and third floors and introducing strong airflow at the topmost levels (e.g., 0.698 m/s at the fifth floor, 70°). These results highlight the role of vertical extension in strengthening wind-driven draw through the external riser and maximising the use of upper-floor suction.

By contrast, under direct wind (0°) and unfavourable directions (90° and 180°), the benefits of added height are less pronounced. At 0° , the three-storey and five-storey models both sustained ≈ 0.48 m/s at the second floor, while the four-storey model dropped slightly (0.402 m/s), suggesting redistribution of airflow when an intermediate level is added. At 90° , all heights maintained functional ventilation, but the five-storey system recorded greater upper-floor performance (0.435 m/s at the third floor, 0.350 m/s at the fourth), while lower floors stayed below 0.25 m/s. At 180° , velocities decreased across all models, with only marginal differences between the 3-, 4- and 5-storey cases. The results demonstrate that the WWC system scales effectively with height, improving airflow distribution in mid- and upper-floors under favourable and oblique wind conditions while maintaining adequate performance at lower levels. The

five-storey configuration consistently achieved the strongest extraction at higher levels without sacrificing ground-floor ventilation, confirming the design's suitability for mid-rise applications.

4.8. Influence of surrounding buildings and urban canyon geometry

Fig. 13a compares the cross-sectional velocity contours of the COC1 WWC building at a 0° wind angle ($U_{ref} = 7.59$ m/s) for S/B ratios of 0.5, 1.0, and 2.0, with zoomed-in views of zones A–H. The complementary side-view contours in Fig. 14 illustrate the same channeling behaviour through the street canyon and its vertical impact on the WWC façade. At S/B = 1.0, both views show a clear channeling effect, with high-speed jets (>6 m/s) concentrated within the open passages and lower-velocity wakes (<1.6 m/s) forming immediately behind the façades. The cross-section confirms how these jets impinge on the windward wall, promoting strong penetration in zones A–C, while the roof-level shear layer rises cleanly over the building array. Side zones (D and H) show moderate velocities (0.15–0.30 m/s), while leeward zones (E–G) remain dominated by stagnation (<0.1 m/s), particularly Zone G.

At S/B = 0.5, the narrow canyon confines the flow, forcing jets upward and over the rooftops as shown in Fig. 14, leaving extensive stagnation near the ground and weak, patchy inflow at the windward openings. At S/B = 2.0, the wider spacing allows freer wind entry and stronger façade impingement (>0.45 m/s), but the side-view contours reveal elongated recirculation zones and turbulence developing downstream, reducing ventilation effectiveness for the leeward rooms. Overall, WWCs maintain robust performance in windward zones across all S/B ratios, though leeward operation remains a challenge.

Fig. 13b shows the corresponding SSV contours. At S/B = 0.5, most zones are dominated by blue (<0.10 m/s), with only small localised inflow near openings. At S/B = 1.0, windward zones show moderate gains (0.15–0.30 m/s) due to vortex-induced recirculation, while side zones improve slightly and leeward zones remain poorly ventilated. At S/B = 2.0, inflow increases near windward openings (>0.35 m/s), but side and leeward zones continue to perform weakly. Compared with WWC, SSV airflow is more sensitive to canyon geometry and consistently weaker, though in some windward cases at S/B = 1.0 SSV catches up due to upstream vortices boosting façade pressures.

The WWC system consistently outperforms SSV, particularly in sustaining airflow across multiple façades. While SSV remains vulnerable to confinement and wake effects, WWC operation benefits from channelled flow and suction effects that improve windward and side performance. These findings highlight the importance of considering urban canyon geometry in system design and suggest that WWCs may require design refinements or hybrid strategies for leeward façades, whereas SSV is best limited to windward or parallel exposures in dense layouts.

At a 0° wind angle (southern façade, $U_{ref} = 7.59$ m/s), the influence of neighbouring buildings and varying street-to-building (S/B)

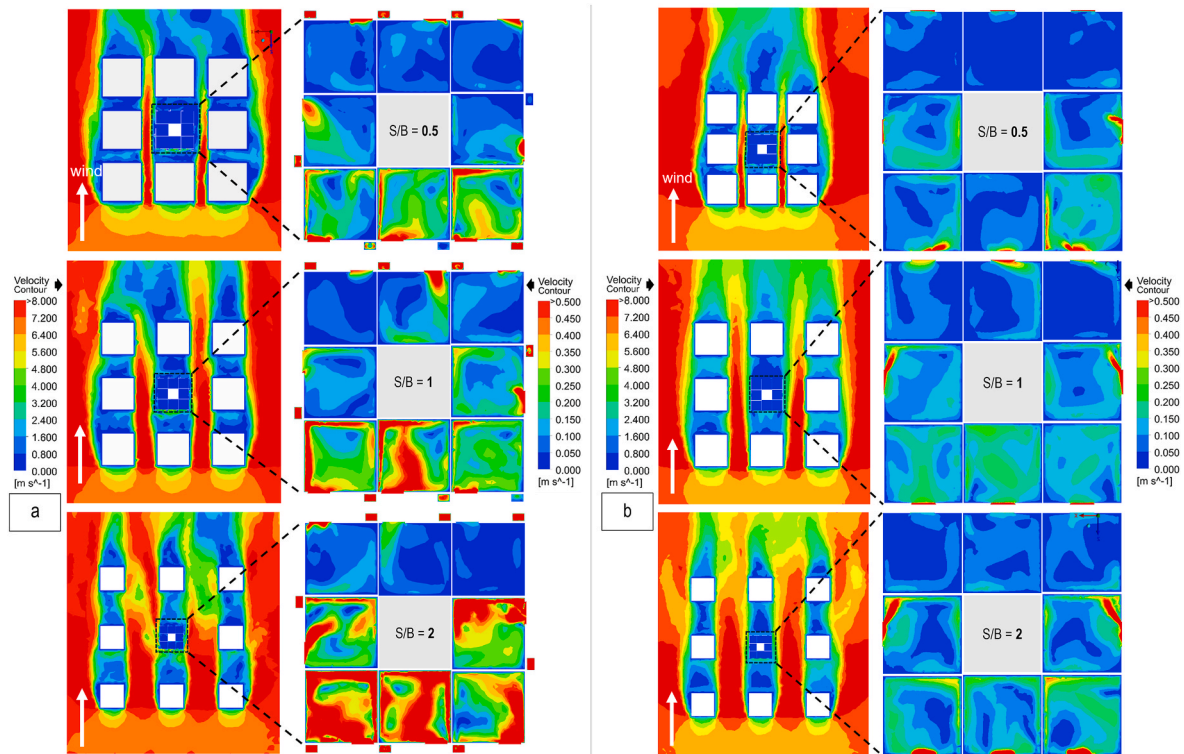


Fig. 13. Cross-sectional plan view velocity contours of (a) WWC and (b) SSV airflow at 0° wind angle ($U_{ref} = 7.59$ m/s) with zones A–H; comparing street-to-building (S/B) ratio = 0.5, 1.0, 2.0.

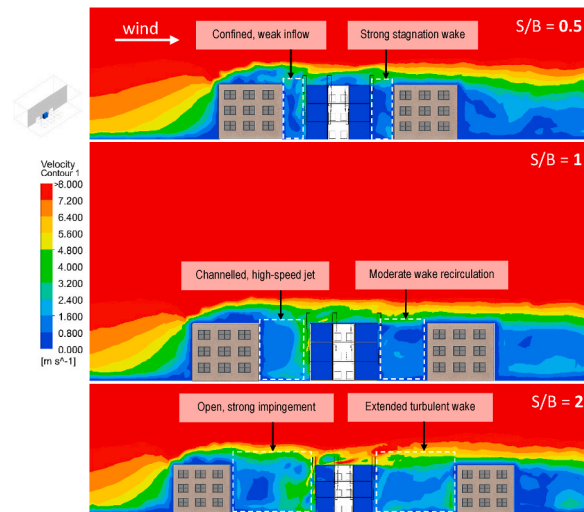


Fig. 14. Cross-sectional side view velocity contours of WWC airflow at 0° wind angle ($U_{\text{ref}} = 7.59$ m/s) comparing street-to-building (S/B) ratio = 0.5, 1.0, 2.0.

ratios is clearly evident (Fig. 15a). Windward zones (A, B, C) recorded the highest airflow velocities, with consistent gains as S/B increased from 0.5 to 2.0. In Zone A the ground floor rose from 0.056 m/s at ratio 0.5 to 0.355 m/s at ratio 2.0, while the second floor improved from 0.207 m/s to 0.354 m/s. Zone B showed greater sensitivity, with second-floor airflow rising from 0.252 m/s to 0.554 m/s. Zone C also benefitted strongly, the second floor increasing from 0.314 m/s to 0.611 m/s. These results confirm the aerodynamic advantage of direct wind exposure, with wider canyons reducing blockage and enhancing penetration, especially at higher levels.

Moderate but steady improvements were observed for side zones (D and H). Zone D's second floor increased from 0.100 m/s to 0.307 m/s, and Zone H's from 0.101 m/s to 0.368 m/s, showing that wider canyons can improve airflow even under parallel wind exposure. Leeward zones (E, F, G) recorded the lowest velocities due to wake and shielding. Some modest gains occurred (e.g., Zone E first floor to 0.118 m/s), but others declined, such as Zone G second floor from 0.085 m/s at ratio 0.5 to 0.040 m/s at ratio 2.0, reflecting persistent low-pressure recirculation. The results show that windward orientation and larger canyon widths deliver the strongest performance, while side zones benefit moderately and leeward zones remain weak. Crucially, the WWC remains effective even under neighbouring and confined conditions, sustaining functional flow across most zones. In urban canyon settings, the WWC also benefits from elevated exposure at upper floors while maintaining useful flow at lower levels, confirming its robustness as a passive ventilation strategy.

For SSV, at a 0° wind angle (southern façade, $U_{\text{ref}} = 7.59$ m/s), its performance across the zones was strongly influenced by canyon geometry and neighbouring obstructions, with overall velocities much lower than those recorded for the WWC system (Fig. 15b). Windward zones (A–C) recorded the highest SSV velocities, with gains as the S/B ratio widened, though performance remained inconsistent. In Zone A, the ground floor increased from 0.081 m/s at ratio 0.5 to 0.244 m/s at ratio 2.0, while the second floor rose from 0.071 m/s to 0.191 m/s. Zone B was more variable, with the ground floor dropping at ratio 1.0 before reaching only 0.059 m/s at ratio 2.0, though the second floor benefitted at 0.203 m/s (ratio 1.0). Zone C performed comparatively better, with ground and second floors exceeding 0.23 m/s at ratio 2.0. Interestingly, in these windward cases SSV sometimes narrowed the gap with WWC, likely due to recirculation or vortices generated by upstream buildings that increased façade pressures and aided airflow penetration.

Side zones (D and H) showed moderate but stable performance. Zone D's second floor stayed within 0.122–0.142 m/s across all ratios, while Zone H recorded slightly higher values, with first- and second-floor velocities between 0.118 and 0.139 m/s, indicating limited sensitivity to canyon width. Leeward zones (E–G) consistently produced the weakest results. Although Zone E's ground floor rose modestly to 0.100 m/s at ratio 2.0, most floors in Zones F and G remained below 0.11 m/s, with some values declining as canyon width increased, reflecting persistent shielding and wake effects.

Overall, SSV shows low airflow potential with only marginal sensitivity to S/B ratio. Windward rooms gain the most and can occasionally benefit from upstream-induced recirculation, but average performance is still less than half that of WWC under the same conditions. Side façades maintain weak but steady flows, and leeward zones remain largely ineffective regardless of spacing. These results underline the limitations of SSV in dense urban canyons, where airflow is dominated by façade orientation and turbulence, while also highlighting that neighbouring buildings can in some cases enhance SSV through vortex-driven effects. Importantly, the findings also suggest it may be worth rethinking WWC designs for leeward applications, particularly in sheltered corners such as Zone G, where in some cases SSV performance can equal or exceed WWC.

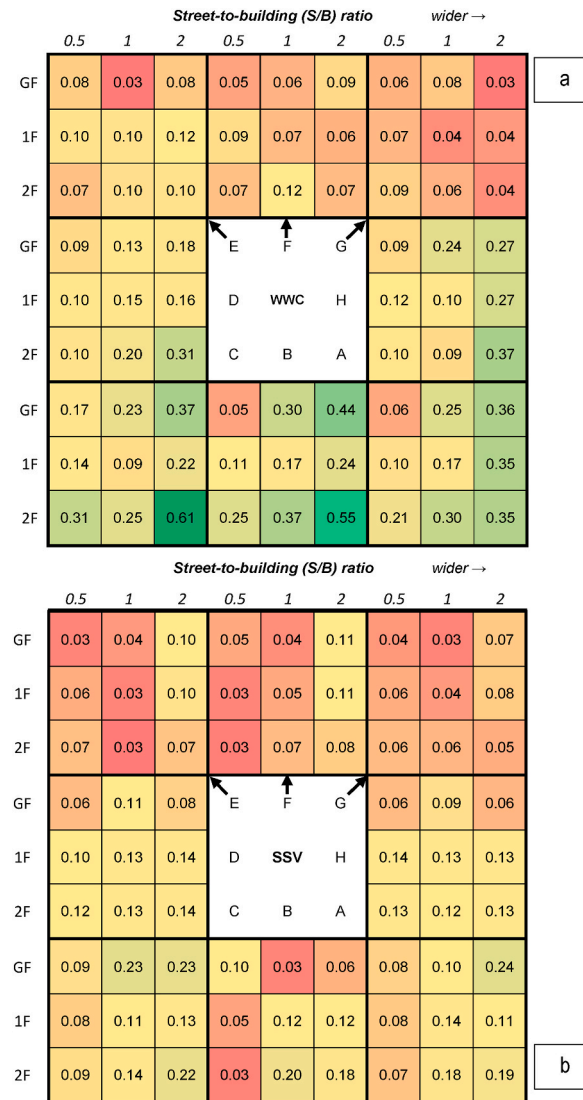


Fig. 15. Summary of average indoor airflow velocity results (m/s) for (a) WWC and (b) SSV at 0° wind angle ($U_{ref} = 7.59$ m/s), across zones A–H, comparing street-to-building (S/B) ratios of 0.5, 1.0, and 2.0.

5. Discussion

5.1. Synthesis of key findings

When results are aggregated across all wind angles and floors, the parametric programme established a clear performance hierarchy: COC2 (inlet plane + transitions + enlarged outlets) was the most effective, followed by the plane inlet, COC1 (transitions + enlarged outlets), and the single-parameter designs (transitions, enlarged outlet), which on average outperformed the Base WWC and SSV. Under oblique winds (30°–70°), COC2 consistently achieved the highest overall indoor velocities and the most uniform floor-to-floor distribution (e.g., at 45°: GF = 0.85 m/s, 1F = 0.81 m/s, 2F = 0.80 m/s). The inlet plane alone produced the strongest single improvement at these angles, with 2F peaking at 1.1 m/s (70°), while two-step riser expansion transitions delivered reliable mid-angle gains with minimal trade-offs. The enlarged outlet preferentially enhanced upper-storey extraction (e.g., 2F 0.41 to 0.51 m/s at 0°) but occasionally weakened ground-floor intake at high obliquity (e.g., 70° GF 0.24 to 0.12 m/s).

Performance under parallel winds (90°) remained the most limited: although COC2 improved airflow at 1F and 2F (0.28 and 0.31 m/s), absolute values remained modest relative to oblique cases. Leeward winds (180°) were similarly challenging, yet COC2 still produced measurable gains (e.g., GF 0.13 to 0.23 m/s), demonstrating enhanced resilience under adverse exposures. Overall, the findings confirm that combining inlet capture, smooth internal transitions, and outlet relief provides a balanced, high-performance configuration capable of maintaining effective natural ventilation across diverse wind conditions.

5.2. Flow mechanisms underpinning the gains

The observed improvements are consistent with aerodynamic mechanisms that increase the driving pressure difference while reducing energy losses along the intake–exhaust path. The inlet plane functions as a small guide vane or splitter plate: it aligns the near-façade stream, strengthens and thickens the approach jet, and helps stabilise flow separation at the opening edges. This is especially effective at oblique angles (30° – 70°), where the incident flow carries sufficient momentum but poor directional alignment; the plane converts that lateral momentum into a more coherent inflow that penetrates deeper indoors. The additional riser expansion transitions reduce abrupt area changes along the vertical exhaust duct, lowering minor losses and improving entrainment into the riser. Their progressive enlargement with height accommodates cumulative flow and maintains a more even vertical pressure gradient. Enlarged outlets lower discharge resistance, reinforcing upper-storey extraction and enhancing the wind-induced suction. Acting together in COC2, these elements target all three flow stages, capture (inlet), conveyance (transitions), and discharge (outlet), producing a smoother flow path, a flatter angle-sensitivity curve, and balanced velocities across floors.

5.3. Trade-offs and interactions

Because pressure is redistributed along the intake–exhaust pathway, single-parameter modifications can shift where benefits appear. Enlarging the outlet without complementary inlet or transition measures can redistribute the pressure field, often strengthening upper-floor extraction under windward to moderately oblique winds, but in some cases weakening ground-floor intake and reducing performance at high obliquity (e.g., 70°). In contrast, the inlet plane increases local windward pressure and improves capture, making its gains most pronounced where capture is limiting (oblique or near-parallel winds) and more neutral where suction already dominates (e.g., windward 2F). The additional exhaust-duct transition are typically the least risky intervention: they reduce internal losses and often improve vertical continuity, although benefits can diminish when the available driving pressure is weak (e.g., leeward exposure).

The combined configurations exhibit clear synergistic effects. The integration of two-step riser expansion transitions and enlarged outlets establishes a lower-loss airflow pathway that enables the pressure gains generated by the inlet plane to be transmitted more effectively along the vertical riser. This complementary interaction accounts for the superior performance of COC2, in which enhanced airflow capture, reduced internal resistance, and improved discharge collectively produce a marked improvement in ventilation continuity and velocity uniformity across all floors.

5.4. Robustness under windward, oblique, parallel, and leeward conditions

Performance generally increases from windward (0°) to oblique angles (30° – 70°), peaking near 60° – 70° , where inlet capture and vertical pressure draw act synergistically to maximise flow. Velocities then decline at 90° and 180° , where façade pressures are more strongly influenced by cross-flow, recirculation, and wake effects. Even so, the optimised WWC maintains a functional baseline at these challenging angles. At 90° , COC2 raises indoor velocities at 1F and 2F to 0.28–0.31 m/s, despite cross-flow dominance. At 180° , the gains are smaller but remain measurable across floors (e.g., GF = 0.23 m/s with COC2), indicating that the combined optimisation can partially mitigate leeward shielding by improving intake capture and reducing internal losses along the flow path. Across all wind conditions, the optimised WWC configurations outperform SSV by a wide margin, although isolated windward SSV cases within dense urban canyons may occasionally benefit from vortex-driven façade pressures generated by upstream buildings.

5.5. Urban canyon effects and height scaling

Surrounding buildings influence the pressure field near the façade and determine how much wind energy reaches the ventilation openings. When the street-to-building ratio (S/B) is 0.5, the narrow spacing causes flow confinement and widespread stagnation. At S/B = 1.0, the spacing allows the formation of strong, channelled air streams between buildings. When the ratio increases to S/B = 2.0, windward exposure improves further, but recirculating wakes remain behind leeward façades. The WWC system makes good use of this channelled flow in windward and side zones, maintaining clear performance advantages over SSV, which is much more sensitive to geometry and generally performs poorly in leeward positions. In practical terms, WWCs should be prioritised on façades that face the prevailing wind or along street canyons where air channeling occurs. Side façades can also be effective, while leeward façades may require additional features such as cowls, adjustable dampers, or hybrid assistance to maintain adequate ventilation.

Increasing building height enhances vertical airflow and roof-level extraction without significantly reducing ventilation on lower floors. In the four- and five-storey models, the middle and upper floors experienced the greatest improvements under favourable wind directions (for example, 2F = 0.72–0.87 m/s at 20°), while ground-floor airflow remained within a stable, functional range. Greater height therefore strengthens the wind-induced pressure gradient along the external riser, increasing roof-level suction and reinforcing vertical flow continuity. Any design changes that reduce airflow resistance along the vertical duct, such as adding transition sections or gradually enlarging the cross-section, become more effective as height increases. Minor reductions in lower-floor airflow can be balanced by slightly adjusting the duct size, adding local transitions, or narrowing the top outlet to even out the pressure distribution.

5.6. Limitations

The CFD framework used steady-state RANS and focused on mean ventilation metrics. Although validated against wind-tunnel

data, this approach cannot capture transient effects such as fluctuating façade pressures, particularly relevant at parallel (90°) winds. Consequently, predictions at these orientations carry higher uncertainty, and short-term variations or peak flows remain unresolved. The building model was idealised, omitting interior details and solar loading. In addition, thermal buoyancy effects were not included in the main parametric analysis, and ventilation performance was therefore assessed primarily under wind-driven conditions. In practice, these factors can alter absolute ventilation rates but may not change the relative ranking of design measures such as transitions, outlet enlargement, or inlet planes.

The present analysis further assumes that the WWC inlet and outlet are the only active airflow paths for each zone, with all other façade openings sealed. In real buildings, occupant behaviour or mixed façade strategies for example, the coexistence of WWC and single-sided ventilation (SSV) openings may introduce additional pressure-driven pathways. Under such conditions, openings exposed to negative pressure could draw air from adjacent spaces or external sources, potentially allowing warm or polluted air to enter the indoor environment. These cross-transmission effects were not considered in the current study and warrant dedicated investigation, particularly for buildings with heterogeneous ventilation strategies or high occupant interaction.

Furthermore, boundary conditions were based on wind tunnel measured atmospheric boundary layer profiles and simplified surroundings for isolated and urban canyon cases. Real sites exhibit more complex terrain roughness, shielding, and wind variability that reshape façade pressures and incidence frequencies. For deployment in practice, the optimised WWC geometries should be paired with site-specific wind assessments derived from meteorological records, microclimate CFD, or field measurements. The parameter space was limited to key geometric features and did not include opening aspect ratios, louvres, or dynamic controls. Future work should apply URANS or LES for selected cases, extend optimisation, and evaluate operational issues such as fouling, damper drift, and maintenance access to ensure that the WWC's predicted benefits are achievable and sustainable in real-world use.

6. Conclusions and future work

This study employed a wind tunnel-validated steady-state RANS ($k-\epsilon$ RNG) CFD framework to conduct a detailed parametric analysis of a façade-integrated Wall Windcatcher (WWC) for multi-storey natural ventilation. Validation against wind-tunnel measurements demonstrated low errors under windward and oblique conditions, with larger but acceptable deviations under parallel winds where the flow is more unsteady, providing a reliable foundation for subsequent design assessment. Compared with an equivalent single-sided ventilation (SSV) baseline, the WWC variants produced higher mean floor-average indoor velocities overall and significantly reduced stagnation, with the performance gap widening under oblique winds, conditions under which SSV typically deteriorates rapidly.

Individually, the three geometric modifications targeted different sources of aerodynamic loss. The additional riser expansion transition introduced near the upper-floor outlet (creating a two-step riser enlargement) generally improved performance and floor-to-floor balance at mid-range wind angles by reducing internal losses and strengthening continuity into the vertical duct. Enlarging the outlet generally enhanced upper-storey extraction by reducing back pressure but could lower ground-floor intake at highly oblique wind directions when applied alone. The thin inlet plane produced the most direction-dependent improvements, significantly enhancing airflow capture and incoming flow alignment as the wind shifted toward oblique directions; under normal wind incidence, gains were more modest because inflow alignment was already favourable. When applied together, the measures acted synergistically: COC1 (transitions + enlarged outlet) delivered robust multi-floor gains particularly under windward and oblique winds, while COC2 (adding the inlet plane) achieved the highest and most uniform velocities, with peak results at 60° – 70° and measurable improvements even under leeward (180°) winds. Overall, the ranking derived from aggregate metrics was $\text{COC2} > \text{inlet plane} > \text{COC1} > \text{transitions only} > \text{enlarged outlet only}$.

Increasing the building height from three to four and five storeys showed that the WWC system works well in taller buildings without significantly reducing airflow on the lower floors. The added height mainly strengthened ventilation on the middle and upper floors by improving the vertical flow connection, while the ground floor stayed within a stable performance range across different wind angles. In the urban tests, windward zones (A–C) performed best and improved as the street-to-building ratio (S/B) increased. Side zones (D and H) also worked effectively and gained from wider street canyons that allowed stronger wind channels. Leeward zones (E–G) remained limited by wake effects, showing little or irregular improvement with S/B changes. In practical terms, designers should focus WWC systems on windward and side façades that receive stronger airflow, reduce losses within the vertical exhaust riser, and combine outlet enlargement with progressive riser expansion transitions to keep airflow balanced across floors. Inlet planes or similar guiding features should be added where oblique winds are common to help capture airflow more effectively.

Future work should advance in five main areas. (1) Use URANS or LES for key cases, especially parallel and leeward winds, to capture unsteady flow effects and assess short-term comfort and air quality. (2) Couple airflow with thermal effects and realistic room layouts, while integrating pollutant transport and comfort metrics. (3) Expand the design space through systematic optimisation. (4) Enhance urban microclimate analysis using calibrated CFD or field data to better resolve terrain roughness, shielding, and canyon effects for façade selection and sizing. (5) Develop and test field prototypes, focusing on modular, maintainable units with balancing controls, verified through commissioning and long-term monitoring. Fire safety, weatherproofing, drainage, acoustics, and maintenance access should be incorporated in parallel with development.

The results show that a retrofit-focused WWC system can perform better than SSV in multi-storey buildings when the air intake,

flow path, and outlet are designed to work together. COC2 gives the best overall performance and handles different wind directions well, while COC1 offers a strong but simpler alternative. With further studies using unsteady flow modelling, broader design testing, local wind analysis, and real building trials, the WWC concept can be developed into practical design guidelines and modular retrofit solutions that provide reliable ventilation for multi-floor buildings.

CRediT authorship contribution statement

Salah Almazmumi: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carlos Jimenez-Bescos:** Supervision. **John S. Owen:** Writing – review & editing. **John Kaiser Calautit:** Writing – review & editing, Supervision, Investigation, Conceptualization, Formal analysis, Project administration, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Salah Almazmumi reports financial support was provided by Saudi Arabian Cultural Bureau. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

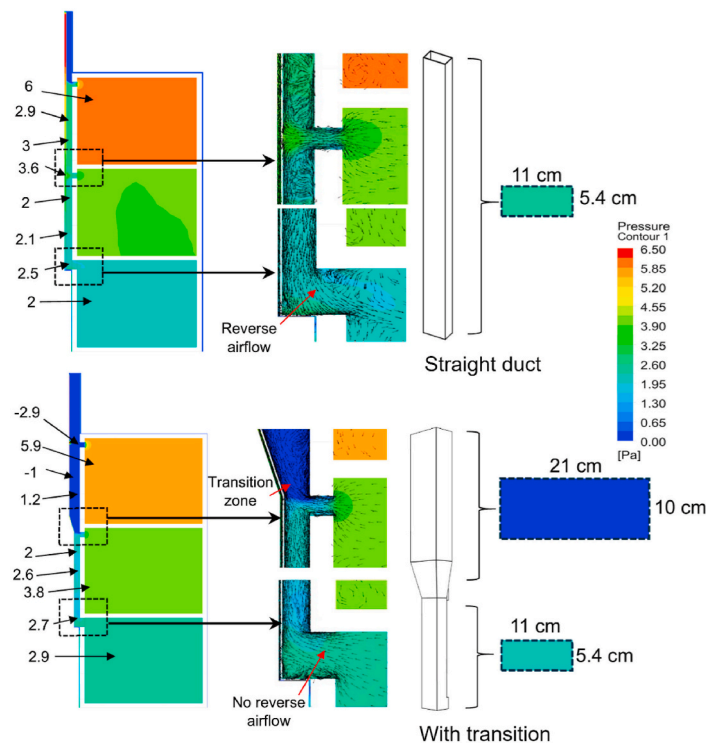


Fig. A1. Pressure contours and velocity vectors in the WWC with straight exhaust duct and transition sections

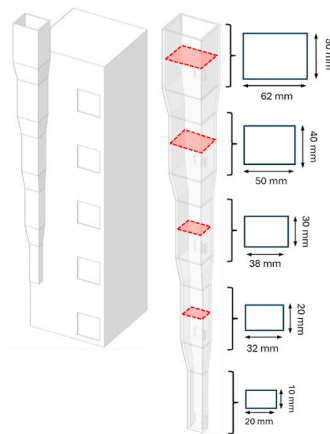


Fig. A2. 3D view of the five-story model configured with COC1 parameters, featuring additional exhaust-duct transitions and enlarged outlet openings to optimize airflow performance.

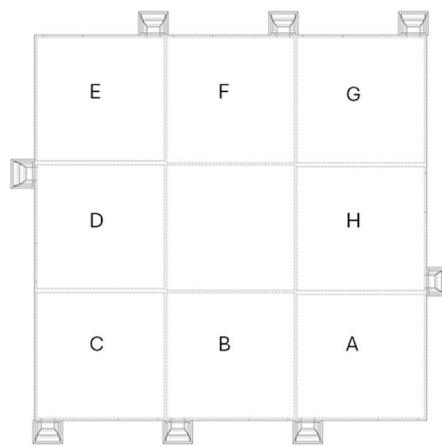


Fig. A3. Plan view of the WWC model showing the zoning layout. Zones (A), (B), and (C) are located on the windward side (0°), zone (H) on the right facade (90°), zones (E), (F), and (G) on the leeward side (180°), and zone (D) on the left facade (270°). The central zone represents the building core or service area and is not used in airflow analysis.

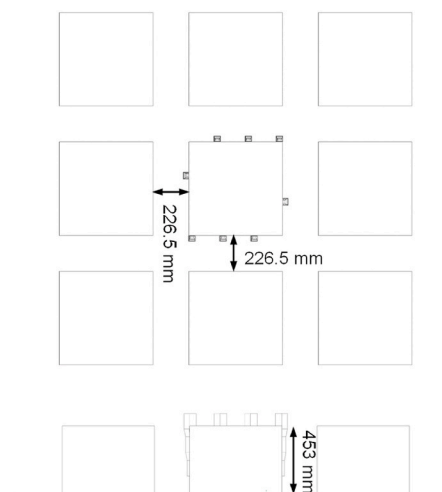


Fig. A4. Top and front views of the WWC model within an urban configuration representing a street-to-building height ratio of 0.5. The building height is 453 mm, and the surrounding street canyon width is 226.5 mm on all sides.

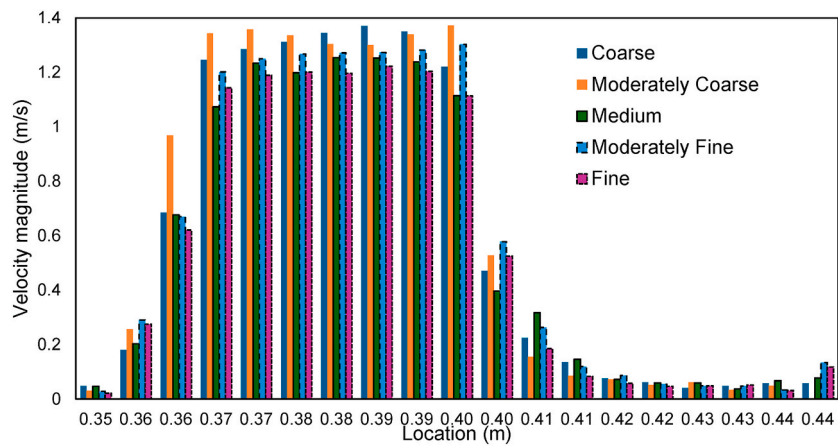


Fig. A5. Grid sensitivity analysis.

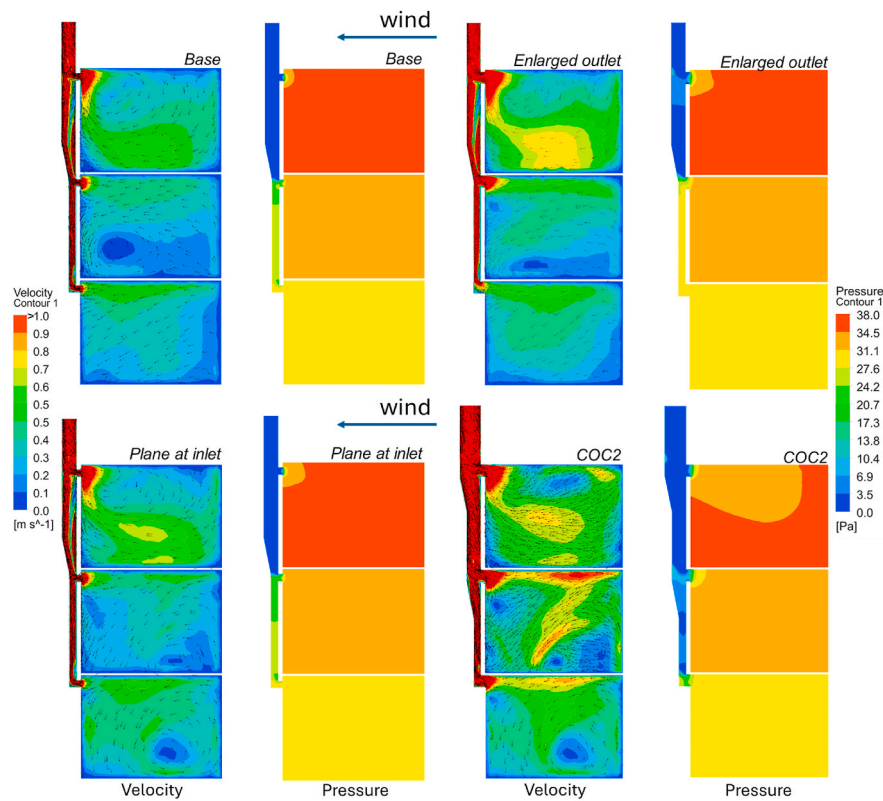


Fig. A6. Cross-sectional velocity vectors and pressure contours comparing different WWC configurations at 0° wind.

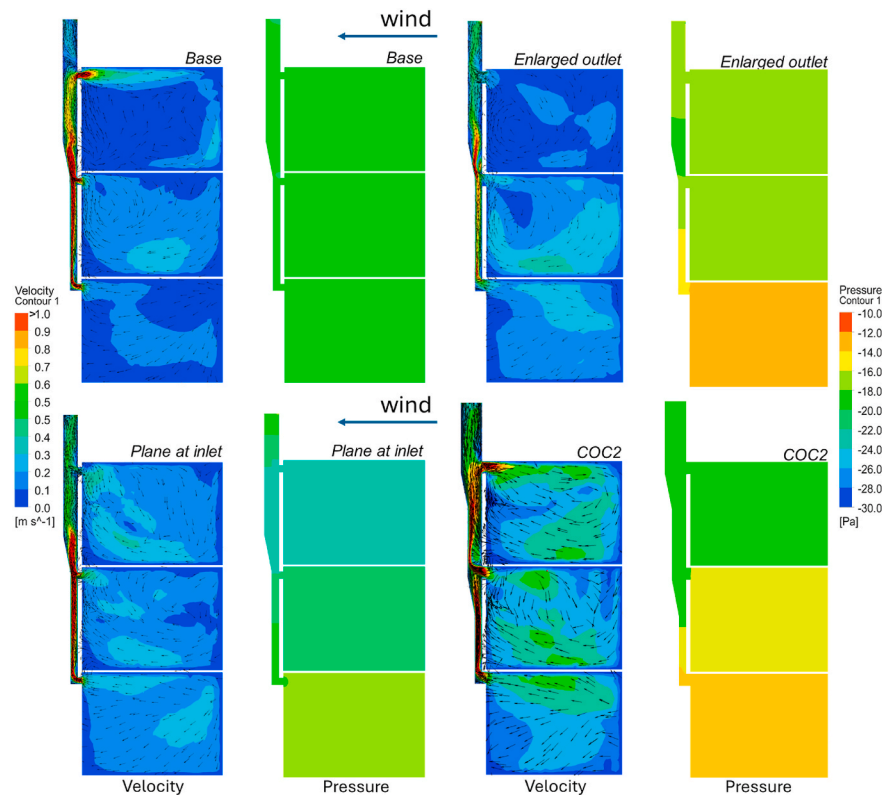


Fig. A7. Cross-sectional velocity vectors and pressure contours comparing different WWC configurations at 180° wind.

Data availability

Data will be made available on request.

References

- [1] B. Güneralp, Y. Zhou, D. Ürgü-Vorsatz, M. Gupta, S. Yu, P.L. Patel, M. Fragkias, X. Li, K.C. Seto, Global scenarios of urban density and its impacts on building energy use through 2050, *Proc. Nat. Acad. Sci. USA (PNAS)* 114 (34) (2017) 8945–8950.
- [2] D. Booker, G. Petrou, L. Chatzidiakou, D. Das, F. Farooq, L. Ferguson, O.E.I. Jutila, K. Milczewska, M. Modlich, A. Moreno-Rangel, S.K. Thakrar, A.M. Yeoman, M. Davies, M.I. Mead, M.R. Miller, O. Wild, Z. Shi, A. Mavrogianni, R.M. Doherty, Ten questions concerning the future of residential indoor air quality and its environmental justice implications, *Build. Environ.* 244 (2025) 112957.
- [3] J.I. Levy, K. Kibilko, Indoor air quality in multi-family housing: drivers and interventions, *Curr. Environ. Health Rep.* 12 (1) (2025) 4.
- [4] F. Muhsin, W.F.M. Yusoff, M.F. Mohamed, A.R. Sopian, CFD modeling of natural ventilation in a void connected to the living units of multi-storey housing for thermal comfort, *Energy Build.* 144 (2017) 1–16.
- [5] J. Niu, Some significant environmental issues in high-rise residential building design in urban areas, *Energy Build.* 36 (12) (2004) 1259–1267.
- [6] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on buildings energy information: trends, end-uses, fuels and drivers, *Energy Rep.* 8 (2022) 626–637.
- [7] J.K. Calautit, L.X. Yong, Fad or future? Navigating challenges and proposing holistic solutions in sustainable building design, *One Earth* 6 (11) (2023) 1430–1434.
- [8] H. Sun, R. Bensalem, A. Dik, Z. Tao, Z. Wang, C. Jimenez-Bescos, J.K. Calautit, The impact of courtyard roof shape on adjacent building natural ventilation and passive cooling, *J. Build. Eng.* 111 (2025) 113331.
- [9] H.-Y. Zhong, J. Sun, C. Lin, et al., Single-sided natural ventilation in buildings: a critical literature review, *Build. Environ.* 212 (2022) 108797.
- [10] A. Aflaki, N. Mahyuddin, M.R. Baharum, The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: a field study, *Energy Build.* 126 (2016) 146–158.
- [11] C.-R. Chu, Assessment of year-round wind-driven ventilation by an integrated ventilation model, *Build. Environ.* 243 (2023) 110710.
- [12] S. Almazmumi, J.S. Owen, C. Jimenez-Bescos, J.K. Calautit, Numerical modeling and wind tunnel testing of a novel wall windcatcher natural ventilation system for multi-floor buildings, *Energy Build.* 349 (2025) 116427.
- [13] Z.T. Ai, C.M. Mak, Determination of single-sided ventilation rates in multistory buildings: evaluation of methods, *Energy Build.* 69 (2014) 292–300.
- [14] P. Prajongsan, S. Sharples, Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts, *Build. Environ.* 50 (2012) 104–113.
- [15] C. Zhou, Z. Wang, Q. Chen, Y. Jiang, J. Pei, Design optimization and field demonstration of natural ventilation for high-rise residential buildings, *Energy Build.* 82 (2014) 457–465.
- [16] H.L. Gough, J.F. Barlow, Z. Luo, M.-F. King, C.H. Halios, C.S.B. Grimmond, Evaluating single-sided natural ventilation models against full-scale idealised measurements: impact of wind direction and turbulence, *Build. Environ.* 170 (2020) 106556.

- [17] S.F. Díaz-Calderón, J.A. Castillo, G. Huelsz, Natural cross-ventilation configurations: Comparison using different evaluation parameters, *J. Build. Eng.* 98 (2024) 111130.
- [18] F. Jiang, S. Tao, Q. Tao, Z. Li, Y. Yuan, J. Zheng, The effect of louver blinds on the wind-driven cross ventilation of multi-storey buildings, *J. Build. Eng.* 54 (2022) 104614.
- [19] D. Miše, C. Irrenfried, W. Meile, G. Brenn, H. Kozmar, Wind-driven natural ventilation of cubic buildings in rural and suburban areas, *J. Build. Eng.* 87 (2024) 108740.
- [20] W. Pan, S. Liu, S. Li, X. Cheng, H. Zhang, Z. Long, T. Zhang, Q. Chen, A model for calculating single-sided natural ventilation rate in an urban residential apartment, *Build. Environ.* 147 (2019) 372–381.
- [21] J.O.P. Cheung, C.-H. Liu, CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings, *Energy Build.* 43 (5) (2011) 1149–1158.
- [22] Z. Zhang, W. Yin, T. Wang, Y. Li, Y. Zhong, G. Zhang, Potential of cross-ventilation channels in an ideal typical apartment building predicted by CFD and multi-zone airflow model, *J. Build. Eng.* 44 (2021) 103408.
- [23] X. Zhang, J.W.G. Buddhika, J. Wang, A.U. Weerasuriya, K.T. Tse, Numerical investigation of effects of trees on cross-ventilation of an isolated building, *J. Build. Eng.* 73 (2023) 106808.
- [24] C.A. Varela-Boydo, S.L. Moya, R. Watkins, Analysis of traditional windcatchers and the effects produced by changing the size, shape, and position of the outlet opening, *J. Build. Eng.* 33 (2021) 101828.
- [25] B.R. Hughes, J.K. Calautit, S.A. Ghani, The development of commercial wind towers for natural ventilation: a review, *Appl. Energy* 92 (2012) 606–627, <https://doi.org/10.1016/j.apenergy.2011.11.066>.
- [26] M. Liu, C. Jimenez-Bescos, J.K. Calautit, CFD investigation of a natural ventilation wind tower system with solid tube banks heat recovery for mild-cold climate, *J. Build. Eng.* 45 (2022) 103570.
- [27] J.K. Calautit, B.R. Hughes, A passive cooling wind catcher with heat pipe technology: CFD, wind tunnel and field-test analysis, *Appl. Energy* 162 (2016) 460–471.
- [28] P. Nejat, M.S. Ferwati, J. Calautit, A. Ghahramani, M. Sheikshahrokhdehkhordi, Passive cooling and natural ventilation by the windcatcher (Badgir): an experimental and simulation study of indoor air quality, thermal comfort and passive cooling power, *J. Build. Eng.* 41 (2021) 102436.
- [29] J. Li, J. Calautit, C. Jimenez-Bescos, W. Song, S. Riffat, Q. Chen, Climate-adaptive windcatcher natural ventilation integrated with passive and low-energy technologies: a review of current and future developments, *Build. Environ.* 284 (2025) 113436.
- [30] M. Liu, P. Nejat, P. Cao, C. Jimenez-Bescos, J.K. Calautit, A critical review of windcatcher ventilation: micro-environment, techno-economics, and commercialisation, *Renew. Sustain. Energy Rev.* 191 (2024) 114048.
- [31] S. Almazmumi, H. Sun, M. Liu, J. Calautit, C. Jimenez-Bescos, A novel wall windcatcher (WWC) natural ventilation system evaluated through CFD and experimental field testing – a solution to single-sided ventilation in multi-story buildings? *Build. Environ.* 283 (2025) 113307.
- [32] H. Sun, J.S. Owen, S. Almazmumi, C. Liu, M. Mohammadi, A. Dik, C. Jimenez-Bescos, J.K. Calautit, Pollutant cross-transmission in courtyard buildings: wind tunnel experiments and computational fluid dynamics (CFD) evaluation, *Build. Environ.* 264 (2024) 111919.
- [33] M. Mohammadi, J.K. Calautit, J.S. Owen, C. Gromke, Y. Wu, H. Liu, Inter-room pollutant transmission routes in naturally ventilated street canyon buildings, *J. Build. Eng.* 79 (2023) 107510.
- [34] H.P.A.H. Irwin, The design of spires for wind simulation, *J. Wind Eng. Ind. Aerod.* 7 (3) (1981) 361–366.
- [35] E. Simiu, R.H. Scanlan, *Wind Effects on Structures: Fundamentals and Applications to Design*, third ed., John Wiley & Sons, New York, 1996.
- [36] J.K. Calautit, B.R. Hughes, Measurement and prediction of the indoor airflow in a room ventilated with a commercial wind tower, *Energy Build.* 84 (2014) 367–377.
- [37] F. Jomehzadeh, H.M. Hussen, J.K. Calautit, P. Nejat, M.S. Ferwati, Natural ventilation by windcatcher (Badgir): a review on the impacts of geometry, microclimate and macroclimate, *Energy Build.* 226 (2020) 110396.
- [38] D. Eryener, Performance investigation of a solar updraft tower concept with downdraft windcatcher, *Energy Convers. Manag.* 286 (2023) 117055.
- [39] R. Ramponi, B. Blocken, CFD simulation of cross-ventilation flow for different isolated building configurations: validation with wind tunnel measurements and analysis of physical and numerical diffusion effects, *J. Wind Eng. Ind. Aerod.* 104–106 (2012) 408–418.
- [40] Q. Chen, Comparison of different $k-\epsilon$ models for indoor air flow computations, *Numer. Heat Tran., Part B: Fund.* 28 (3) (1995) 353–369.
- [41] Ansys Inc, *Ansys fluent theory guide 2021R2* [online]. Available at: <https://www.ansys.com/>, 2021. (Accessed 12 June 2024).
- [42] Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, T. Shirasawa, ALJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, *J. Wind Eng. Ind. Aerod.* 96 (10–11) (2008) 1749–1761.
- [43] P.J. Roache, Perspective: a method for uniform reporting of grid refinement studies, *J. Fluid Eng.* (1994) (if applicable, otherwise unpublished technical note—please confirm source).
- [44] H. Wang, Q. Chen, A new empirical model for predicting single-sided, wind driven natural ventilation in buildings, *Energy Build.* 54 (2012) 386–394.
- [45] X. Zhang, A.U. Weerasuriya, K.T. Tse, CFD simulation of natural ventilation of a generic building in various incident wind directions: comparison of turbulence modelling, evaluation methods, and ventilation mechanisms, *Energy Build.* 229 (2020) 110516.
- [46] Y. Choi, D. Song, How to quantify natural ventilation rate of single-sided ventilation with trickle ventilator? *Build. Environ.* 181 (2020) 107119.