International Journal of GEOMATE, April, 2025 Vol.28, Issue 128, pp.117-124
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.128.g14283
Geotechnique, Construction Materials and Environment

CFD SIMULATIONS AND VALIDATION FOR PEDESTRIAN WIND COMFORT: INSIGHTS FROM A UNIVERSITY CAMPUS OUTSIDE BANGKOK

Chakrit Suvanjumrat[1,4], Aekapob Naksusuk[2], Jadsupa Porananont[3] and *Jetsadaporn Priyadumkol[1,4]

[1]Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Thailand; [2]Department of Chemical Engineering, Faculty of Engineering, Mahidol University, Thailand; [3]CADFEM (Thailand) Company Limited, Thailand; [4]Laboratory of Computer Mechanics for Design (LCMD), Faculty of Engineering, Mahidol University, Thailand.

*Corresponding Author, Received: 21 Dec. 2024, Revised: 27 Jan. 2025, Accepted: 30 Jan. 2025

ABSTRACT: Pedestrian wind comfort is a critical factor in urban design, particularly in tropical climates where outdoor spaces play a vital role in daily activities. This study focuses on enhancing the applicability of Computational Fluid Dynamics (CFD) in assessing pedestrian comfort in Southeast Asia's urban contexts, where challenges such as high wind speeds and limited experimental validation persist. Using Mahidol University's Salaya campus in Nakorn Pathom, Thailand, as a case study, we address regional gaps in CFD simulations by excluding natural elements like vegetation to focus on the built environment. High-accuracy CFD simulations, validated through experimental measurements (R^2 = 0.9713), were used to model wind speeds and analyze pedestrian comfort across various outdoor spaces under four prevailing wind directions. The findings reveal critical opportunities to improve outdoor spaces, such as seating and relaxation areas, to enhance both academic and recreational activities. This study not only provides actionable insights for Mahidol University but also offers a scalable methodology that can be applied to other urban settings in tropical climates, emphasizing the need for accurate CFD validation and sustainable, comfortable urban design.

Keywords: Wind comfort, Pedestrian-level wind (PLW), Computational Fluid Dynamics, Built environment and modeling.

1. INTRODUCTION

Pedestrian wind comfort is a critical consideration in urban planning, especially in regions where high wind speeds affect safety, thermal comfort, and outdoor usability. Computational Fluid Dynamics (CFD) has emerged as a key tool for simulating and analyzing wind conditions, enabling planners to optimize design elements for improved pedestrian comfort. However, significant challenges remain, particularly in tropical urban contexts like Southeast Asia. Many studies neglect the incorporation of natural elements, such as vegetation, which significantly influence wind flow and pedestrian comfort. Additionally, the limited validation of CFD models with experimental data raises concerns about their reliability in real-world applications. These challenges are especially pronounced in Southeast Asia, where distinct climatic and architectural conditions have yet to be adequately explored. Addressing these gaps is crucial for improving the applicability of CFD in diverse urban contexts.

Various studies have employed CFD simulations [1-5], utilizing traditional techniques like wind-tunnel measurements and steady-state RANS simulations for high wind amplification factors. Advanced approaches, such as Large Eddy Simulation (LES) and Particle Image Velocimetry (PIV), offer greater precision but are constrained by cost and complexity [1]. Recent research has explored CFD's potential in tropical urban contexts. For example, 3D steady-state RANS simulations, validated with on-site anemometer data, have demonstrated the accuracy of the SST k-ω model in capturing urban wind flow [2]. Thermal comfort in tropical climates has also been a focus, with a study conducted at Chulalongkorn University in Bangkok, Thailand, assessing outdoor thermal comfort and highlighting the importance of cooling devices and vegetation in enhancing campus usability [3]. Furthermore, innovative design strategies, such as lift-up building configurations, have been shown to improve pedestrian wind comfort, with CFD simulations indicating improvements of up to 36.35% in residential areas [4]. Additionally, studies on urban morphology have revealed that the complexity of cityscapes has minimal impact on the number of wind directions required for reliable CFD predictions [5].

Integrating natural elements, such as vegetation, has also gained attention. For example, recent studies highlight that vegetative barriers like hedges and trees not only reduce wind velocities but also improve thermal comfort, with trees demonstrating a greater impact on temperature reduction [6]. Moreover, advancements in statistical methods, including the Weibull distribution and Gram–Charlier series, have provided accurate estimations of extreme wind speeds using LES data, offering valuable insights for urban wind environment design [7].

While these advancements highlight CFD's utility, significant challenges remain, particularly in Southeast Asia. Many studies fail to incorporate natural elements, such as vegetation, which influence wind flow and pedestrian comfort. Additionally, limited validation with experimental data raises concerns about CFD's reliability in real-world applications. These gaps are especially pronounced in Southeast Asia, where climatic and architectural conditions are distinct yet underexplored. Addressing these issues is essential for enhancing the applicability of CFD in diverse urban contexts.

Building upon this background, the present study focuses on Mahidol University's Salaya campus in Nakorn Pathom, Thailand, specifically addressing regional gaps in CFD simulations for pedestrian wind comfort. Unlike previous studies that have often focused on generalized urban settings or incorporated vegetation into their simulations, our study excludes vegetation to focus solely on the built environment, providing a more accurate validation of CFD models for predicting velocity contours and pedestrian wind comfort in Southeast Asia's tropical climate.

The paper is structured as follows: Section 2 discusses wind comfort criteria and the impact of building geometry and wind shear. Section 3 outlines a methodology. Section 4 presents the measurement process. Section 5 covers the numerical approach. Section 6 analyzes the results, focusing on validation, wind flow dynamics, and pedestrian comfort. Section 7 concludes with key findings and future urban planning applications.

2. RESEARCH SIGNIFICANCE

This study addresses key regional gaps in pedestrian wind comfort research by applying validated CFD simulations to the tropical context of Mahidol University's Salaya campus. Unlike prior studies, it excludes vegetation to isolate the impact of built environments on wind flow, offering more accurate velocity contour predictions. The strong agreement between experimental and simulation results enhances the reliability of CFD tools for Southeast Asian urban planning. The findings support sustainable campus design by identifying discomfort zones and proposing passive strategies, such as windbreak placement, to reduce energy use, enhance comfort, and contribute to climate-resilient outdoor spaces.

2.1 Wind Comfort Criteria

Wind comfort criteria, such as thresholds for acceptable wind speeds, play a key role in evaluating the suitability of outdoor environments for walking, sitting, or recreational activities. [8] developed wind comfort criteria based on existing standards [9-11], categorizing pedestrian wind comfort into five distinct levels, with mean wind velocity serving as the threshold parameter. Notably, these criteria set the exceedance probability for all activities at 20%, mirroring the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standard of 80% for indoor comfort. Table 1 provides a detailed overview of these wind comfort criteria. The criteria are evaluated at a height of 1.5 meters above ground level, where wind velocities typically increase with height. These criteria are designed to be straightforward and easily interpretable by end users, including developers, architects, city planners, and the general public.

Table 1. Wind comfort criteria by [8]

Category	Mean wind velocity	Exceedance Probability
Sitting	<2.5 m/s	20%
Standing	2.5 m/s - 3.89 m/s	20%
Walking	3.89 m/s - 5 m/s	20%
Uncomfortable	>5 m/s	20%
Severe	>14.44 m/s	20%

2.2 Wind Flow Around Buildings: Impact of Geometry and Wind Shear

Flow patterns around buildings are shaped by the interaction of wind with the structure's geometry, surrounding environment, and wind shear effects. As wind approaches a building, it forms a high-pressure zone on the windward side, slowing down and stagnating near the surface. The flow is then deflected upward, around the sides, and over the roof, creating areas of accelerated flow and reduced pressure. At sharp edges, wind separates from the surface, generating turbulence and recirculation zones characterized by vortices. Behind the building, in the wake region, the airflow becomes turbulent, forming complex patterns of eddies and swirling motion.

Wind shear further influences these patterns by causing variations in wind speed and direction with height. As wind moves from the ground level to higher elevations, it experiences a velocity gradient due to frictional forces from the terrain and neighboring structures. This gradient intensifies flow separation, vortex formation, and turbulence, particularly for tall buildings, which intercept stronger winds at higher elevations. These winds are redirected downward, contributing to the downwashing effect near the base, often resulting in swirling turbulence and increased wind activity at the pedestrian level.

Additionally, oblique winds deflected by a building can lead to corner acceleration effects, where wind speeds rise significantly around building corners due to rapid flow deflection and compression.

Gaps between buildings may channel wind, forming high-speed jets that further influence pedestrian wind comfort. The combined effects of geometry, surrounding structures, and wind shear modify the extent of wake turbulence, influencing structural loads, pedestrian comfort, and energy efficiency. Understanding these dynamics is crucial for optimizing building designs to balance stability, functionality, and environmental harmony [12,13]

3. METHODOLOGY OVERVIEW

This study integrates experimental measurements and Computational Fluid Dynamics (CFD) simulations to evaluate pedestrian wind comfort at the Faculty of Engineering, Mahidol University's Salaya campus. The methodology follows a two-step approach. The first step involves a field survey and experimental measurements (Section 4), where wind data from 2017 to 2023 is analyzed, and wind speed is measured at various campus locations using anemometers. The second step uses CFD simulations (Section 5), starting with the creation of a 3D model of the campus. The model is divided into small cells for precise wind calculations, and boundary conditions such as wind direction and velocity are applied. Finally, CFD simulations predict wind flow across the campus, providing insights into pedestrian-level wind comfort.

4. MEASUREMENT

4.1 Field Survey

Salaya, Nakorn Pathom (latitude 13.78° N, longitude 100.32° E), is situated in a tropical climate north of the equator. The predominant wind directions are south, west, and north, with wind speeds ranging between 1 and 3 m/s. This data is derived from historical records maintained by the Meteorological Office in Nakorn Pathom over a seven-year period. Analysis of wind data from 2017 to 2023 indicates that wind patterns can be broadly categorized into three periods: from February to May, winds generally come from the south; from June to September, winds predominantly blow from the west; and from October to January, winds are typically from the north.

4.2 Experimental Measurements

The climatic conditions at Mahidol University were characterized by low-to-medium wind velocities, which were used as input for the numerical model. The model's accuracy was assessed by comparing the simulated air velocities with experimental data collected in June 2024. Fig. 2 illustrates the map of the study area and the group of buildings analyzed, showing the recorded outdoor conditions (air velocity). Air velocity was measured using the EXTECH AN100 CFM/CMM anemometer [14], which has a resolution of 0.01 m/s and an accuracy of ±3% of the reading. The vane of the anemometer was aligned with the wind direction to ensure precise measurements. Measurements were taken three times per session, with the device consistently positioned 1 meter above the floor in the engineering areas. The study focused on the Faculty of Engineering on the Mahidol University, Salaya campus, which includes four buildings: Building 1 (EG1), Building 2 (EG2), Building 3 (EG3), and Building 4 (EG4). Wind velocity was measured at eight locations around the engineering area to assess pedestrian wind comfort in these outdoor spaces: Positions 1-4 are between Buildings EG1 and EG2, forming a lane; Positions 5-6 are within the Activity Plaza and lawn; and Positions 7-8 are along the road between Buildings EG1 and EG3.

The field survey and simulations did not account for natural elements such as trees and vegetation, focusing instead on isolating the influence of the built environment on wind flow and pedestrian comfort. This approach prioritizes precise validation of the CFD model while simplifying real-world conditions.

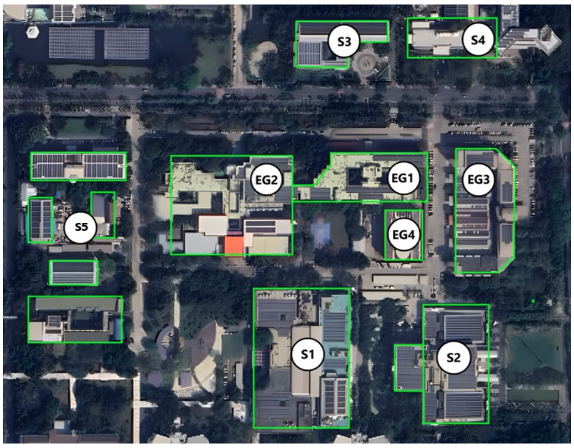


Fig. 1 An overview of a section of buildings at Mahidol University's Salaya campus

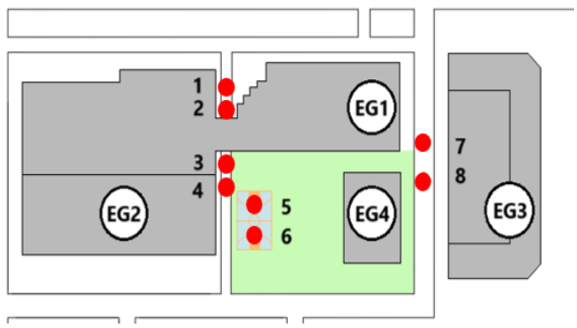


Fig. 2 The utilized locations selected in the experiments and simulations

5. NUMERICAL DETAILS

This paper utilized ANSYS® 2022 software [15], a registered trademark of Ansys Inc., to analyze wind patterns around the campus, with a particular emphasis on the Engineering (EG) buildings and their vicinity. This study utilized steady-state calculations for the numerical simulations, where the problem domain was divided into numerous small cells using the finite volume method, with variable values stored at the center of each cell. The SIMPLEC discretization algorithm was employed for pressure-velocity coupling, which is appropriate for steady flow conditions. The CFD simulations were performed using the commercial CFD code Fluent and the 3D steady RANS equations. The model was initialized using FMG and incorporated the realizable k-ε turbulence model with enhanced wall treatment [15-18], as recommended by [19]. The realizable k-ε turbulence model [20,21] was used for closure, with default turbulence parameters applied. These default settings are commonly used in standard simulations and provide reliable results for flow turbulence modeling in urban environments. Second-order discretization schemes were applied to both convective and viscous terms in the flow equations. Simulations were performed for four wind directions (North, South, West, and East) to cover a range of potential conditions. Iterations continued until scaled residuals showed minimal further reduction, with convergence achieved at an accuracy of 10^{-6} for absolute residual variables, ensuring high precision.

5.1 Geometry

The dimensions of the computational domain were selected to effectively predict flow patterns around the buildings. These dimensions follow established best practices for CFD simulations. Specifically, the simulation used a computational domain measuring 1064 m (Height) × 1010 m (Width) × 175 m (Length). The distance from the edges of the buildings to the domain boundaries in the north, south, east, and west directions is set at 12 times the maximum building height (25 m). This configuration ensures that the computational domain is large enough to accurately capture flow dynamics, while also maintaining a high resolution to improve simulation accuracy.

5.2 Mesh Details

The computational domain is discretized using poly-hexcore grids, with meticulous adjustments to mesh density to accurately represent flow in boundary layers and properly capture boundary layer separation. An inflation layer is added to grids near the building surfaces to achieve a y+ value of 200, which is recommended for the realizable k-ε turbulence model with wall functions. This configuration resulted in a total of 1,736,925 grid elements used in the simulation as shown in Fig.4. Additionally, the average orthogonal quality and skewness are 0.865 and 0.0088, respectively, indicating that the mesh quality is suitable for use with the ANSYS Fluent solver.

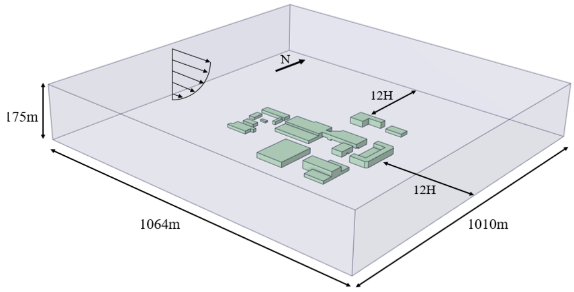
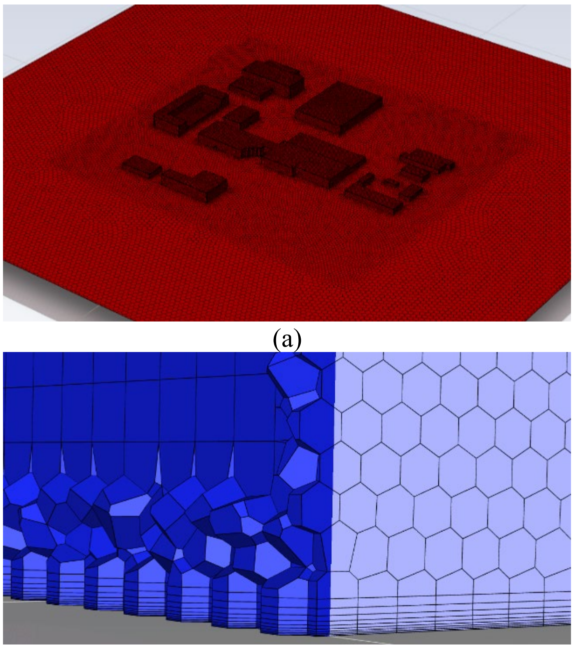


Fig. 3 Geometry of buildings in the three-dimensional domain



(a)

(b)

Fig. 4 Generated mesh of (a) the computational domain and (b) the close-up of the boundary layer mesh

5.3 Boundary Conditions

The incoming wind velocity distribution is modeled using a power-law approach to simulate wind conditions and estimate the average velocity profile, which is crucial for evaluating pedestrian wind comfort in various campus areas.

$$U = U_g \left(\frac{Z}{Z_g} \right)^{\alpha} \quad (1)$$

In the power-law model, U represents the mean wind speed, U_g denotes the gradient wind speed, which is set within the range of 1–3 m/s, Z is the height above ground level, Z_g is the depth of the boundary layer (set at 40 meters), and α is the power-law exponent. The value of α varies based on terrain type: α=0.14 for open country, α=0.25 for suburban areas, and α = 0.33 for urban environments. For this study, α was uniformly set at 0.33 [22]. The outlet pressure boundary condition is specified as zero gauge pressure, which is equivalent to atmospheric pressure. The buildings were modeled with no-slip wall boundary conditions, while symmetry boundary conditions were applied at the top and side boundaries.

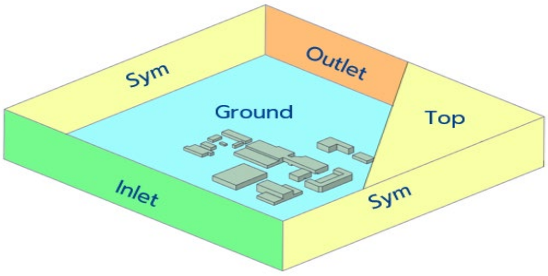


Fig. 5 Boundary conditions

6. RESULTS AND DISCUSSIONS

6.1 Evaluation of Experimental Data and Computational Results

Comparisons were made with physical experiments to validate the numerical simulations. In this study, air velocity was measured at designated points to check the wind speeds in the Engineering area. A velocity inlet of 2.3 m/s from the west was used for validation. The measured results were compared with those from the numerical simulations, as shown in Fig. 6. The air velocity trends at eight points, measured 1 meter above ground, were found to be consistent between the experimental data and the simulations. The correlation between the measured data and the CFD simulation results was linear (Fig. 6), with a coefficient of determination R^2 near 0.9713. The slope of the linear regression for indoor temperatures deviated from unity, at approximately 0.76. This study focused exclusively on the velocity field at Mahidol University, without considering the effects of trees and other objects on airflow patterns, which could affect simulation accuracy. Future research will address this by incorporating additional measurement points within the EG buildings area to improve the precision of wind comfort parameter calculations.

6.2 Wind velocity distribution around buildings and its impact on pedestrian wind comfort

Based on the simulation results at the height of 1.5 meters above ground, the wind flow patterns around the Faculty of Engineering area reveal a complex interplay between wind dynamics and the geometry and spatial configuration of surrounding buildings, significantly affecting pedestrian wind comfort. As illustrated in Fig. 7, the simulations analyzed wind speed of 3 m/s originating from the north, west, south, and east, showcasing the influence of directional flow, velocity gradients, and shear effects.

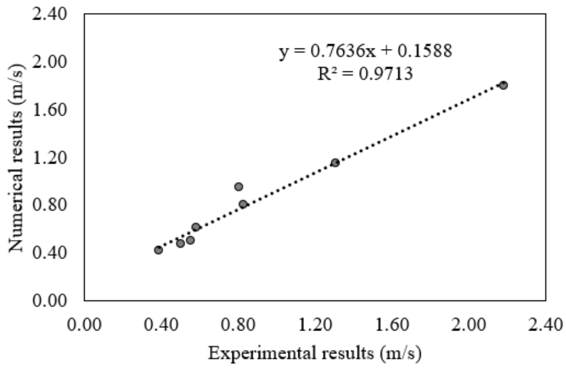


Fig. 6 Velocity validation

6.2.1 North Direction

The northward wind flows through buildings S3 and S4 before reaching the Faculty of Engineering. The velocity distribution reveals the air splitting at the windward side and converging at the leeward side of buildings EG1 and EG3. The highest wind speeds are concentrated at the front corners of buildings EG3 and EG2 and along adjacent roads. In contrast, areas shielded by building geometry, such as the basketball court and lawn behind EG1, experience significantly reduced speeds of approximately 0.4 m/s, offering more comfortable conditions for pedestrians.

6.2.2 West Direction

Westward winds interacting with the S5 building group are redirected upon reaching the Faculty of Engineering area, encountering obstructions such as building EG2. This results in reduced wind speeds in sheltered zones like the basketball court and lawn, where velocities are approximately 0.4 m/s. In contrast, velocity contours reveal significantly higher wind speeds, exceeding 2.0 m/s, around the fronts of buildings EG1 and EG2 and along the side of EG3. These elevated speeds are attributed to the alignment and orientation of the EG buildings relative to the wind direction, which minimize flow separation and maintain streamlined, accelerated airflow along aligned surfaces. The building configuration thus plays a pivotal role in shaping localized wind dynamics, reinforcing the influence of geometry on flow patterns.

6.2.3 South Direction

Under southerly wind conditions, high-speed flows (up to 2.8 m/s) dominate pedestrian zones between EG1 and EG2. The basketball court and lawn also experience elevated velocities, indicating reduced sheltering in this direction. Building EG2, situated downstream of S1 at a corner, amplifies wind acceleration at its upstream corners, where wind speeds exceed the entry-point velocity by approximately 30%. This behavior illustrates how upstream obstructions and sharp corners amplify wind effects locally. The wind velocity contours identify sheltered zones behind EG1 and EG3 as highly suitable for sedentary outdoor activities, with wind speeds as low as 0.4 m/s. Conversely, areas near the fronts of EG2 and EG3 experience elevated velocities that are less comfortable for pedestrians.

6.2.4 East Direction

The simulation results for eastward wind conditions show that areas in front of buildings EG1 and EG2 experience high wind speeds, reaching up to 3.6 m/s. These higher wind velocities are less comfortable for pedestrians, as they can cause discomfort. This area corresponds to the parking lot. In contrast, areas such as the basketball court and lawn, located further from the buildings, experience significantly lower wind speeds, ranging from 0.4 to 0.8 m/s, which are more favorable for pedestrian comfort.

6.3 Pedestrian Comfort Results and Recommendations

As shown in Fig. 8, the results indicate that the Faculty of Engineering and its surrounding areas are suitable for sedentary outdoor activities, providing favorable conditions for sitting and standing throughout the year. Based on the CFD simulations and wind comfort analysis, several interventions are proposed to enhance pedestrian comfort. These include architectural modifications such as windscreens, canopies, and rounded building corners to deflect airflow and reduce wind acceleration in high-speed zones. In more sheltered areas, like those behind specific buildings, adding seating and shaded spaces could improve comfort. To address wind-related challenges, targeted interventions, such as wind barriers near high-speed zones and adjustments to building layouts, are recommended to reduce the impact of prevailing winds. While these interventions were not included in the current simulations, their incorporation in future studies could provide a more accurate representation of wind flow and pedestrian comfort in real-world settings. Further research could validate the effectiveness of these modifications, enhancing the realism and applicability of CFD models for urban wind comfort analysis.

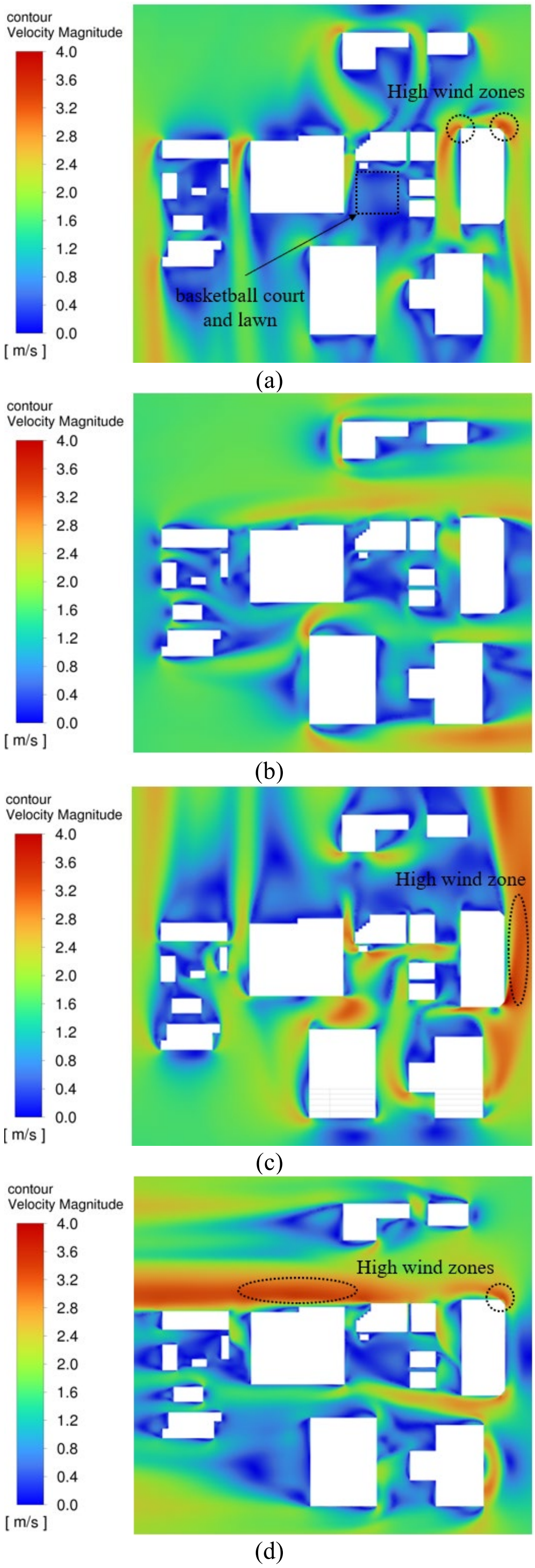
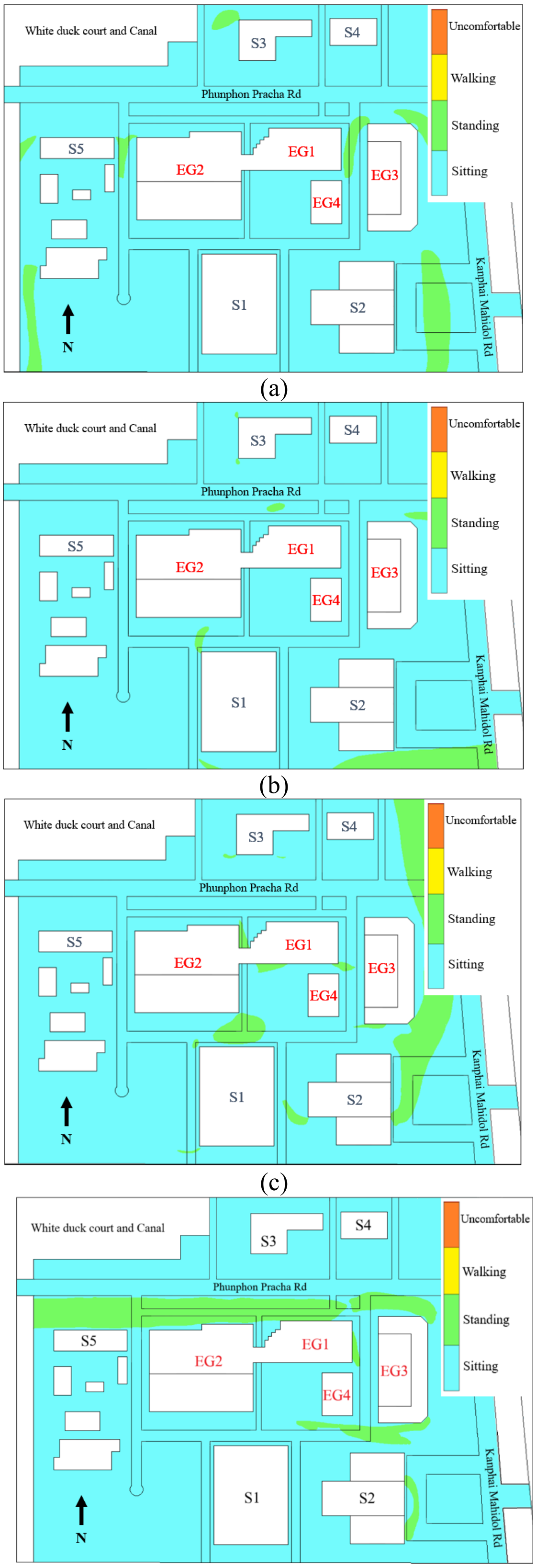


Fig. 7 Velocity contours at a pedestrian level (1.5 m above the ground) with wind speeds of 3 m/s from (a) north, (b) west, (c) south, and (d) east directions



(d)

Fig. 8 Assessment results of the pedestrian level wind comfort with wind direction from (a) north, (b) west, (c) south, and (d) east

7. CONCLUSIONS

This study assessed pedestrian-level wind comfort around the EG buildings, identifying areas suitable for student activities. Strong agreement between numerical and experimental results validated the CFD approach, highlighting its value in evaluating wind impacts and discomfort levels. However, the focus on wind speeds of 1–3 m/s from specific directions limits broader applicability. Optimizing wind comfort is crucial for addressing discomfort and supporting campus life. The findings of this study highlight the potential of wind management strategies to improve pedestrian comfort while supporting sustainability goals. By placing windbreaks in high-speed wind areas, such as EG2 and EG3, we can reduce the need for mechanical cooling, thereby lowering energy consumption and carbon emissions. Additionally, these interventions contribute to urban heat island mitigation and promote green spaces that enhance climate resilience. Future work should quantify energy savings and carbon reduction while incorporating real environmental factors, such as vegetation and seasonal wind variations, to enhance the accuracy of wind comfort assessments and support strategies for optimizing pedestrian comfort, safety, and sustainability.

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