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Article

A Computational Fluid Dynamics (CFD) study on the effectiveness of trees on pedestrian level wind environment in urban areas

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ABSTRACT

The present study aims to investigate the role of vegetation in regulating pedestrian-level wind on Imam Street. Imam Street is one of the main streets of Tabriz city, and the wind speed at pedestrian level has made pedestrians feel uncomfortable, especially in the cold season. The method of the present study is descriptive-analytical research, in which numerical simulation was carried out to simulate wind flow for the current state and different proposed states using Dlubal RWIND 2.02 software. To this end, the effects of height, distance, and arrangement of vegetation (along with tree benches) (as the independent variables) on pedestrian-level wind speed (as the dependent variable) were investigated, and the relationships between the variables were examined using Spearman's correlation.

The findings indicated that planting trees with a height of 6 meters, spaced at a distance of 3 meters according to density pattern 1, can enhance wind comfort on Imam Street by reducing the wind speed at the pedestrian level by 60%. The results showed that the use of vegetation compatible with the climate, at a given distance and according to a proper pattern, can significantly reduce wind speed. The surrounding tree benches direct the airflow towards the street and moderate the wind speed at the pedestrian level.

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INTRODUCTION

Promoting pedestrian-oriented principles in urbanism has enhanced the importance of urban sidewalks as places for pedestrians' attendance and activities. Walking is the simplest way of moving in city spaces, which is done independently with no need for any tools (Heath et al., 2011). The main features of the walking route network are accessibility, safety and security, continuity, shortness of the route, visual appeal, and climatic comfort (Iran Ministry of Roads & Urban Development, 2020), among which climatic comfort is the most important factor for pedestrians'

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attendance and activities in urban open spaces. In outdoor spaces, climatic comfort is influenced by factors such as temperature, humidity, wind, and vegetation, among which temperature, humidity, and wind are environmental factors affected by solar radiation and airflow (Holman, 2010).

Wind speed is one of the most important climatic factors affecting comfort in urban open spaces. It is influenced by numerous design parameters at the urban and architectural scales (Saadatjoo & Saligheh, 2021; Saadatjoo, 2022a; Haghshenas et al., 2021). Factors such as the construction of high-rise buildings and inattention to the prevailing urban wind in the design of arterial roads can lead to increased urban wind speed, disruption of functions, and reluctance to attend urban open spaces. Despite the very high importance of climatic comfort in urban open spaces, designers and architects do not pay much attention to it, and in their designs, they settle for the provision of comfort in interiors (Saadatjoo et al., 2021; Rose et al., 2011; Saadatjoo et al., 2018). Urban wind speed is influenced by the characteristics related to building blocks, access networks, and elements on the surface of roads (Saadatjoo, 2022b). Therefore, changing the physical characteristics of surrounding buildings, the direction and width of roads, and the elements on sidewalks can greatly influence the urban wind flow pattern (Willemsen & Wisse, 2007; Hariri et al., 2016; Saadatjoo, 2023).

Vegetation and urban furniture, in addition to playing their functional roles, can help to adjust pedestrian-level wind by redirecting and blocking it. Urban furniture is divided into four main categories according to its functions: street furniture, park furniture, traffic furniture, and information and advertising structures (Pakzad, 2005). Climatic and local considerations are among the urban furniture design considerations in the design, construction, and installation phases (Zangiabady & Tabrizi, 2004). New studies indicate that the presence of urban furniture, such as billboards, trees, long flower boxes, etc., can greatly adjust wind speed at the pedestrian level and provide comfort for pedestrians (Ricci et al., 2022; Zheng et al., 2020). The presence of furniture on sidewalks, oriented according to prevailing urban wind direction, and proper geometry of the furniture can redirect wind towards vehicular routes and reduce wind speed on sidewalks (Mahgoub & Ghani, 2021a).

Climate-related arrangements and considerations should be applied to urban furniture. In areas with strong local winds, urban furniture should be arranged to expose space users to the least negative wind pressure, while in hot climates, the arrangement should allow natural cool breezes. Trees, in particular, can provide necessary shade and partially control airflow (Mortezaie, 2003). The sidewalks on Imam Street, due to high-rise buildings and alignment with Tabriz's prevailing wind direction, are exposed to very high wind speeds, especially in colder seasons, causing problems for pedestrians such as wind discomfort. This study aims to examine vegetation's and urban furniture's role in reducing wind speed and adjusting pedestrian-level wind flow on Imam Street in Tabriz. This research explores two main questions: How do trees and urban furniture, such as benches, influence wind flow patterns and speed in urban areas? Also, how can different tree sizes and planting arrangements mitigate wind and enhance citizen comfort?

Research Background

Wind speed and patterns in urban districts are influenced by the physical structure of surrounding buildings, access networks, and elements such as greenery and furniture. Numerous studies have investigated factors influencing wind speed in urban districts and their effects on urban wind patterns. Over the years, various research has examined wind flow around high-rise buildings, providing significant insights into building height, shape, and orientation on wind speed and turbulence. Kuo et al. studied the effects of high-rise buildings on pedestrian-level wind in downstream street canyons using wind tunnel test results and examined the suitability of an urban design specification. According to this research, street-level wind speed rises with increased building height and decreases with wider streets (Kuo et al., 2020).

Zahid Iqbal and Chan (2016) studied combined effects of various geometrical variables, such as re-entrant corners of surrounding buildings, wind incident angle, passage angle, and building separation on pedestrian-level wind. Their results indicated that wind circulation at pedestrian-level re-entrant corners is significantly affected by building orientation and separation (Zahid Iqbal & Chan, 2016). Van Druenen et al. (2019) examined the relationship between Pedestrian-Level Wind (PLW) and ground-floor building elements, finding a significant effect of permeable walls on pedestrian wind speed (Van Druenen et al., 2019). Lin et al. (2023) examined variations in the downwash effect related to flow pattern changes and wind speed near the front stagnation height. The results confirmed that, for buildings with the same aspect ratios but different sizes in the same boundary layer flow, similar downwash flow patterns could be assumed (Lin et al., 2023).

Recent studies examined the effect of elevated walkways on mean wind velocity and gust wind velocity (pedestrian-level wind) in three-dimensional (3D) ideal urban street canyons using large eddy simulations. The results indicated that elevated walkways adversely affect pedestrian-level wind environments (Chen et al., 2023). Beranek and Van Koten (1979) studied the relationship between building height and wind comfort, showing that increased wind speed around buildings taller than 50 meters significantly reduces pedestrian comfort (Beranek & Van Koten, 1979). Zhang et al. (2017) concluded, through wind tunnel tests, that lifting the ground level of high-rise buildings and modifying the geometric form of the central core at the ground level influences pedestrian-level wind speed. In a recent study, Zhang et al. (2023) investigated the effects of ratio and position of lift-up design on pedestrian-level wind environments around a residential complex, using field measurements and Computational Fluid Dynamics (CFD) simulation. They showed that the lift-up position, whether at both ends or in the middle, had a significant effect on mean wind velocity ratios (Zhang et al., 2023).

Najaf-Khosravi et al. demonstrated that modifying the geometric form of buildings can alter urban wind flow patterns at the pedestrian level. In particular, modifications such as chamfering and recessing lower floors, especially the ground floor, were effective in improving urban wind flow speed (Hariri et al., 2016). PLW is influenced by urban constructions' physical features and post-construction elements. Previous research has mainly focused on how elevated floors, corners, aspect ratios, and permeable surfaces impact urban wind behavior. Various studies have examined parameters such as elevated floors (Liu et al., 2016), lift-up design (Du et al., 2017; Zhang et al., 2017), canopies (Van Druenen et al., 2019), urban morphology (Javanroodi et al., 2018), building dimensions (Tsichritzis & Nikolopoulou, 2019; Tamura et al., 2019), corner configurations (Wang et al., 2015), roof shapes (Abohela et al., 2013), layouts (Miao & Lau, 2023), and area density, revealing a significant connection between construction elements and urban wind performance.

In recent years, studies on urban furniture have investigated specific elements' effects on wind speed by simulating each in urban spaces. Blocken et al. (2004) studied pedestrian wind comfort in the Silvertop Tower passages, defining an automatic control system to enhance wind behavior. Sliding doors act as actuators controlled by an algorithm based on local wind measurements (Blocken et al., 2004). Aguinaga et al. (2019) conducted wind tunnel tests with Particle Image Velocimetry and CFD simulations to optimize urban district design, focusing particularly on vegetation use. They evaluated six windbreak strategies, such as canopies, porous frameworks, trees in rows, and elements positioned 4 meters above the ground (Aguinaga et al., 2019). Mahgoub and colleagues (2021) focused on windbreaks like fences, vegetation barriers, and perforated facades, applying them in various contexts as wind moderators. In this study, CFD numerical results were compared with experimental outcomes. The porous media model's mean velocity and pressure drop values achieved average errors of 10.5% and 12% (Mahgoub & Ghani, 2021b).

Teshnehdel et al. (2020) used ENVI-met to evaluate tree cover's effect on microclimate and pedestrian comfort in Tabriz, Iran. According to results, four scenarios with different tree species and patterns were simulated during typical summer and winter days to assess benefits and drawbacks across seasons. Results showed that the best scenario provided effective summer cooling without compromising winter comfort. Summer Ta and Tmrt decreased by 0.29°C and 20.04°C, respectively, while winter Ta and Tmrt reached 6.92°C and 13.22°C, compared to the reference scenario (Ta 6.28°C & Tmrt 23.47°C) (Teshnehdel et al., 2020). Kang and Kim (2015) studied trees and vegetation's influence on scalar dispersion and flow in urban canyons. They simulated lateral building rows and centrally positioned trees as simple cubes using Computational Fluid Dynamics (CFD) and compared these to wind tunnel results. Findings indicated that increasing tree density near an upwind building wall reduces wind speed due to trees' drag effect (Kang & Kim, 2015). Zheng et al. (2020) studied airflow around a three-dimensional model of urban trees, conducting wind tunnel tests and on-site measurements to determine the drag coefficient (Cd) for four common subtropical tree species. They established the Cd variation range for various tree species and showed a negative relationship between Cd and wind speed (U) (Zheng et al., 2020). Kang (2020) conducted wind tunnel tests to demonstrate how trees improve pedestrian wind comfort at Pukyong National University. Wind comfort was evaluated by wind inflow direction and observed frequency. Results confirmed trees significantly improved pedestrian wind comfort when horizontal airflow passed through them but showed minimal improvement where airflow descended rapidly along tall building walls (Kang et al., 2020).

Ricci et al. (2022) focused on vegetation's effect on urban wind mitigation around a vertical green tower. They performed wind tunnel tests on a model without surroundings for 12 wind directions and three series of measuring positions, concluding that vegetation notably improves urban wind comfort (Ricci et al., 2022).

A review of literature on vegetation's influence on urban thermal comfort revealed that most studies used software like ENVI-met to evaluate plant effects on urban thermal comfort. Although ENVI-met assesses wind behavior alongside comfort parameters such as temperature and humidity, its wind analysis accuracy is limited. Other studies focused on plants' impact on wind behavior using CFD software and wind tunnels also exhibit gaps. Most studies investigated trees' effects on pollutant particles in urban spaces. Another group used highly abstract models, simulating trees as cubes differing significantly from actual tree structures, resulting in less accurate findings. Additional research examined vegetation's influence on wind flow without considering buildings. Only a limited number of studies have explored vegetation's impact in real-world cases, like university campuses. To date, no research has investigated vegetation effects on pedestrian pathways within a realistic urban model.

This study's innovation lies in modeling a real case with detailed building structures, positioning trees along the street based on urban planning principles, and integrating street furniture and benches. Another innovation of this research is in tree modeling. Previous studies used simplified cubic models for trees, which differ greatly from actual tree structures. In contrast, this study uses spheres and cylinders to create a more accurate geometric representation, providing more precise results on urban wind behavior. Previous research addressed the increase in urban wind speed due to factors such as building geometry and height, but limited investigations developed solutions to reduce disruptive wind speeds in urban districts. Additionally, studies related to tree arrangement and wind speed mainly focused on forests and green areas, with none investigating trees' effects at the pedestrian level.

Sidewalks are among the urban open spaces where design considerations are crucial. Therefore, in this study, the effect of tree presence on reducing city wind speed was investigated, along with the integration of urban furniture. The impact of urban furniture, along with trees of specific sizes planted at designated distances and densities in urban open spaces, including sidewalks, has not been previously studied. Planting trees and embedding urban furniture on urban sidewalks can significantly reduce disruptive wind speed at pedestrian level in cold and mountainous climates.

MATERIALS AND METHODS

The present study is descriptive-analytical research carried out through quantitative analysis and using measurable variables. First, general and basic issues related to wind flow and pedestrian comfort in urban spaces were reviewed through library studies. The case study was selected through a comprehensive field study in Tabriz city, where we assessed wind speed, wind direction, and wind nuisance levels using the DT-8894 anemometer-flowmeter. To gauge perceived discomfort caused by high wind speeds among local residents, we conducted a survey. This survey included questions about the frequency and intensity of discomfort, specific troublesome locations, and impact on daily activities. To confirm citizens' discomfort from high-speed, disruptive wind on the site, a survey of 300 people, according to Cochran's sample size, was conducted, and the area was selected for wind speed investigation and simulation. A review of meteorological data from the past decade (2011-2021) revealed that Tabriz's coldest days occur from January 25 to February 20, with the coldest hours between 5-7 pm. Five specific dates were randomly selected within this period for a survey conducted on January 25, January 30, February 10, February 20, and February 23 in 2022 at 6 pm. The questionnaire was designed to assess local residents' and pedestrians' comfort levels regarding factors like wind, coverage, and activities. To ensure representative results, efforts were made to distribute the survey equitably between male and female participants. Additionally, a diverse age range was included, from children to seniors, capturing perspectives from various backgrounds for a comprehensive understanding of community comfort levels. Data was analyzed to identify areas with the highest reported levels of wind-related discomfort. Statistical analysis revealed that the sidewalk on Imam Street, between Abresan and the Daneshgah traffic circle, had the greatest volume of traffic and the highest annoying wind speeds. Follow-up observations and additional wind speed measurements in this area validated our findings, confirming the residents' reports of discomfort.

Next, the available high-level documents of Tabriz city were studied, and annual meteorological data was collected from the relevant organizations. The obtained wind speed for Tabriz city over the last ten years (2011-2021) was adjusted for the studied fabric and intended height. In this research, tree height, distance, and arrangement, along with tree benches, were considered independent variables, while pedestrian-level wind speed was the dependent variable.

To analyze wind flow in the urban space, various software such as SimScale, Envimet, Ansys Fluent, Ansys Airpak, etc., are applied. Considering the importance of walls, materials, and details evaluated in the case study design, the low accuracy of flow simulation in Envimet software, and the limitations of Fluent, Airpack, and SimScale software in urban wind simulation, this research used Dlubal RWIND Simulation 2.02 software to analyze and simulate wind flow. This software can process and numerically calculate complex geometries. In this software, the computational domain meshing is estimated based on the defined model's dimensions, and users can choose the network dimensions and number of meshing before performing numerical calculations. This software can simulate wind flow in urban spaces on a real scale. It has been used for wind flow simulation in major cities, including London and New York.

Finally, due to the non-parametric nature of the simulation software's output data, Spearman's correlation was used to analyze data correlations and investigate whether variable relationships were significant or random.

Case Study: Tabriz City

Tabriz city, with an area of about 25,056 hectares, is located between northern latitudes of 38°01' and 38°08' and eastern longitudes of 46°05' and 46°22'. The average elevation of the city is estimated to be about 1460 m above sea level (Naqsh Mohit Consulting Engineers, 2016). The annual wind rose diagram of Tabriz city shows that about 6.28% of winds blew at speeds of 1 to 3 m/s, and 54.72% at an average speed of 3 to 5 m/s, both classified as weak breezes. About 23.62% of winds blew at an average speed of 5 to 7 m/s, classified as relatively strong winds. Approximately 2.99% of winds blew at an average speed above 7 m/s. During the year, the east wind (27.63% of total winds) is considered the prevailing wind, the northeast wind (2.19%) is the secondary wind, and the south wind blows less frequently than any other (2.58%) (Naqsh Mohit Consulting Engineers, 2016) (Figure 1).

The sidewalk on Imam Street is one of Tabriz city's busiest sidewalks. It is located between two important and large traffic circles called Daneshgah and Abresan. Every day, a large number of pedestrians, especially Tabriz University students, pass through this area. Interviews with pedestrians imply that in certain sections, high wind speed causes discomfort. Due to cold weather in the last six months of the year, wind nuisance is more pronounced and noticeable in cold seasons. Additionally, wind speed is higher in colder than in warmer seasons. The buildings surrounding the sidewalk average seven floors in height, with the tallest building located on the northwest side of the Daneshgah traffic circle, standing at 25 floors. This 25-story Bolour Tower is considered the main cause of pedestrian discomfort on the sidewalk. The Gostaresh Hotel, with 14 floors, and other buildings with 11 and 10 floors in the study area further increase wind speed. Approximately 100 meters on each side of the street were chosen as the study area (Figure 2).

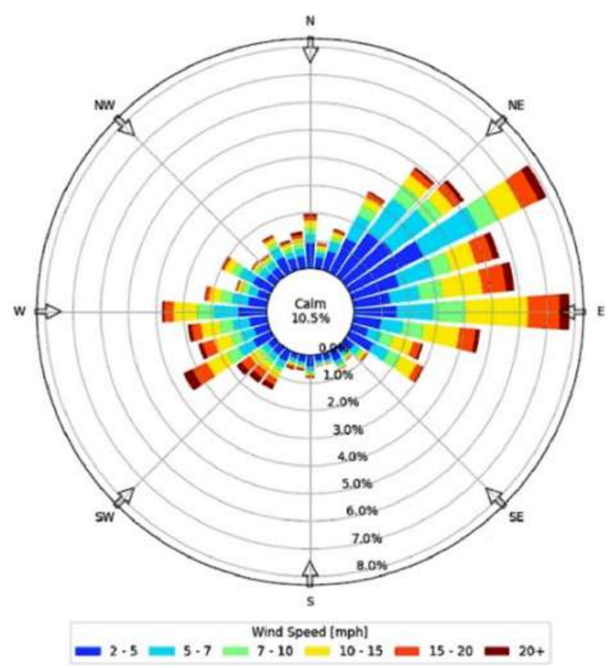

Figure 1. The wind rose diagram of Tabriz city according to meteorological statistics (Court, 2017).

Figure 2. **(a)** Aerial image of the studied area; **(b)** View from the Daneshgah traffic circle (the Bolour Tower with 25 floors is seen on the right side of the figure); **(c)** View from studied area and Bolour tower; **(d)** View from the Abresan traffic circle; S1) Floor map; S2) Environment analysis map; S3)Mass-Space map; S4) Area Density map.

Simulation

Boundary Conditions and Solution Method

In this research, the AIJ (Architectural Institute of Japan) guideline was used to determine the computational domain (Tominaga et al., 2008). Wind tunnel dimensions were selected based on the tallest building height (H=75m) in the study area. The side walls and windward front were set at 5H, and the leeward front was set at 15H (Figure 3).

The appropriate turbulence model was selected by reviewing previous studies and comparative studies at the city scale. Most wind flow simulations on the city scale use the k-ω turbulence model for its high compliance with wind tunnel test results (Javanroodi et al., 2018; Saadatjoo et al., 2023). Boundary domain conditions were as follows: symmetry for walls and ceiling, smooth surface (V=0) for the floor,

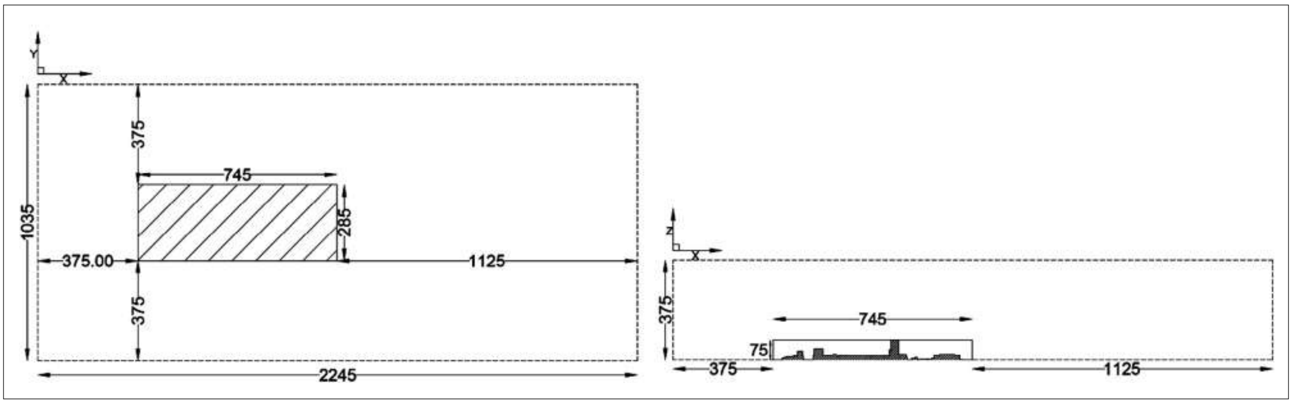

Figure 3. The dimensions of the computational domain and the location of the studied area in the computational domain.

velocity inlet for the flow inlet plane (wind profile), and zero-pressure for the outlet.

According to Tabriz city's meteorological data, the average wind speed during the six coldest months of the year at a 10-meter height over a 10-year period (2011-2021) is 3.69 m/s, with a maximum speed of 15.7 m/s in the prevailing east and northeast directions (Weatherspark, 2022). To obtain the wind speed profile and logarithmic wind speed diagram in the computational domain, wind speed was adjusted to the intended height and area texture (Aynsley, 2007). In simulations, the basic wind speed at a pedestrian height of 1.75 m was set at 3.96 m/s, calculated by equating the device-measured speed to the intended texture and height.

Software Validation

Dlubal RWIND Simulation 2.02 software was validated using the Japanese wind tunnel test experimental data (Tominaga & Mochida, 2016). This wind tunnel consists of 9 blocks (8 cube blocks measuring 0.2×0.2×0.2, and one rectangular block measuring 0.2×0.2×0.4), spaced 0.2 meters apart, with 120 measurement points between the blocks at a height of 0.02 meters (Figure 4).

Figure 5 compares the results of the wind tunnel experiment and RWIND SIMULATION software. For the measurement points defined in the model for the results of the wind tunnel experiment and the software, Root Mean Squared Error (RMSE) was estimated as 0.23, 0.22, and 0.20 for 3 grid types (coarse, medium, and fine), respectively. According to these values, the error rate of the software is very low and the results are acceptable. Figure 6 shows the wind flow pattern and wind speed in the model simulated by RWIND software at the height of 0.02 m from the floor in the form of a graphic contour.

Grid-Independent Solution

To ensure grid independence of the solution, four different grids with varying accuracies (90%, 80%, 70%, and 60%) and 4,780,801, 10,038,403, 11,601,269, and 28,713,619 meshes, respectively, were created using Dlubal RWIND Simulation 2.02 software, and the simulation results were

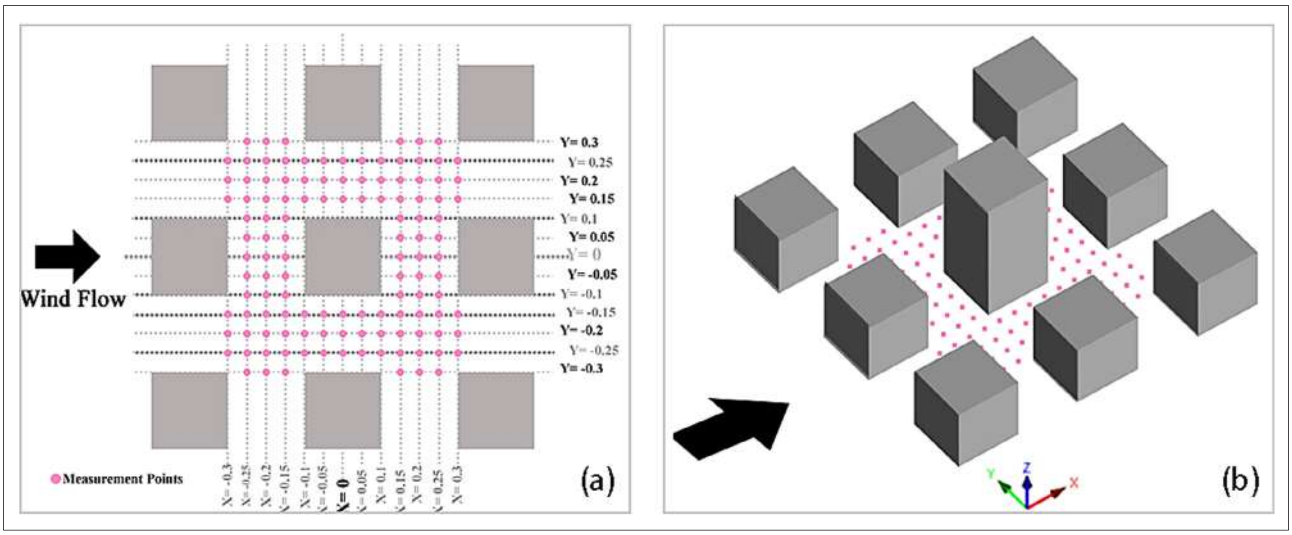

Figure 4. **(a)** Perspective of the simulated AIJ wind tunnel model and measurement points, **(b)** Plan of the simulated AIJ wind tunnel model and the location of the measurement points.

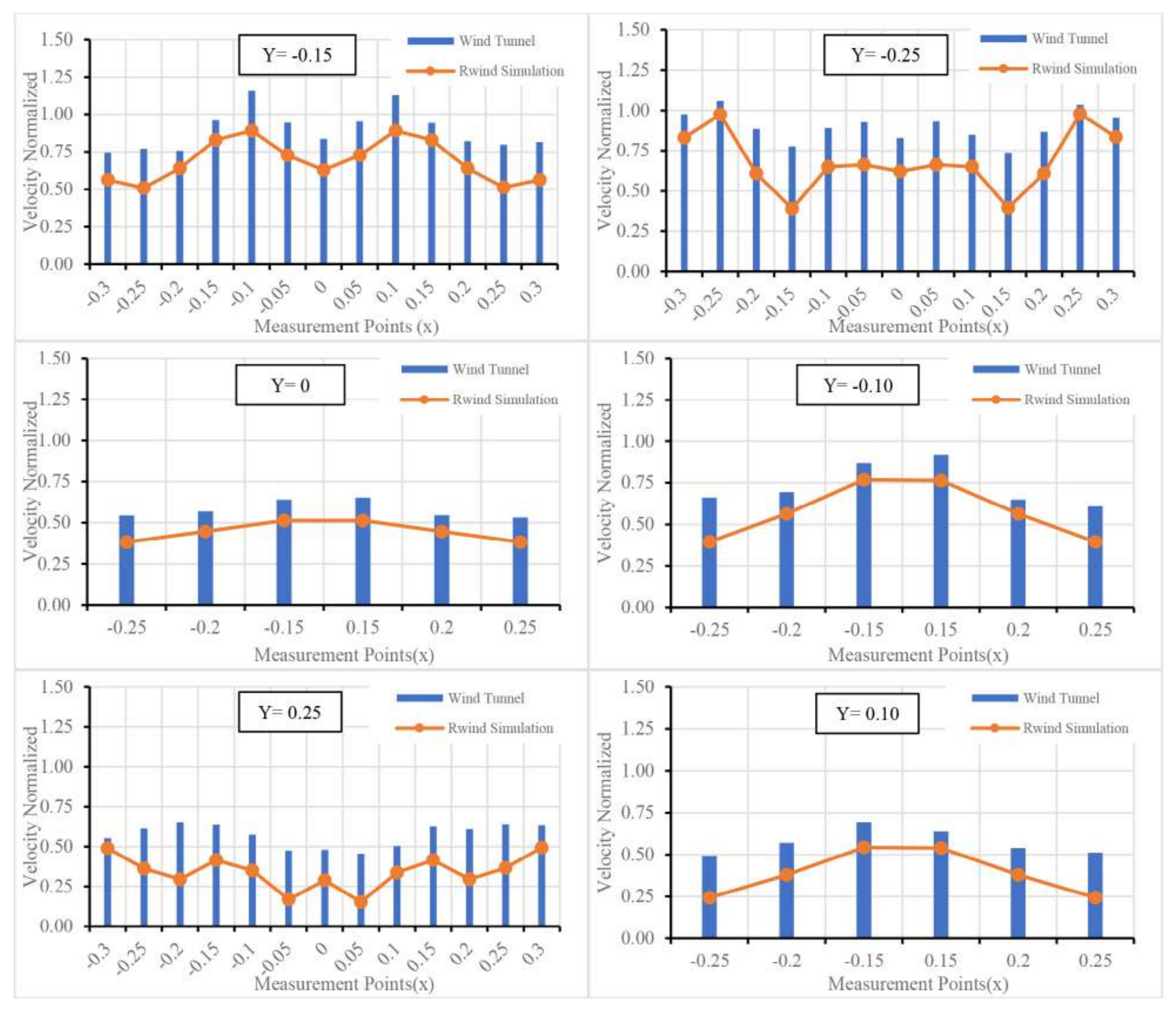

Figure 5. Comparison of the results of the RWIND Simulation software and wind tunnel experiment.

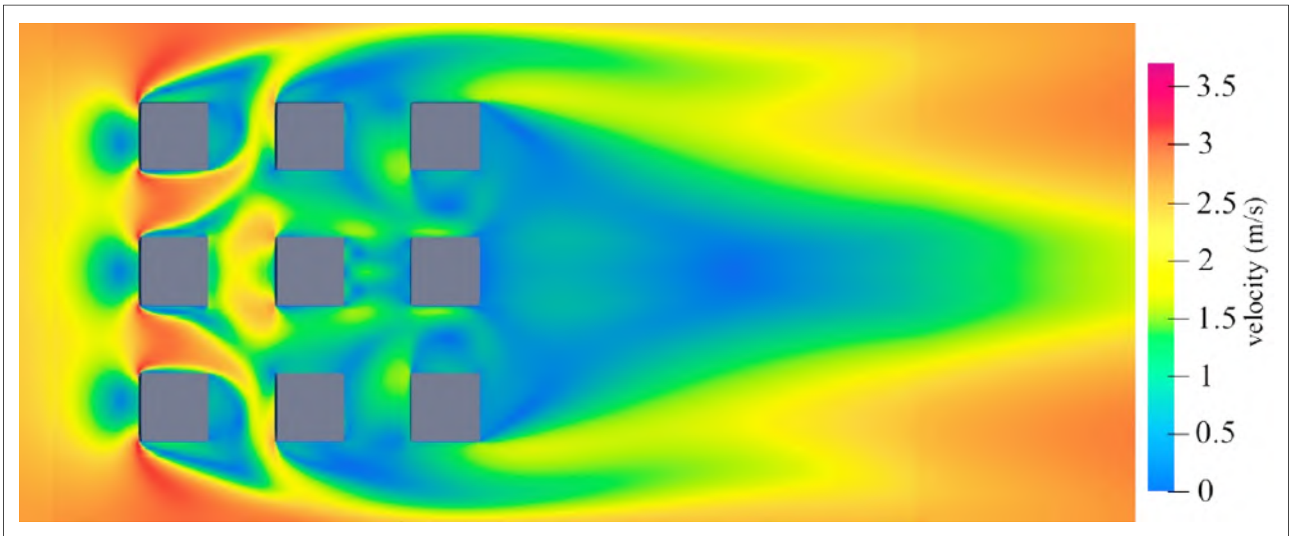

Figure 6. AIJ wind tunnel simulation and speed contours at the 0.02-m level.

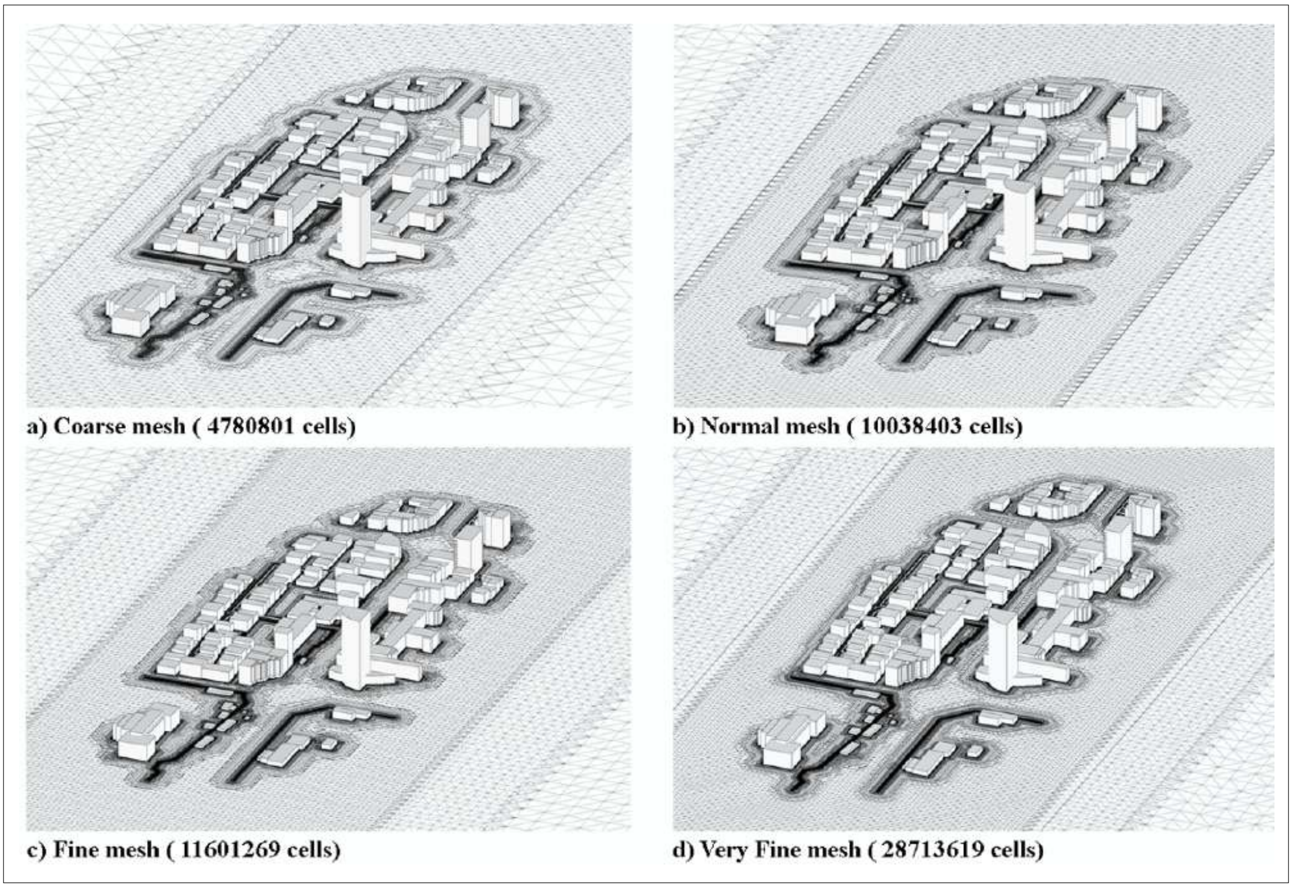

Figure 7. Different meshing modes of the computational domain to investigate the grid independency of the solution.

compared (Figure 7). Analyses indicated that the mesh network in the computational domain with 11,601,269 meshes achieved the most ideal solution accuracy for this study (Figure 8).

After examining different mesh network accuracies, meshing with 80% accuracy and 11,601,269 meshes was selected as the optimal configuration and used for simulations. Figure 9 shows the target area with 80% accuracy and 11,601,269 meshes.

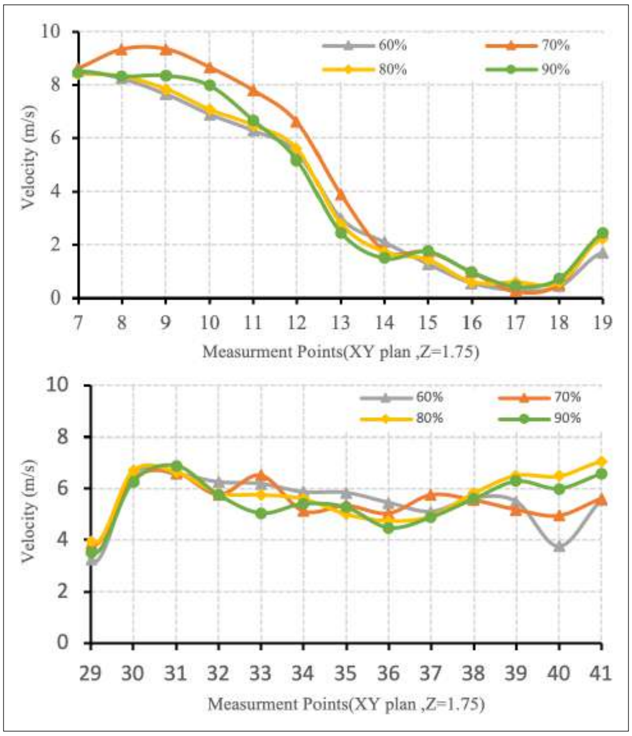

Figure 8. Comparison of the results of simulations with 4 different mesh sizes (very fine to coarse).

Wind Comfort Criteria

Isyumov and Davenport's criteria classify wind speed in terms of comfort for specific urban open space activities into four categories: good, tolerable, unpleasant, and dangerous. This standard, based on the Beaufort scale, defines wind speed evaluation indicators for four common open space activities (fast walking, walking, short-term sitting, and long-term sitting). The Beaufort scale was developed for wind speed at a height of 10 meters above ground, so these values were converted for pedestrian level (1.75 m) (Table 1) (Isyumov & Davenport, 1975). According to Davenport's standard, wind speeds above 7.2 m/s disturb pedestrians' comfort during fast walking.

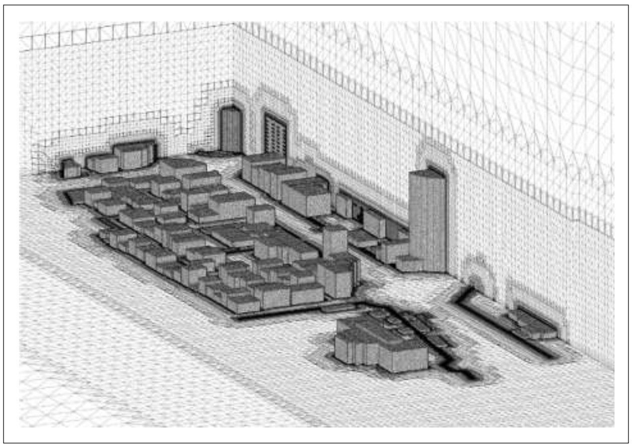

Figure 9. The structured mesh network in the computational domain according to the investigation of the grid independency of the solution with 11601269 meshes.

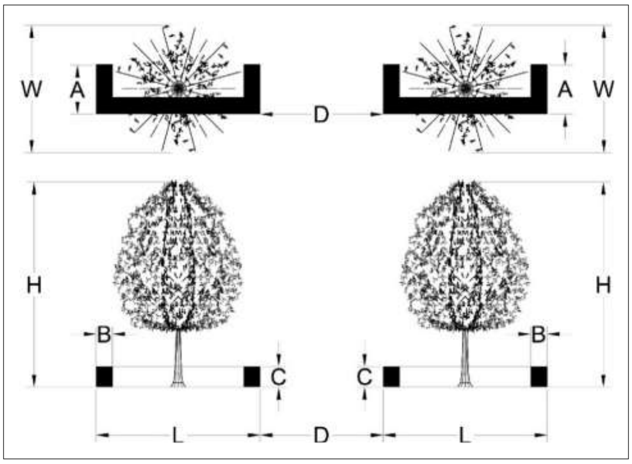

Figure 10. Dimensioning the simulated model of the tree and urban furniture in the software.

Simulation Models

The urban furniture models simulated in this research are combinations of trees and tree benches (Figure 10). Tree benches of identical dimensions were used across different models, with variations in tree sizes, tree spacing, and tree arrangement patterns in different models (Table 2).

Speed Measurement Points

In this study, measurement points were positioned 2 m from building facades on sidewalks along both sides of Imam Street. According to Iranian road and urban development guidelines, the effective limit of sidewalks is considered 3.5 m for high-density areas (Iran Ministry of Roads & Urban Development, 2020). Additionally, a 30 cm distance from the building edge is set according to these guidelines. An area along Imam Street between Abresan and Daneshgah traffic circles, with a sidewalk width of 1.2 m for pedestrian furniture, was considered. In total, 45 measurement points were established on the north and south sidewalks of Imam Street, with a measurement height of 1.75 m, according to Isyumov and Davenport's climatic comfort criteria (Figure 11).

RESULTS

The study area was simulated with a length of 745 m, width of 285 m, and height of 75 m using Dlubal RWIND Simulation software. Figure 12 shows the speed contour at a height of 1.75 m (according to Davenport's comfort criteria). Simulation results indicate that 20% of the pedestrian-level speed measurement points (at 1.75 m from the sidewalk floor) on Imam Street sidewalks do not meet climatic comfort standards. Results show an average wind speed of 4.43 m/s across the sidewalk.

Investigating the Effect of Tree Size on Pedestrian-Level Wind Speed

To investigate the effect of tree size on pedestrian-level wind speed, three different tree heights (with benches) were analyzed: 4 m, 5 m, and 6 m. Tree model height changes were applied as scale changes, meaning that tree height adjustments included dimensional changes across all parts, including the crown. Analyses showed that average wind speed at measurement points decreased by 52%, 60%, and 61% for tree heights of 4 m, 5 m, and 6 m, respectively. Wind speed in site areas outside the comfort range (20% of total points) decreased by 65% on average, bringing all points within comfort range. With increased simulated

Table 1. Davenport's criteria. Wind speeds in m/s at a height of 1.75 m (Isyumov & Davenport, 1975).

Activity	Places	Sensory Level			
		Good	Tolerable	Unpleasant	Dangerous
Walking fast	Sidewalks	(5.3~7.2)	(7.2~9.3)	(9.3~11.5)	(11.5~)
Strolling, Skating	Skating rinks, Parks, Entrances	(3.7~5.3)	(5.3~7.2)	(7.2~9.3)	(11.5~)
Short-term Sitting	Plaza areas, Parks	(2.2~3.7)	(3.7~5.3)	(5.3~7.2)	(11.5~)
Prolongs Sitting	Outdoor restaurants, Theatres	(~2.2)	(2.2~3.7)	(3.7~5.3)	(11.5~)
Tolerance			<1/week	<1/month	<1/year

Table 2. Dimensions and specifications of the simulated furniture model in the research.

Arrangement Pattern	D(m)	C(m)	B(m)	R(m)	A(m)	W(m)	L(m)	H(m)	Model
1-1	3	0.5	0.4	2.5	1.2	2.5	4	4	T.H4
1-1	3	0.5	0.4	3.1	1.2	3.1	4	5	F.H5
1-1	3	0.5	0.4	3.7	1.2	3.7	4	6	F.H6
1-1	3	0.5	0.4	2.5	1.2	2.5	4	4	F.D3
1-1	4	0.5	0.4	2.5	1.2	2.5	4	4	F.D4
1-1	5	0.5	0.4	2.5	1.2	2.5	4	4	F.D5
1-1	3	0.5	0.4	2.5	1.2	2.5	4	4	F.A1
1-2	3	0.5	0.4	2.5	1.2	2.5	4	4	F.A2
1-3	3	0.5	0.4	2.5	1.2	2.5	4	4	F.A3

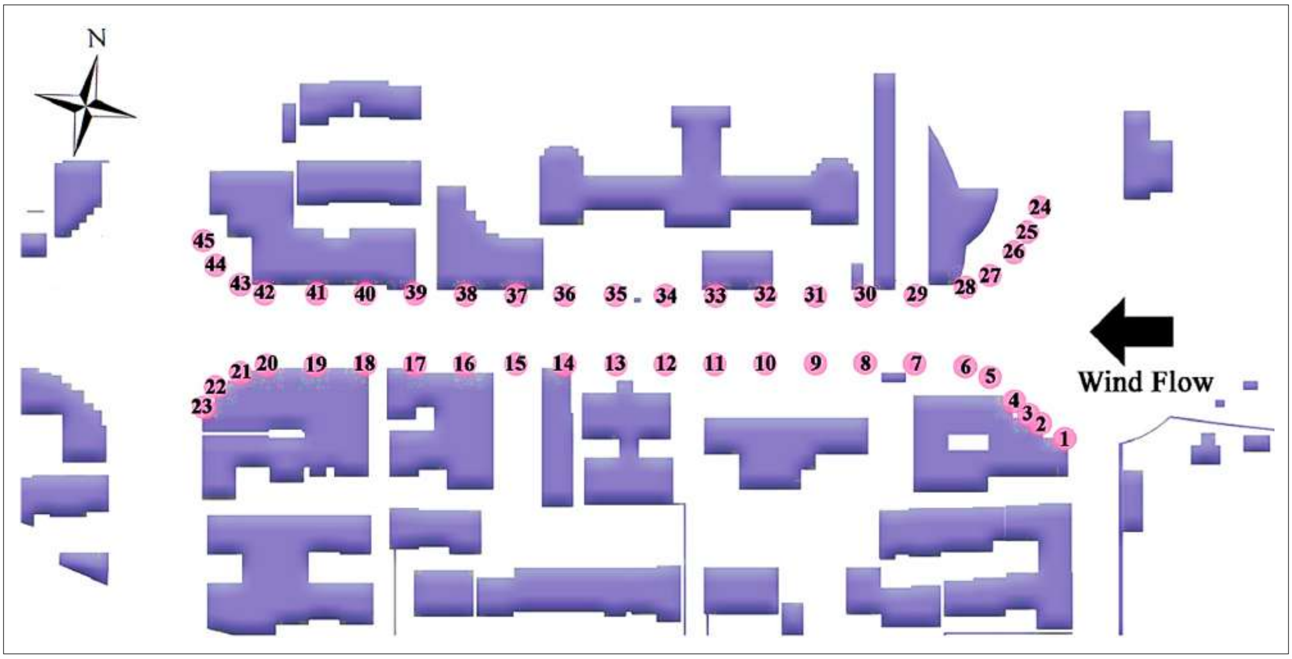

Figure 11. Measurement points in the study area in the XY plane and at the height of 1.75 m from the floor.

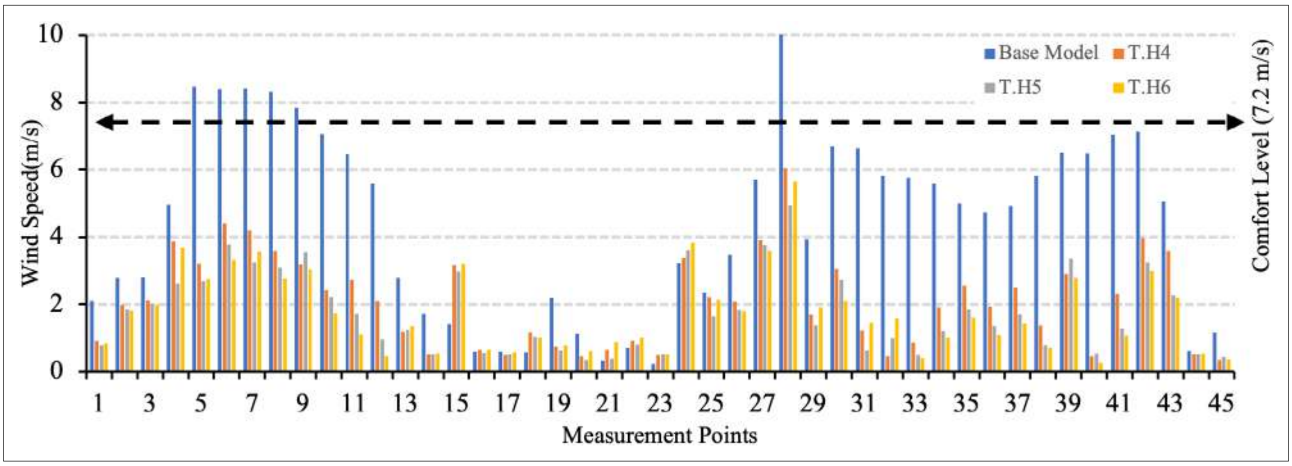

Figure 12. Comparison diagram of wind speeds at the measurement points for the current state, TH4, TH5, and T.H6.

furniture height and dimensions, average wind speeds for configurations TH4, TH5, and TH6 were estimated at 2.1, 1.74, and 1.70 m/s, respectively.

As shown in Figure 12, 71% of measuring points (middle sidewalk area) experienced a pedestrian-level wind speed decrease of over 50%, while wind speed around Bolour Tower (points 5 to 8 and 23 to 28) decreased comparatively less. Due to the non-parametric distribution of the speed variable, Spearman's correlation analysis using SPSS 23 software showed a moderate inverse relationship between tree height and pedestrian-level wind speed, with ρ=-0.101 and P-value= 0.243, indicating statistical significance.

Investigating the Effect of Tree Spacing on Pedestrian-Level Wind Speed

Results of first-stage flow simulations indicated that the TH4 configuration performed better than other configurations (TH5 and TH6). Therefore, in the tree spacing investigation stage, tree height was set at 4 m, and tree spacing was analyzed at distances of 3, 4, and 5 m.

Simulation results showed that planting trees at 3, 4, and 5 m intervals reduced pedestrian-level wind speed by 52%, 49%, and 49%, respectively. Figure 13 shows that increased tree spacing correlates with higher wind speed on sidewalks. Thus, for urban spaces with annoying wind, furniture should be placed closer together compared to areas without disruptive wind.

Simulations demonstrated that planting trees with tree benches on both sides of Imam Street at specified distances would bring all sidewalks within climatic comfort standards, and wind speed would not disrupt pedestrian comfort. As shown in Figure 13, at 60% of measurement points (first and middle sidewalk sections), pedestrian-level wind speed decreases by over 50%, while a smaller decrease is seen near Bolour Tower (points 5 to 8 and 23 to 28), particularly on the northern sidewalk. Due to the non-parametric variable distribution, Spearman's correlation analysis was used. The correlation coefficient between tree spacing and pedestrian-level wind speed was estimated at 0.016, indicating a direct relationship, with a P-value=0.428 confirming the significance of this relationship.

Investigating Tree Arrangement Patterns on Pedestrian-Level Wind Speed

Analysis of simulated models in the second research stage showed that tree density spaced at 5 m intervals reduces pedestrian-level wind speed by approximately 49%, with all points along the sidewalk within comfort range. Thus, a 5 m distance between urban furniture was chosen as optimal, providing a broader view and landscape compared to dense tree arrangements. In the next step, the tree arrangement pattern shown in Figure 13 was simulated. Results indicate that arrangement pattern does not directly reduce average wind speed. The T.A2 model performed with greater efficiency compared to others. Figure 14 shows that, in the T.A2 model, 55% of measurement points showed pedestrian-level wind speed decreases of over 50%, with significant reductions in wind speed near Bolour Tower (points 5 to 8 and 23 to 28), particularly on the southern sidewalk. Figures 15 and 16 display speed contours and a speed comparison diagram at measurement points, respectively.

DISCUSSION AND CONCLUSION

In modern urbanism, the rise of high-rise buildings and cities' increasing height density have made intensified wind speed around such buildings a crucial issue for pedestrian comfort. The importance of this issue doubles when high-rise buildings are constructed next to high-traffic urban sidewalks without adherence to engineering standards for pedestrians' wind and climatic comfort. The findings of this research align with studies focusing on physical factors in urban open spaces (Mahgoub &

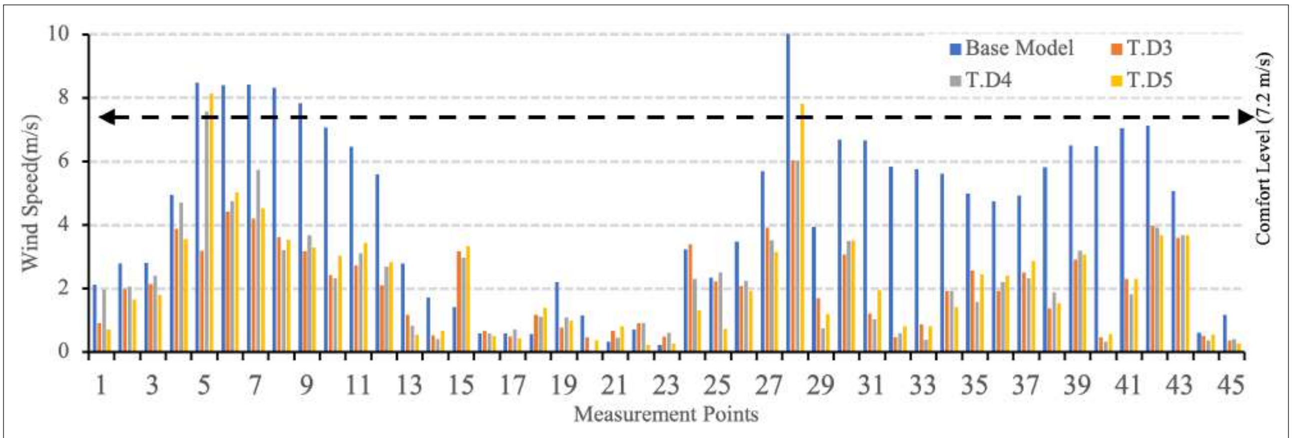

Figure 13. Comparison diagram of wind speeds at the measurement points for the current state, TD3, TD4, and TD5.

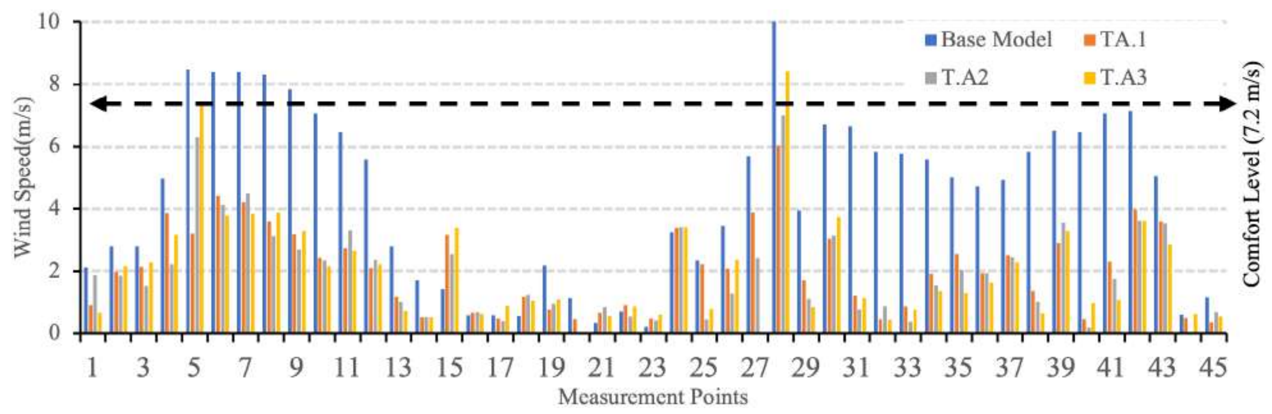

Figure 14. Comparison diagram of wind speeds at measurement points for the current state, T.A1, T.A2, and T.A3.

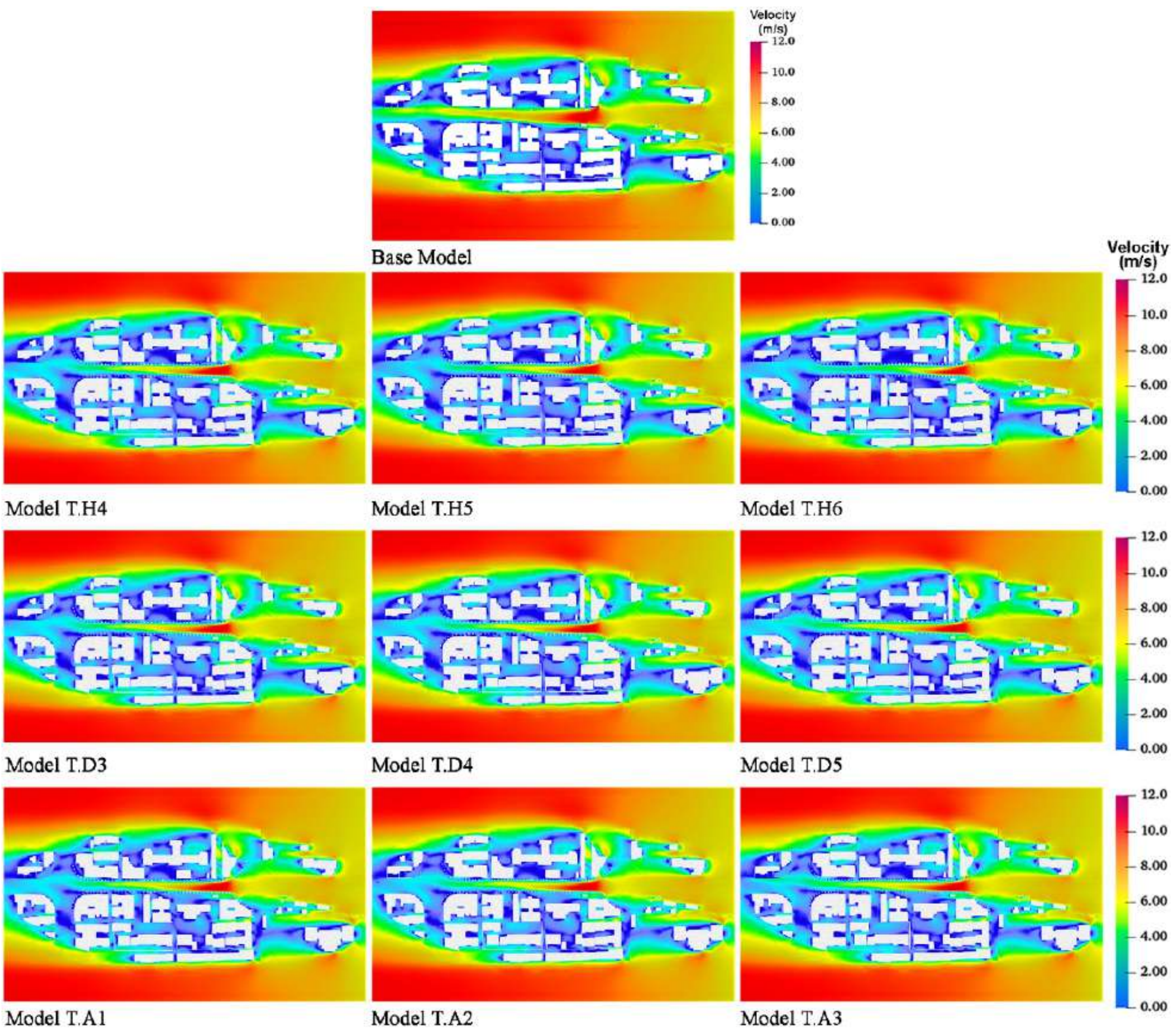

Figure 15. The speed contour of the models simulated in the XY plane and at the height of 1.75 meters.

Ghani, 2021a); and in the context of simulating wind flow at the pedestrian scale and reducing wind flow speed in urban spaces (Aguinaga et al., 2019; Blocken et al., 2004). Environmentally, this study investigates trees' impact on urban wind flow, consistent with (Zheng et al., 2020). The research also aligns thematically with Zheng et al. (2020), evaluating wind flow's relationship with tree rows and arrangements in urban areas. Meanwhile, this research is distinguished as one of few studies in urban planning that investigates the climatic effect of combined trees and urban furniture in pedestrian areas using wind flow simulation. The sidewalk of Imam Street in Tabriz exemplifies the conditions discussed, where high wind speed causes pedestrian discomfort and various problems for residents. This study has therefore sought to examine multiple vegetation-related variables to adjust wind flow and provide wind comfort in the study area through numerical simulations. The findings indicate:

- Around the Bolour Tower (a 25-story building), pedestrian-level wind speed does not meet comfort standards according to Davenport's criteria.

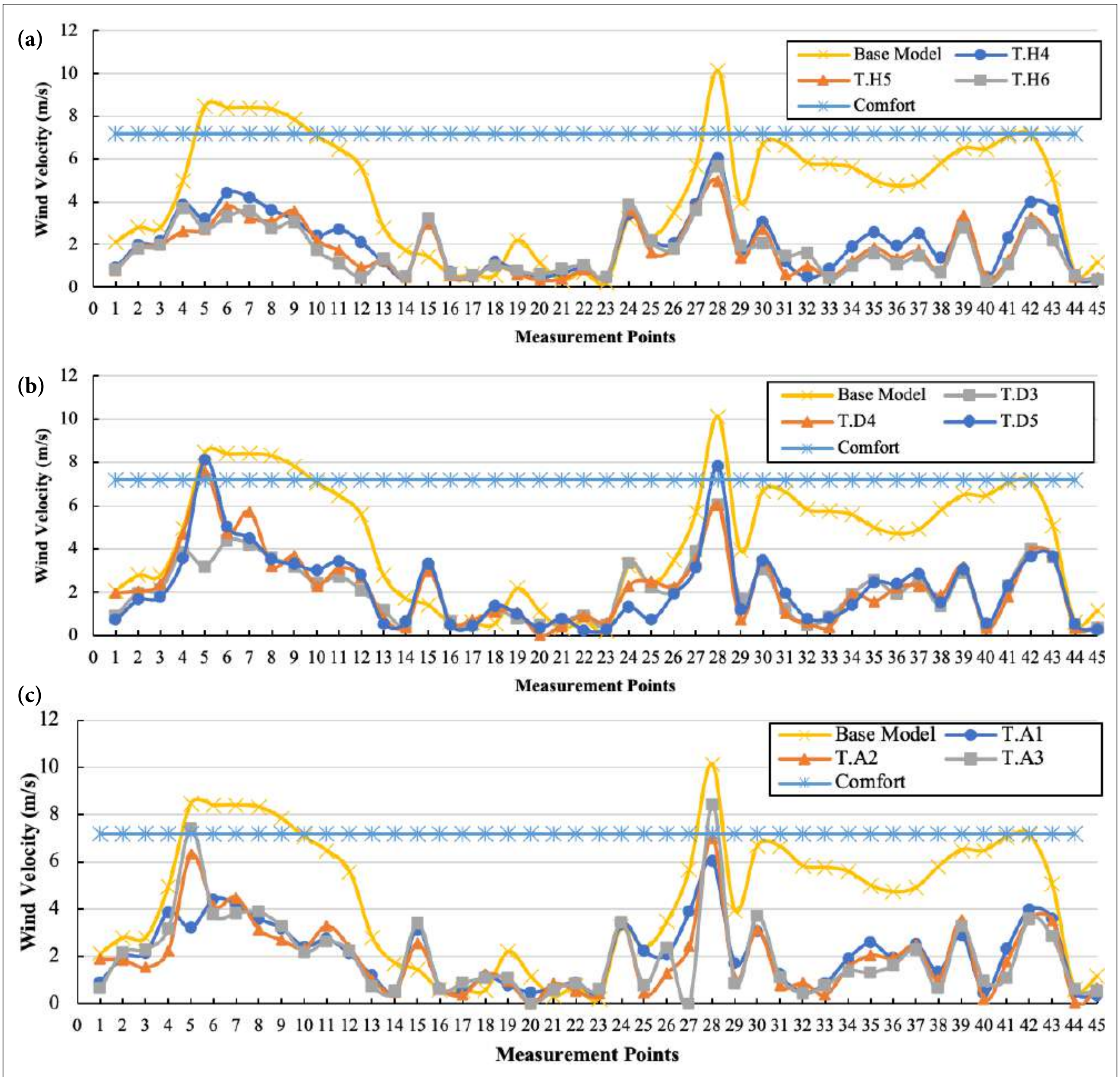

Figure 16. Pedestrian-level wind speed comparison diagrams: **(a)** speed diagram measurement points at the height of 1.75 m for the simulated models T.H4, T.H5, and T.H6 (height variable), **(b)** speed diagram at measurement points at the height of 1.75 m for simulated models T.D3, T.D4, and T.D5 (tree spacing variable), and **(c)** speed diagram at measurement points the height of 1.75 meters for simulated models T.A1, T.A2, and T.A3 (tree arrangement pattern variable).

- Nine different vegetation models, combined with urban furniture (tree bench and tree), were simulated to assess each model's effectiveness in reducing wind speed.
- Initial analysis of tree height across three heights (4, 5, and 6 m; TH4, TH5, and TH6, respectively) showed that the presence of pedestrian furniture reduces pedestrian-level wind speed by 52%, 60%, and 61%, respectively, with an inverse relationship between tree height and wind speed. Additionally, all measurement points in the simulation were within the comfort range, with no points outside pedestrian comfort.
- In the second analysis stage, examining tree spacing at three distances (3, 4, and 5 meters; T.D3, T.D4, and T.D5, respectively) revealed that increased tree spacing is negatively effective in reducing pedestrian-level wind speed. Reductions in wind speed were observed for T.D3, T.D4, and T.D5 models at 52%, 49.7%, and 49.3%, respectively.
- In the third analysis stage, tree arrangement patterns (T.A1, T.A2, and T.A3, respectively) were studied, showing wind speed reductions of 52%, 55%, and 58%, respectively. All defined measurement points in each case were within the comfort range (Figure 17).

This research reveals that vegetation can reduce disruptive wind speeds by 50-60%, providing pedestrian comfort. Findings offer urban designers effective solutions for adjusting wind flow and improving comfort on Imam Street's sidewalks.

Comparison of the Results of the Present Study and Previous Ones

The present research investigated and compared pedestrian-level wind speed across various models by accurately modeling trees alongside urban furniture on sidewalks.

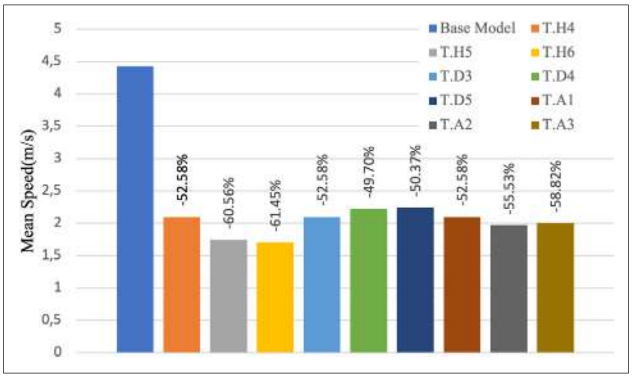

Figure 17. Comparison diagram of the average wind speed in the model without furniture and the simulated models and the average reduction rate in the wind speed compared to the current state.

The study also examined whether significant relationships exist between analyzed variables, including tree size, tree spacing, and tree arrangement pattern with wind speed. Previous studies have used symbolic, simplified tree models, such as a combination of spherical volume with a cylindrical rod or a square cube with a cylindrical rod for urban tree simulations. In contrast, the real tree model used here, featuring a crown with numerous branches and leaves, influences meshing and speed analysis around the tree, yielding results more applicable to real-world urban spaces. While simplified tree models reduce mesh count and analysis time, the real tree model requires a supercomputer with a multi-core system and RWIND 2.02 software. This configuration enhances simulation speed and provides results closer to experimental data compared to other software.

Earlier studies investigated tree row arrangements in open urban spaces, such as plazas and academic campuses, examining tree arrangement patterns, tree density, and row angles' effects on wind flow direction and tree use as windbreaks.

Research Limitations

The present study's area was modeled using statistical data and GIS maps of Tabriz city from 2015-2016. Considering changes in urban texture and new constructions, field observations and panoramic photographs of the study area were used alongside existing documents to match models to the current state as closely as possible. Using updated files with shorter time intervals can improve urban study and modeling quality. Additionally, due to typical case study dimensions in urban studies, which usually cover a specific zone (e.g., a park, plaza, academic site) or line (e.g., an urban street and sidewalk), CFD analysis requires a powerful supercomputer with a multi-core system to expedite result analysis and reduce processing time.

Suggestions for Further Research

- Wind flow control in urban spaces is influenced by multiple factors, and this research investigated the combination of trees with urban furniture (tree benches). Future studies could investigate other multifunctional urban furniture, including kiosks and lighting elements.
- This research excluded land slope effects on sidewalk wind flow. It is suggested to consider site slope and include it in future simulations.
- Only Davenport's pedestrian comfort criteria were used in this research. Other climatic comfort criteria could be applied in future wind flow simulations in urban spaces.

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REFERENCES

Abohela, I., Hamza, N., & Dudek, S. (2013). Effect of roof shape, wind direction, building height and urban configuration on the energy yield and positioning of roof mounted wind turbines. Renew Energy, 50, 1106–1118.

Aguinaga, S., Virel, M. D. D. E., Guilhot, J., Caniot, G., Sanquer, S., Dias, D., & Nguyen, C. (2019). Design of the Citadel of Bonifacio urban area through experimental and numerical assessment of pedestrian comfort. https://cstb.hal.science/hal-02309712v1/document

Aynsley, R. (2007). Natural ventilation in passive design. Royal Australian Institude of Architects.

Beranek, W. J., & van Koten, H. (1979). Limiting wind nuisance around buildings, part 1. Kluwer Technical Books.

Blocken, B., Roels, S., & Carmeliet, J. (2004). Modification of pedestrian wind comfort in the Silvertop Tower passages by an automatic control system. J Wind Eng Ind Aerodyn, 92(10), 849–873.

Chen, L., Mak, C. M., Hang, J., Dai, Y., Niu, J., & Tse, K. T. (2023). Large eddy simulation study on pedestrian-level wind environments around elevated walkways and influential factors in ideal urban street canyons. Build Environ, 235, 110236.

Court, A. (2017). Wind roses. Weather, 18, 106–114.

Du, Y., Mak, C. M., Liu, J., Xia, Q., Niu, J., & Kwok, K. C. S. (2017). Effects of lift-up design on pedestrian level wind comfort in different building configurations under three wind directions. Build Environ, 117, 84–99.

Haghshenas, M., Hadianpour, M., Matzarakis, A., Mahdavinejad, M., & Ansari, M. (2021). Improving the suitability of selected thermal indices for predicting outdoor thermal sensation in Tehran. Sustain Cities Soc, 74, 103205.

Hariri, M. T. R., Khosravi, S. N., & Saadatjoo, P. (2016). The impact of high-rise building form on climatic comfort at the pedestrian level. J Archit Urban Plann, 9(17), 61–77.

Heath, T., Oc, T., & Tiesdell, S. (2011). Public places - urban spaces. Routledge.

Holman, J. P. (2010). Heat transfer. Mc Graw Hill.

Iran Ministry of Roads & Urban Development. (2020). Urban highways and streets design guide, section 10: Pedestrian ways. Deputy of Transportation Islamic Republic of Iran.

Isyumov, N., & Davenport, A. G. (1975). The ground level wind environment in built-up areas. Proceedings of the 4th International Conference on Wind Effects on Buildings and Structures, Heathrow, Cambridge University Press, pp. 403-422.

Javanroodi, K., Mahdavinejad, M., & Nik, V. M. (2018). Impacts of urban morphology on reducing cooling load and increasing ventilation potential in hot-arid climate. Appl Energy, 231, 714–746.

Kang, G., & Kim, J. J. (2015). Effects of trees on flow and scalar dispersion in an urban street canyon. Atmos, 25, 685–692.

Kang, G., Kim, J., & Choi, W. (2020). Computational fluid dynamics simulation of tree effects on pedestrian wind comfort in an urban area. Sustain Cities Soc, 56, 102086.

Kuo, C. Y., Wang, R. J., Lin, Y. P., & Lai, C. M. (2020). Urban design with the wind: Pedestrian-level wind field in the street canyons downstream of parallel high-rise buildings. Energies, 13(11), 2827.

Lin, Q., Ishida, Y., Tanaka, H., Mochida, A., Yang, Q., & Tamura, Y. (2023). Large eddy simulations of strong wind mechanisms at pedestrian level around square-section buildings with same aspect ratios and different sizes. Build Environ, 243, 110680.

Liu, J., Niu, J., & Xia, Q. (2016). Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort. Build Environ, 105, 185–97.

Mahgoub, A. O., & Ghani, S. (2021a). Numerical and experimental investigation of utilizing the porous media model for windbreaks CFD simulation. Sustain Cities Soc, 65, 102648.

Mahgoub, A. O., & Ghani, S. (2021b). Numerical and experimental investigation of utilizing the porous media model for windbreaks CFD simulation. Sustain Cities Soc, 65, 102648.

Miao, Y., & Lau, S. S. Y. (2023). Effect of linear building blocks on the wind environment of streets between high-rise buildings: A case of Hong Kong. Int Rev Spat Plann Sustain Dev, 11, 63–77.

Mortezaie, R. (2003). Approaches in urban furniture design. Theran Municipal Agency.

Naqsh Mohit Consulting Engineers. (2016). Tabriz city development and construction plan, Tabriz. Ministry of Roads and Urban Development Publisher.

Pakzad, J. (2005). Design guides for urban spaces in Iran. Ministry of Housing.

Ricci, A., Guasco, M., Caboni, F., Orlanno, M., Giachetta, A., & Repetto, M. P. (2022). Impact of surrounding environments and vegetation on wind comfort assessment of a new tower with vertical green park. Build Environ, 207, 104809.

Rose, L., Horrison, E., & Venkatachalam, L. J. (2011, February 24-26). Influence of built form on the thermal comfort of outdoor urban spaces. 5th Int Conf Int Forum Urbanism, Singapore.

Saadatjoo, P. (2022a). Investigating the effect of building facade recess on urban wind flow performance. Armanshahr Archit Urban Dev, 14(37), 43–60.

Saadatjoo, P. (2022b). Investigating the effect of building geometry on outdoor wind flow performance in residential complexes. J Renew New Energy, 9(2), 69–79.

Saadatjoo, P., & Saligheh, E. (2021). The role of buildings distribution pattern on outdoor airflow and received daylight in residential complexes; Case study: Residential complexes in Tehran. Naqshejahan-Basic Stud New Technol Archit Plann, 11(3), 67–92.

Saadatjoo, P., Badamchizadeh, P., & Mahdavinejad, M. (2023). Towards the new generation of courtyard buildings as a healthy living concept for post-pandemic era. Sustain Cities Soc, 97, 104726.

Saadatjoo, P., Mahdavinejad, M., & Zhang, G. (2018). A study on terraced apartments and their natural ventilation performance in hot and humid regions. Build Simul, 11(2), 359–72.

Saadatjoo, P., Mahdavinejad, M., Zhang, G., & Vali, K. (2021). Influence of permeability ratio on wind-driven ventilation and cooling load of mid-rise buildings. Sustain Cities Soc, 70, 102894.

Tamura, Y., Xu, X., & Yang, Q. (2019). Characteristics of pedestrian-level mean wind speed around square buildings: Effects of height, width, size and approaching flow profile. J Wind Eng Ind Aerodyn, 192, 74–87.

Teshnehdel, S., Akbari, H., Di Giuseppe, E., & Brown, R. D. (2020). Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran. Build Environ, 178, 106899.

Tominaga, Y. & Mochida, A. (2016). AIJ benchmarks for validation of CFD simulations applied to pedestrian wind environment around buildings. Archit Inst Japan.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. J Wind Eng Ind Aerodyn, 96(10–11), 1749–61.

Tsichritzis, L., & Nikolopoulou, M. (2019). The effect of building height and façade area ratio on pedestrian wind comfort of London. J Wind Eng Ind Aerodyn, 191, 63–75.

Van Druenen, T., van Hooff, T., Montazeri, H., & Blocken, B. (2019). CFD evaluation of building geometry modifications to reduce pedestrian-level wind speed. Build Environ, 163, 106293.

Wang, B., Cot, L. D., Adolphe, L., Geoffroy, S., & Morchain, J. (2015). Estimation of wind energy over roof of two perpendicular buildings. Energy Build, 88, 57–67.

Weatherspark. (2022). Climate and Average Weather Year-Round in Tabriz Iran. https://weatherspark.com/y/104056/Average-Weather-in-Tabriz-Iran-Year-Round

Willemsen, E., & Wisse, J. A. (2007). Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. J Wind Eng Ind Aerodyn, 95(9), 1541–1550.

Zahid Iqbal, Q. M., & Chan, A. L. S. (2016). Pedestrian level wind environment assessment around group of high-rise cross-shaped buildings: Effect of building shape, separation and orientation. Build Environ, 101, 45–63.

Zangiabady, A., Tabrizi, N. (2004). Design and planning of urban furniture. Isfahan Uni Human Res J, 22, 45–66

Zhang, X., Gao, Y., Tao, Q., Min, Y., & Fan, J. (2023). Improving the pedestrian-level wind comfort by lift-up factors of panel residence complex: Field-measurement and CFD simulation. Build Environ, 229, 109947.

Zhang, X., Tse, K. T., Weerasuriya, A. U., Li, S. W., Kwok, K. C. S., Mak, C. M., Niu, J., & Lin, Z. (2017). Evaluation of pedestrian wind comfort near 'lift-up' buildings with different aspect ratios and central core modifications. Build Environ, 124, 245–57.

Zheng, S., Guldmann, J. M., Liu, Z., Zhao, L., Wang, J., Pan, X., & Zhao, D. (2020). Predicting the influence of subtropical trees on urban wind through wind tunnel tests and numerical simulations. Sustain Cities Soc, 57, 102116.