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Investigating the Effect of Building Facade Recess on Urban Wind Flow Performance*

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ABSTRACT

The current study aimed to investigate the effect of form characteristics of a high-rise building on urban wind flow. The study sample is a neighborhood unit consisting of 9 mid-rise building blocks. The target building is a 9-storey building located in the center of the complex, and structural changes were applied to it. In the first step, a rigid building and five models with different volumetric structures were simulated, and one of the efficient modes was selected from them. Then, by changing the height of the body recesses, the effect of this variable was investigated on the wind behavior around the building. The research method in the first part is a descriptive method with library study tools, and the research strategy in the second part is quasi-experimental. CFD simulations and numerical analysis were performed using Ansys Airpak 3.0.16 software. Studies have revealed that geometric structure changes can affect the wind behavior around the building and the surrounding paths. Among the aerodynamic areas around buildings, the back-to-the-wind area and the squinch had the most, and the wind-facing areas had the least positive impact due to geometric changes. The results revealed that regular distribution of body recess in the height of the building could help ventilate the passages by increasing the surrounding wind speed. The result of these changes is, at best, an average increase of 48.33% and a maximum urban wind speed of 16.89% compared to the rigid model. Investigation of the change in the height of body recesses on urban wind potential attested that there is no direct relationship between this component and the efficiency of urban ventilation. In the meantime, models with terrace heights of 1.5 and 2.5 meters showed the best and weakest performance in amplifying the wind flow around the pedestrian level, respectively.

Keywords: Building Form, Urban Wind, Body Recess, Wind Speed.

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1. INTRODUCTION

Nowadays, growing construction density in cities has unsettled the urban wind flow pattern (Chen & Norford, 2017; Yim et al., 2009). This issue has become problematic due to the lack of comfort for pedestrians, especially in metropolises such as Tehran (Du, Mak, Kwok, et al., 2017). Despite the excessive prominence of urban ventilation, designers do not pay much attention to this category, and in their designs, they suffice to ventilate natural spaces (Rose et al., 2011). Outdoor climatic comfort is affected by factors such as humidity, wind, temperature, and vegetation, among which temperature, humidity, and wind as environmental factors are affected by radiation and airflow. Urban wind speed is influenced by characteristics related to building blocks and access grids. Consequently, alterations in density, distance, height, and form of buildings and the orientation and width of passages can momentously affect the pattern of urban wind flow (Willemsen & Wisse, 2007).

Consolidation of wind flow is one of the main goals of urban designers in hot climates. Increasing urban wind flow in open urban environments helps ventilate and reduce particulate matter (Buccolieri et al., 2010). The stagnation of the flow and concentration of pollutants in big cities is a problem that has become more and more common in metropolises. This study aims to increase the wind speed around high-rise buildings[1] and its effect on urban wind flow at the level of pedestrians and investigates the role of building structure change in this area. After explaining the components affecting urban wind, we review the recent studies done in this area. Then, by offering the results of numerical simulations, the role of changes in the shape of the high-rise building on the peripheral flow pattern is determined.

2. RESEARCH BACKGROUND

To take advantage of wind flow or prevent annoying winds in urban open spaces, it is necessary to carefully examine all the physical and dynamic conditions of wind flow around buildings (Bahadori, 1994). Numerous studies have been done to explore the factors affecting wind behavior and the classification of these factors. Aynsley (2007) divides the factors affecting wind behavior into three factors related to the site and landscape: building form and building shell design, interior plan, and interior design (Aynsley, 2007).

Osman (2011) categorized wind behavior factors into three scales: micro, medium, and macro. In this classification, factors related to single building architecture and building components in the micro category, parameters related to the structure of the neighborhood unit in the middle category, and factors related to the urban context are categorized on a large scale (Medhat Osman, 2011). Therefore, the structure of the building shell, building orientation, building proportions[2] , and its form are architectural factors affecting wind behavior around a single building (Saadatjoo et al., 2016; Saligheh & Saadatjoo, 2020)

Factors affecting urban wind behavior can be divided into four categories. The first factor affecting urban wind flow is the design of passages. The width of the passages, the orientation of the passage concerning the direction of the dominant urban wind, and the ratio of the height of the buildings to the width of the passages are the factors affecting the urban wind flow pattern. The second influential factor is the structure of urban neighborhood units. The average height of buildings in a neighborhood unit and the geometric pattern of the distribution of building units are the most important design factors that can dominate the urban wind flow (Saadatjoo & Saligheh, 2021). As well as the urban design components, the structural characteristics of the single building, including the geometric form of the building, height, extensions and protrusions of the body, etc., are among the most significant components that can change the pattern of ambient wind behavior and consequently the flow of surrounding urban passages. Increasing urban airflow due to the distribution of air pollutant particles (Ai & Mak, 2013; Cui et al., 2016; Wu et al., 2017), improving urban natural ventilation (Ng et al., 2011; Yuan & Ng, 2012), and providing thermal comfort and urban wind comfort (Du, Mak, Kwok, et al., 2017, Liu et al., 2016) recover the quality and desirability of urban spaces. In addition to applying numerous solutions related to the category of urban design, including adjusting the angle of passages, the width of passages, urban morphology (Hang et al., 2009), vegetation (Zheng et al., 2020), etc. it is possible to improve the urban flow pattern by making formal changes on the building. Though wind gustiness as a significant indicator also affects the comfort of urban open spaces, its estimation and evaluation are much more complex than measuring the average flow velocity (Isyumov & Davenport, 1975; Melbourne, 1978; Du, Mak, Kwok, et al., 2017).

So far, numerous studies have been conducted to investigate the role of building structures on urban wind and have provided solutions to improve their flow. One of these solutions is to make changes in the corners of the building. Wind tunnel tests performed by Uematsu et al. on four models with different types of corner shapes and different wind directions revealed that the corner shape of the building could have significant effects on wind flow around the building (Uematsu & Isyumov, 1999). The shape of the building roof is another component affecting the wind flow around and inside the building (Aliabadi et al., 2017; Najaf Khosravi et al., 2016). In 2019, in the city of London, areas with dimensions of 500 × 500 meters were selected, and 20 different modes with different elevations and facade proportions (8 different wind directions for each model) were simulated with CFD group software. The results of the research proved the

significant effects of facade proportions on the wind around the building (Tsichritzis & Nikolopoulou, 2019). Hagishima et al. proved a direct relationship between building height and wind aerodynamic behaviors (Hagishima et al., 2009). Variation and height differences in a set of building blocks can increase the potential for natural ventilation at the pedestrian level (Ikegaya et al., 2017). Tamura et al. (2019) used wind tunnel tests to examine the effect of height, width, and proportions of a square building on the wind around the building (Xu et al., 2017). Du et al. (2018) investigated the effect of heights and porosity sizes on wind comfort conditions around a single structure and a set of buildings. This study revealed that increasing the height, installing void on the ground floor, and creating void with large dimensions, have positive effects on increasing wind flow around the building (Du et al., 2018). By simulating nine porous structural morphologies and comparing them with the rigid model, Yuan et al. concluded that the inclusion of porous spaces in the lower levels significantly increases turbulence flow at the pedestrian level (Yuan & Ng, 2012). Though, installing a platform on the ground floor reduces the wind flow around the building (Tsang et al., 2012). Researchers using CFD simulations and wind tunnel tests showed that creating a pilot (empty space) on the ground floor can help improve comfort around the building and increase wind speed by 11% (Du et al., 2018; Du, Mak, Liu, et al., 2017). Chew and Norford attested that pilot building has the potential to increase the flow of narrow urban passages several times (Chew & Norford, 2019). Wind tunnel tests done on nine different models at Hong Kong University revealed that the height and dimensions of the central core are one of the most effective factors in determining the flow behavior of buildings that its ground floor is piloted (Tse et al., 2017). Studies have shown building proportions (length to height ratio) on pilot efficiency and its positive role in the flow around the building (Zhang et al., 2017). Along with these components, the cross-sectional shape of the building is one of the most effective factors in the urban wind flow pattern. By examining three different building models and changing the level of floor failure, Hariri et al. proved the effect of cross-sectional shape on the flow behavior around the building and pedestrian comfort (Hariri et al., 2016).
The recess of the body in the form of creating a terrace, etc., as a change of form, can change the behavior of the surrounding and internal wind of the building. Although so far, several studies have examined the role of terrace and body recess on natural ventilation of indoor spaces (Saadatjoo et al., 2019; Saadatjoo et al., 2018; Saadatjoo et al., 2021; Saligheh & Saadatjoo, 2020), no research examines the role of these structural changes in wind flow around the building.

3. STATEMENT OF THE PROBLEM AND THE RESEARCH PROCESS

3.1. Statement of the Problem

Nowadays, due to the growth of urbanization and the need for housing, a high-rise construction policy is the main approach to construction in large cities such as Tehran. This approach, accompanied by its social, cultural, and economic consequences, has led to changes in the urban climate and a gradual increase in urban temperature. The creation of urban heat islands that have undergone a process of urbanization is due to the characteristics of urban planning, air pollution, heat and warmth concentration, lack of proper urban ventilation, and the existence of impermeable surfaces in the city (Dhalluin & Bozonnet, 2015). It can be accredited that disturbance in urban wind flow is one of the main reasons for forming thermal islands in large cities (Montazeri et al., 2015).
One of the most important effects of tall buildings is the change of urban wind patterns, particularly around buildings. These changes in the urban microclimate are positive or negative depending on the shape, size, and angle of rotation and how it communicates with adjacent buildings (Fadl & Karadelis, 2013). As an annoying factor, tall buildings avoid proper wind flow in large cities. Impediment of natural airflow corridors by high-rise construction and depriving residents of thermal comfort in urban environments leads to the concentration of pollutant particles and lack of proper ventilation of urban spaces. Since comfort and health in the city depend on thermal comfort and ambient winds, particularly on the sidewalk and the extent of pollution (Moonen et al., 2012), mass construction and its consequences gradually reduce the presence of urban spaces and reduce the level of citizens' satisfaction with urban environments. Since the potential of urban ventilation is directly affected by the design components, the need for simulations to investigate the role of design factors on urban wind flow and provide design assistance solutions in this area is supported.

3.2. Research Questions

1. What is the effect of changing the formal structure and geometric characteristics of a high-rise building on the urban wind pattern?
2. What is the most appropriate design solution to enhance the flow around a high-rise building?

3.3. Research Method

The research method in the theoretical studies section is descriptive, and the theoretical data collection is done by studying library resources. Research strategy in the second part of the research is a quasi-experimental strategy performed using CFD simulation tools and numerical analysis of flow. The study of wind behavior was performed using the computer simulation method and Ansys Airpak 3.0.16 software. Validation of software outputs was done based on the results of the tunneling test of AIJ Research Institute of Japan. The simulated model is a set of 9 rigid building blocks that a comparative study of the results with software outputs proved the accuracy of the selected turbulence model, software settings, gridding, etc.

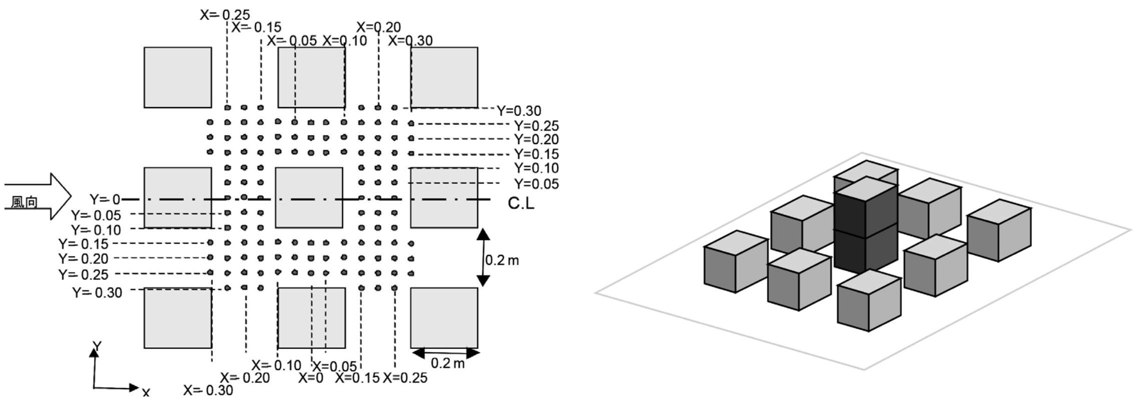
After validating the software outputs, the simulation of the mentioned models was done in several steps. In the first step, after extracting the average and maximum wind speed of Tehran during the last five decades, the data were adjusted regarding the texture and height of the study area. Then, the dimensions of the computational range were determined based on the standards, the desired models were simulated, and the most important urban wind gauges were measured in the desired range. A comparative study of numerical outputs and graphic contours led to the extraction and presentation of an optimal model to improve urban wind flow.

4. SIMULATION

In this section, after introducing the validation process, the researchers will compare the simulation results with the results of wind tunnel tests. After a comparative study and confirmation of the accuracy and validity of the results, research models are introduced. In the following, the simulation conditions, including boundary conditions, type and number of meshes, wind speed profile, turbulence model, etc., are clarified.

4.1. Validation

The validation of the simulation results in this study was based on wind tunnel tests performed at the AIJ[3] Research Institute in Japan. This model consists of 9 rigid building blocks with the same height (0.2 m) and three wind directions of 270, 247.5, and 225. In the present study, to validate the results of software simulations, wind tunnel tests with a wind direction of 270 degrees were used (Tominaga et al ., 2008) (Fig. 1).



A B

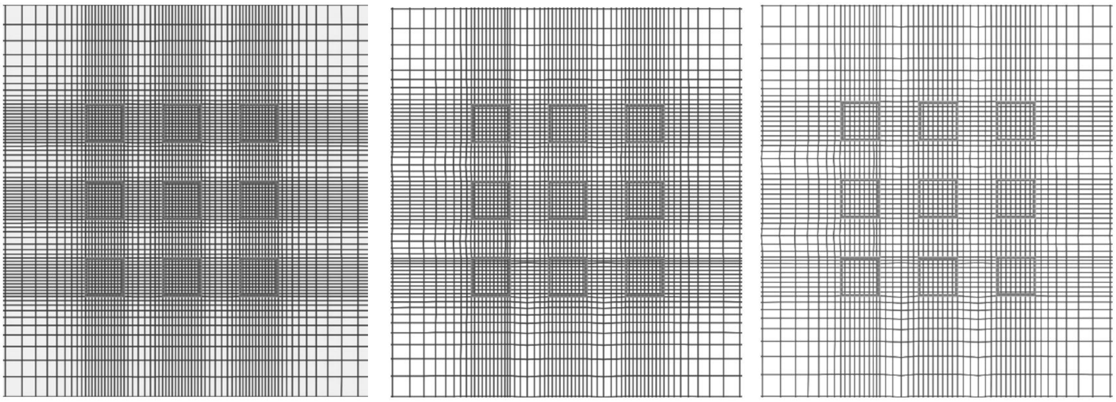
Fig. 1. Models Tested in Wind Tunnels

A) Position of measuring points and arrangement of buildings in the wind tunnel test performed by AIJ, B) Three-dimensional model tested in AIJ wind tunnel tests

The turbulence model used in the simulations is k-ωSST. According to the AIJ standard, the dimensions of the computational amplitude are considered as 5H from the wings and above and 10H in the back-to-the-wind area (Tominaga et al., 2008). Consequently, the dimensions of the range in which the models are located are 1.1 meters, and the dimensions of the computational range are 13 meters in the direction of the X-axis 9 meters in the direction of the Y-axis with a height of 4 meters. The convergence criterion is 10-5 (Asfour, 2010). In order to check the solution independence from the grid[4], the mesh size was changed in three consecutive steps. The growth coefficient of the grid in all three types of 1.2 meshes is structured cubes in all directions and types of meshes. Preceding research and computer simulations of the wind tunnel test results have shown that to achieve precise results a grid with a size of 1.10 of the side length and a maximum growth coefficient of 1.3 is necessary (Mochida et al., 2002). To check the solution independence from the grid, the number of meshes in three different modes is shown in Table 1.

Table 1. Gridding Specifications to Check the Grid-Independent Solution

Minimum Grid Size	Grid Growth Coefficient	Number of Grids	Gridding Name
0.08 Length of the Building Side	1.2	1117168	G1
0.1 Length of the Building Side	1.2	730800	G2
0.12 Length of the Building Side	1.2	554894	G3



A B C

Fig. 2. Three Types of Gridding to Examine the Grid-Independent Solution
A) Fine Gridding G1, B) Medium Gridding G2, C) Large Gridding G3

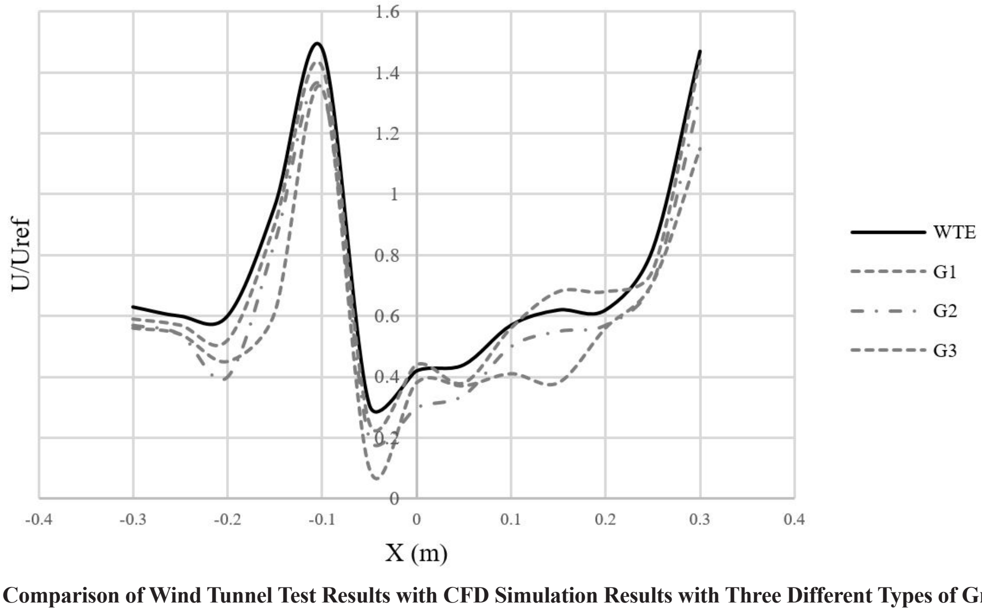


Fig. 3. Comparison of Wind Tunnel Test Results with CFD Simulation Results with Three Different Types of Gridding
Wind speed diagrams measured at base speed in three models with different grids along the Y = 0.25 axis

Investigations revealed that the average difference between the results of CFD simulation and wind tunnel tests was 9%. Accordingly, it can be accredited that the selected turbulence model, boundary layer conditions, and other software settings can be cited and valid, and based on this, simulations of leading research can be done.

The difference between the results obtained from the simulation with G1, G2, and G3 type meshes is equal to 0.049, 0.1, and 0.15, respectively. Accordingly, the G1 mesh type in which the size of the smallest grid is equal to 0.08 length of building side was selected as a suitable mesh.

4.1. Simulation Models

The simulation model in this research is a neighborhood unit consisting of 9 building blocks. The target building is located in the center of the complex, and structural changes are applied to it to analyze the role of these changes on the wind behavior around the building. The structure of the neighborhood unit is designed based on the average height of buildings and the average width of passages (urban morphology) in Tehran. The width of the passages was 18 meters, and the height of the existing buildings in the complex was 15 meters (5-storey building) with a plan of 12 × 18 meters. The target building is a 9-storey block with a height of 27 meters and has a rectangular plan with dimensions of 12 × 18 meters (Fig. 4).

This research has been done in two stages. The first step of the research aims to examine the effect of form and volumetric structure on wind behavior around the building at the pedestrian level. For this purpose, a rigid building and five buildings with different longitudinal sections were simulated and measured natural ventilation potential around the building. The area of all models is equal, and the depth of recesses in all models is 1.5 meters. Since this study aims to investigate the effect of form structure on urban wind flow and internal flow is not examined, building blocks are considered as rigid models without opening (Table 2).

The second step of the research investigates the effect of the recess height on the wind flow pattern around the building and its natural ventilation potential. For this purpose, by changing the height of the recesses from 1.5 to 3.5 meters, five models were simulated in this stage, and the results were compared with each other and with the rigid model. Like the previous stage models, the second stage models are considered rigid and without opening (Table 2).

It should be mentioned that any change in the depth of the terraces, the distribution level of the terraces, the number of terraces, etc., can affect the pattern of internal and peripheral flow of the building (Saadatjoo et al., 2018). As well as the characteristics of the target building, any change in height, proximity, density, the width of passages, etc., surrounding buildings also strongly affect the wind flow pattern. Regarding the extensiveness and array of variables and the impossibility of examining all of them in the form of research, in this research, assuming that all the mentioned variables are constant, the only independent research variable in the first stage is the pattern of recess distribution and in the second stage is the height of recesses in stories.

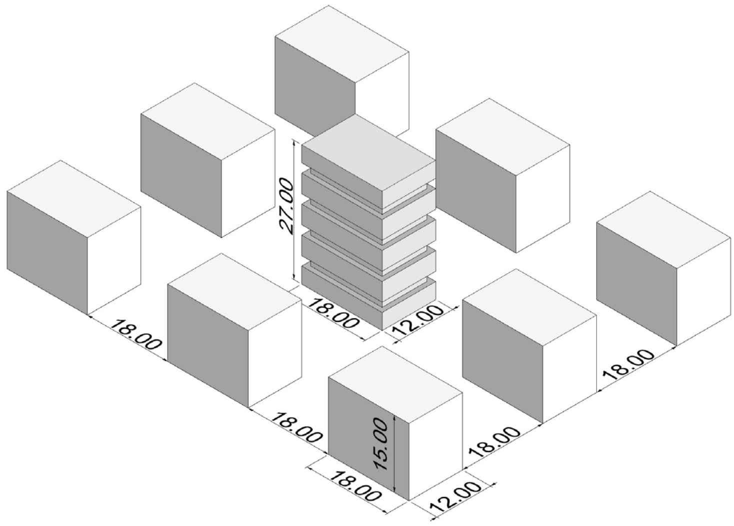


Fig. 4. Simulated Urban Morphology and Location of the Target Building.

Neighborhood units are 5-storey buildings with a height of 15 meters, and the desired model is a 9-storey building with a height of 27 meters, located in the center of the complex.

Table 2. Specifications of the First Step Research Models with Different Longitudinal Sections.

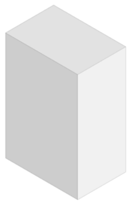
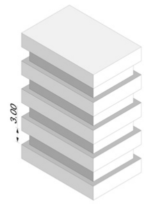
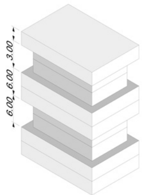
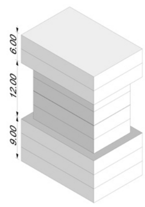
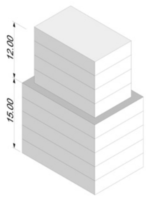
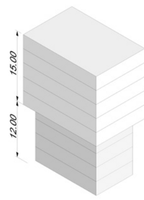
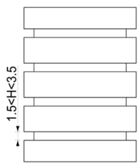
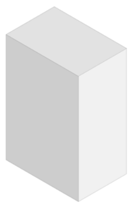
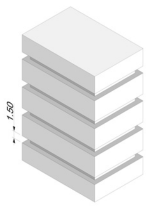
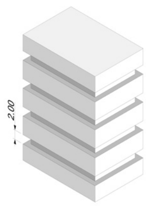
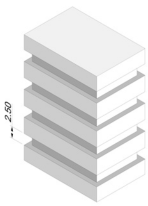
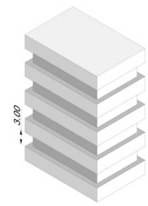
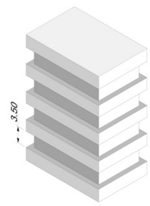
	Solid	A	B	C	D	E
						
Height	27	27	27	27	27	27
Number of Stories	9	9	9	9	9	9
Recess Height (m)	0	1.5	3-6	12	12	12
Recess Depth (m)	0	1.5	1.5	1.5	1.5	1.5
Base (Square Meters)	1944	1620	1620	1620	1620	1620

Table 3. Specifications of the Second Step Research Models. Porous Buildings with Different Porosity Heights

	Solid	A 1.5	A 2	A 2.5	A 3	A 3.5
						
Height	27	27	27	27	27	27
Number of Stories	9	9	9	9	9	9
Recess Height (m)	0	1.5	2	2.5	3	3.5
Recess Depth (m)	0	1.5	1.5	1.5	1.5	1.5

The average and maximum wind speed at the pedestrian level are the two dependent variables of this study to evaluate the wind behavior around the building. For this purpose, the passage around the building was divided into seven cubic areas, and the mentioned variables were measured and recorded in each of these areas. The designated areas cover a distance of 10 meters from the target (central) building, and the wind behavior at this distance from the building is measured and evaluated. The height of the wind behavior measurement area from the floor of the passage to a height of 2 meters above the floor of the passage to completely cover the movement space of pedestrians around the building. The location of the measurement areas relative to the central building and neighborhood units is shown in Figure 5.

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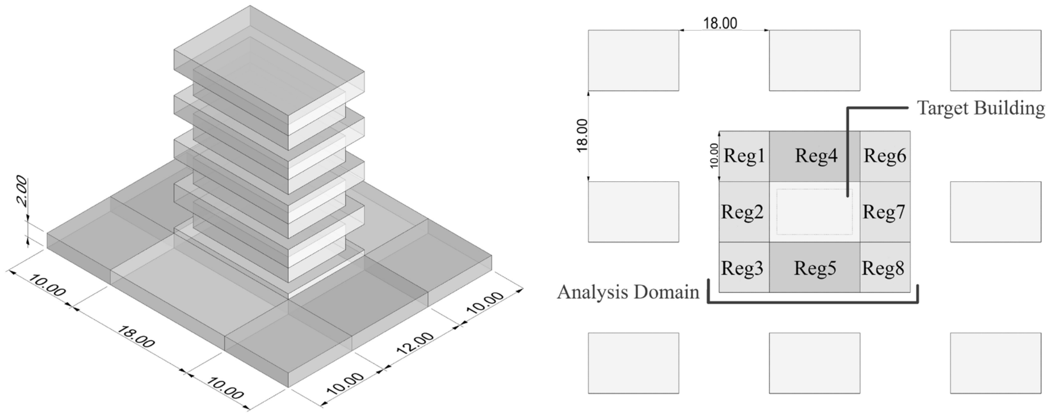

Fig. 5. Position of Measurement Areas Relative to the Central Building and Surrounding Units

To better compare the flow pattern in the studied models, graphic speed contours were extracted from the software and compared. Speed contours were recorded on a plate parallel to the ground at 1.5 m. The position of the contour screen is shown in Figure 6.

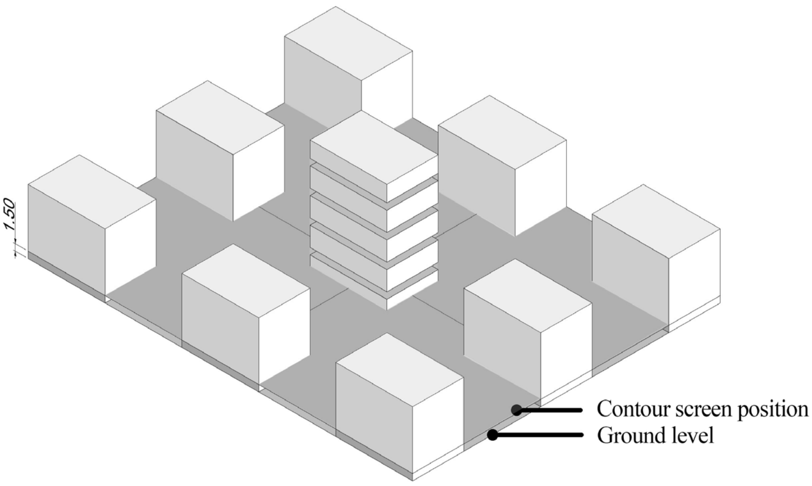

Fig. 6. Position of the Contour Screen Relative to the Building and Ground Level
Graphic wind speed contours are recorded on a screen parallel to the ground and a height of 1.5+ meters.

4.2. Simulation Conditions

The geometric form and structure of buildings and changing the internal flow pattern of the building affect the wind behavior around the building. The wind dynamics analyses were done to investigate the effect of high-rise building geometry on urban wind flow. In this regard, 11 different construction models were simulated, and their results were compared. The computational domain dimensions are defined based on the proposed dimensions of the Japanese AIJ standard. Based on this standard, in the case of flow simulation for a set of buildings, the minimum slope height is equal to 5H, the sides are equal to 5H, and the dimensions of the back-to-wind area are considered to minimize the return flow equal to 10H from the building walls. Since the dimensions of the study area are 72 × 90 meters and the height of the tallest building is 27 meters, the dimensions of the computational range according to the AIJ standard are 477 meters in the x-direction, 360 meters in the y-direction, and 297 meters in the z-direction.

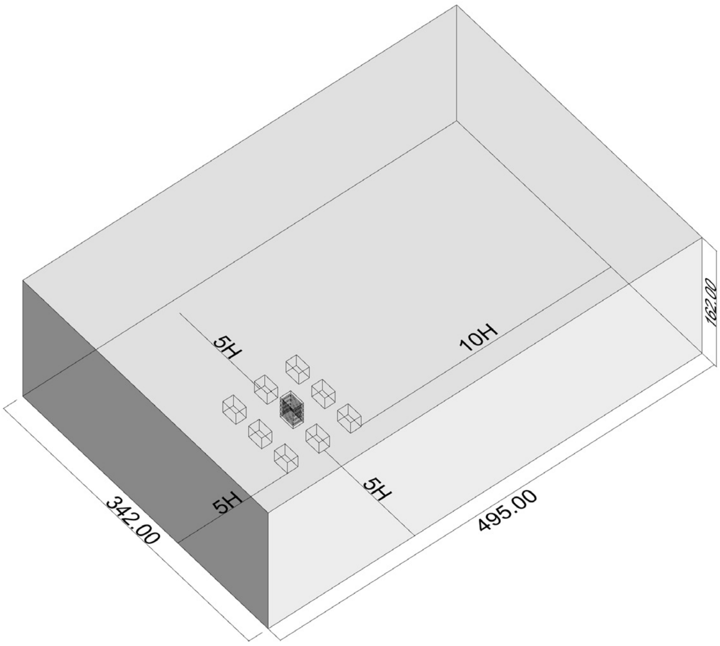

Fig. 7. Computational Range Dimensions and Position of Building Models in the Range.

The second step is to create a mesh grid for the computational domain. According to the dimensions of the computational domain and the studies of solution independence from the grid, 3053142 meshes with a growth coefficient of 1.2 were designed and created. The meshes created are of a cohesive and structured hexahedron. The turbulence model used in the simulations is the k-ωSST model.

The meteorological information used in the simulations is the information of the Mehrabad station during the last 50 years (1965-2014). The use of meteorological information (obtained in the open and at the height of ten meters above the ground) is valid for another place when, firstly, the texture of the place is similar to the texture of the meteorological station in terms of vegetation and architectural construction. Secondly, the height of that place should be close to ten meters from the ground. Otherwise, the wind speed will be different from the available information, and if it is not adjusted, the validity of the information will be reduced. The following equation defined the wind profile at the calculated slope height (0 to 297 m).

$$\frac{\overline{V_z}}{\overline{V_G}} = \left[\frac{Z}{Z_G}\right]^{\alpha} \quad \text{(Relation 1)}$$

In this relation $\overline{V_Z}$ is air velocity at the design site in meters per second and $\overline{V_G}$ is air gradient velocity in meters per second and z height studied in meters and ZG is gradient height in meters and α is the numerical power of the design texture, which is assumed to be 0.36. Meteorological data of Tehran show that the average airspeed during the six warm months of the year is equal to 3.05, and the maximum speed is 32.9 meters per second. The wind direction is defined based on the prevailing wind direction of Tehran and from west to east.

5. FINDINGS

In this study, a wind flow simulation was done for six warm months of the year in Tehran. The most important measures of urban air conditioning potential were average and maximum wind speed was measured at a distance of 10 meters from the perimeter of the building and a height of 2 meters above the ground. The flow measurement ranges are in Figures 5 and 8, and the results of this measurement for each model are shown separately on the grid plan around the building in Tables 4-5. Among the eight areas shown in Figure 8, Reg 1, 2, 3 are in the windward area, Reg4-5 in the squinch area, and Reg 6, 7, 8 areas in the windward area of the building. The two quantities listed in each cell of Table 4 show the top, average flow velocities, and maximum wind velocities.

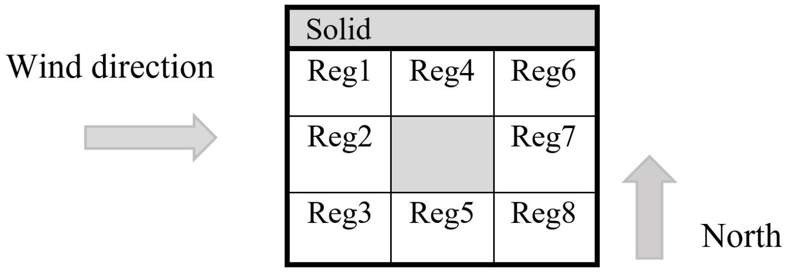

Fig. 8. Name and Position of 8 Peripheral Areas of A-E Models and Rigid Models

Table 4. Mean and Maximum Flow Velocity Values were Obtained from the Simulations in the Peripheral Areas of Models A-E and Rigid Models

Solid			A			B			C			D			E		
0.82	0.56	0.57	1.11	0.73	0.91	1.01	0.72	0.98	0.92	0.68	0.83	0.96	0.61	0.76	0.9	0.81	0.82
1.82	1.51	1.38	2.05	1.72	1.79	1.93	1.76	1.82	1.85	1.57	1.55	1.83	1.51	1.60	21.82	1.65	1.45
0.71		0.17	0.89		0.29	0.82		0.22	0.68		0.31	0.89		0.41	0.71		0.45
1.89		0.60	1.88		0.98	1.76		0.80	1.82		1.10	1.78		1.11	1.61		1.25
0.85	0.59	0.58	1.09	0.8	0.87	1.06	0.82	0.94	0.91	0.63	0.60	1.17	0.76	0.79	0.86	0.73	0.63
1.81	1.52	1.36	1.96	1.77	1.71	1.95	1.76	1.76	1.84	1.47	1.40	1.97	1.73	1.48	1.84	1.61	1.53

Table 5. The Difference between the Mean and Maximum Values of the Flow Velocity Obtained for each Domain with the Base Model (Rigid Building) in Percent

A			B			C			D			E		
+35.36	+30.35	+59.64	+23.17	+28.57	+71.92	+12.19	+21.42	+45.61	+17.07	+8.92	+33.33	+9.75	+44.64	+43.85
+12.63	+13.90	+29.71	+6.04	+16.55	+31.88	+1.64	+3.97	+12.31	+0.54	0	+15.94	0	+29.27	+5.07
+25.35		+70.58	+15.49		+29.41	-0.42		+82.35	+25.35		+141.11	0		+194.11
-0.52		+63.33	-6.87		+33.33	-3.70		+83.33	-6.14		+85	-14.81		+141.66
+28.23	+35.59	+50	+24.70	+38.98	+62.06	+7.05	+6.77	+3.44	+34.64	+28.81	+36.20	+1.17	+23.72	+31.03
+5.28	+16.44	+25.73	+7.73	+15.78	+29.41	+1.65	-3.28	+2.94	+8.83	+13.81	+8.82	+1.65	+5.92	+27.20

Examination of the results recorded in the eight domains around each model revealed that the average and maximum flow velocities in the windward region (Reg 1, 3) had always been positive. The average flow velocity in these two areas increased from 7.05 to 35.36%; the highest growth can be seen in Model A. In the meantime, the maximum wind speed in the two areas increased by 0 to 12.63%, with the highest growth related to Model A. A comparative study of the mean and maximum flow velocities in the two domains Reg1 and Reg 3 indicates that model A has the highest positive difference, and model E has the lowest difference with the rigid model in the two domains.

Despite most of the measured areas showing better behavior than the rigid model with positive growth, the maximum flow velocity on the east front of the building (Reg 2) has decreased. The highest deceleration rate is evident in the E model with -14.81 compared to the base model.

The mean and maximum flow velocities in the squinch regions (Reg 4, 5) indicate a positive growth of both variables compared to the rigid model[5]. The average growth rate of flow velocity is in the range of + 6.77 to +44.64, and the rate of increase of maximum flow velocity is in the range of 0 to 29.27%. A comparative study of the models revealed that the average and maximum wind speed in the squinch of model E are the highest, and model C have the lowest positive growth compared to the rigid model.

The wind speed measurement results in the back-to-wind area (Reg 6, 7, 8) indicated that the wind behavior in this area had been improved by making geometric changes in the shape of buildings. Nevertheless, the speed growth rate and modification of wind flow pattern were different under the influence of the geometric structure of the building; so the average growth wind speed was in the range of 3.44% to

194.11%, and the maximum growth wind speed was in the range of 2.94% to 141.66%.

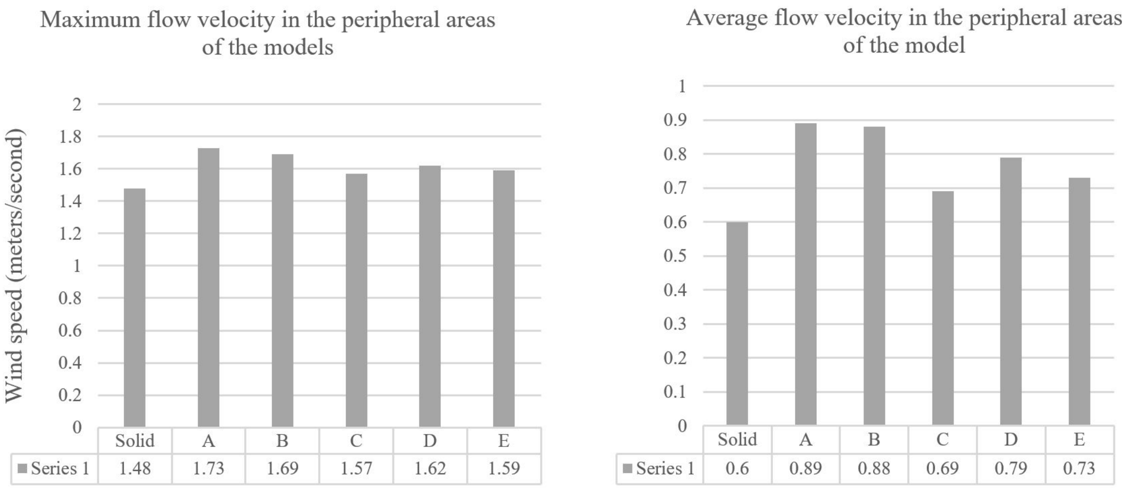

Fig. 9. Graphs of Average Values Obtained for Average and Maximum Flow Velocities in the Eight Surrounding Areas of A-E Models

To better compare the results, the obtained quantities for the two variables of average and maximum flow velocity in the eight areas around the buildings were averaged, and the results were displayed in the form of bar graphs in Figure 9. Comparing the results shows that Model A, with the highest difference from the rigid model, is the best option to improve urban air conditioning. In this model, the average and maximum wind speed around the building has increased by 48.33% and 16.89% compared to the base model (rigid). With almost similar results, Model B is a suitable option after Model A, which can increase the average flow velocity by about 46.66% and the maximum wind speed by 14.18% at the pedestrian level around the high-rise building. Nevertheless, the very small difference between the results of models C and E with the rigid model indicates the inefficiency of these geometric structures to increase the potential of urban wind.

Graphical contours of wind speed on a screen at the height of 1.5 meters above the ground help to study the wind flow pattern in different models (Figure 7).

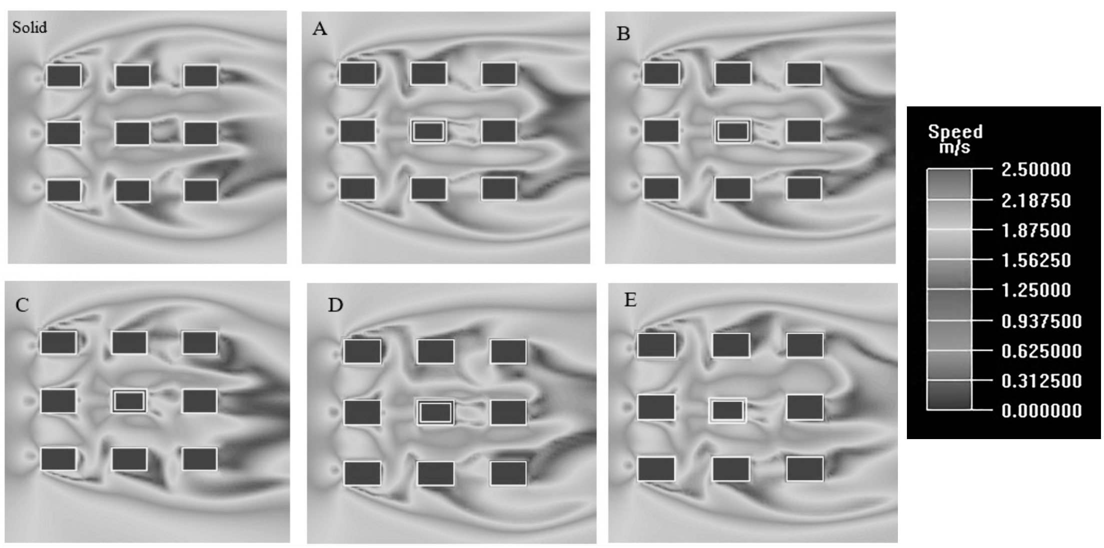

Fig. 10. Graphic Contours of Flow Velocity at 1.5 Meters above the Ground in Models A-E and Rigid Buildings

A comparative study of graphic contours displays that the geometric changes applied in the central building have overshadowed the currents around the building, among which the squinch and back-to-wind areas of the building have been most affected by these changes. Failure in the longitudinal cross-section of the building causes the current to diverge from the straight path and leads to a better flow direction to the area behind the wind of the building. Consequently, the apparent air inaction in this area of the rigid model, by creating longitudinal porosities and fractures of the building body, can be significantly modified and bring comfort to passers-by. Graphic contours indicate that the change in geometric structure and structure of the building cannot significantly affect the flow pattern in the windward area of the building.

The second step of the study examined the effect of the recess height of the body on the ventilation of the passages around the building. The measured areas and the numerical analysis results are shown in Figure 11 and Tables 6-7.

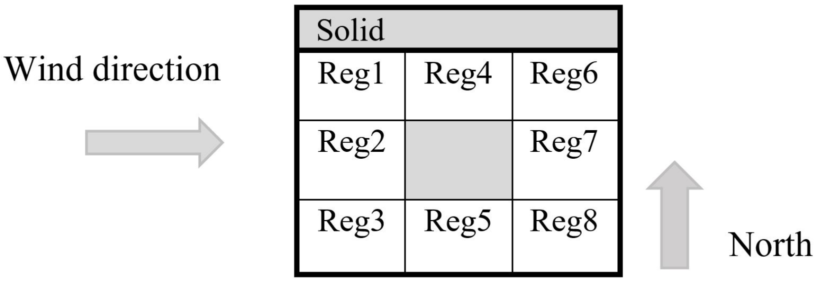

Fig. 11. Name and Position of 8 Peripheral Areas of Models A1.5-A3.5 and Rigid Model

Table 6. Mean and Maximum Values of Flow Velocity Obtained from Simulations in the Peripheral Areas of Models A1.5-A3.5 and Rigid Model

Solid			A1.5			A2			A2.5			A3			A3.5		
0.82	0.56	0.57	1.11	0.73	0.91	1.07	0.73	0.95	1.01	0.69	0.81	1.06	0.81	1.03	1.07	0.78	0.96
1.82	1.51	1.38	2.05	1.72	1.79	1.97	1.7	1.82	1.88	1.49	1.51	1.93	1.76	1.82	1.9	1.66	1.71
0.71		0.17	0.89		0.29	0.85		0.23	0.74		0.3	0.87		0.29	0.85		0.29
1.89		0.60	1.88		0.98	1.8		0.99	1.7		1.04	1.76		0.80	1.73		0.80
0.85	0.59	0.58	1.09	0.8	0.87	1.10	0.79	0.93	1.09	0.79	0.96	1.11	0.87	1.00	1.10	0.85	0.95
1.81	1.52	1.36	1.96	1.77	1.71	1.99	1.73	1.74	1.94	1.68	1.69	1.95	1.76	1.76	1.90	1.68	1.68

Table 7. The Difference between the Mean and Maximum Values of the Flow Velocity Obtained for each Domain with the Base Model (Rigid Building) in Percent

A1.5			A2			A2.5			A3			A3.5		
+35.36	+30.35	+59.64	+30.48	+30.35	+66.66	+23.17	+23.21	+42.10	+29.26	+44.64	+80.70	+30.48	+39.28	+68.42
+12.63	+13.90	+29.71	+8.04	+12.58	+31.88	+3.29	-1.32	+9.42	+6.04	+16.55	+31.88	+4.39	+9.93	+23.91
+25.35		+70.58	+19.71		+35.29	+4.22		+76.47	+22.53		+70.58	+19.71		+70.58
-0.52		+63.33	-4.76		+65	-10.05		+73.33	-6.87		+33.33	-8.93		+33.33
+28.23	+35.59	+50	+29.41	+33.89	+60.34	+28.23	+33.89	+65.51	+30.58	+47.45	+72.41	+29.41	+44.06	+63.79
+5.28	+16.44	+25.73	+9.94	+13.81	+27.94	+7.18	+10.52	+24.26	+7.73	+15.78	+29.41	+4.97	+10.52	+23.52

The results obtained from the second stage of the simulations revealed that in all models, the average and maximum flow velocities in the Rg1, three regions increased compared to the rigid model. In these two areas, the average changes in flow velocity compared to the base model are in the range of +23.17 to +35.36, and the changes in maximum flow velocity are in the range of +3.29 +12.63. The highest increase in flow velocity in these two areas is related to model A1.5 and the lowest value is related to model A2.5. The highest positive growth of average and maximum flow velocities was observed in the squinch areas compared to the rigid structure in model A3 and the lowest value was observed in model A2.5.

The quantitative results obtained from the simulation of the models indicate an average increase and a decrease in the maximum flow velocity relative to the rigid model in the windward region. The average flow velocity in this area increased from 4.22% to 25.35%; meanwhile, the maximum wind speed values have been reduced by up to 10%. Among the five models tested, model A1.5 showed the best and A2.5 the weakest flow pattern in this range.

The mean and maximum flow velocities in the squinch areas (Reg 4, 5) indicate a positive growth of the mean and maximum wind speed variables compared to the rigid model. The average growth rate was 23.21% to 47.45% in this area, and the maximum growth rate was 9.93% to 16.55%.

Examination of the results in the back-to-wind area (Reg 6, 7, 8) indicated that by making geometric changes, the flow behavior in the back-to-wind area of the building has improved compared to the rigid model. Geometric alterations of the building with a significant increase in the average flow velocity in the range of 35.29% to 80.70% and maximum wind speed with an increase of 9.42 to 73.33% have eliminated the stagnation in this area in the rigid model and have improved urban wind ventilation. At large, it can be indicated that the wind flow velocity in the back-to-wind area of the building had the lowest growth in the A3.5 model and the highest growth in the A3 model compared to the rigid model.

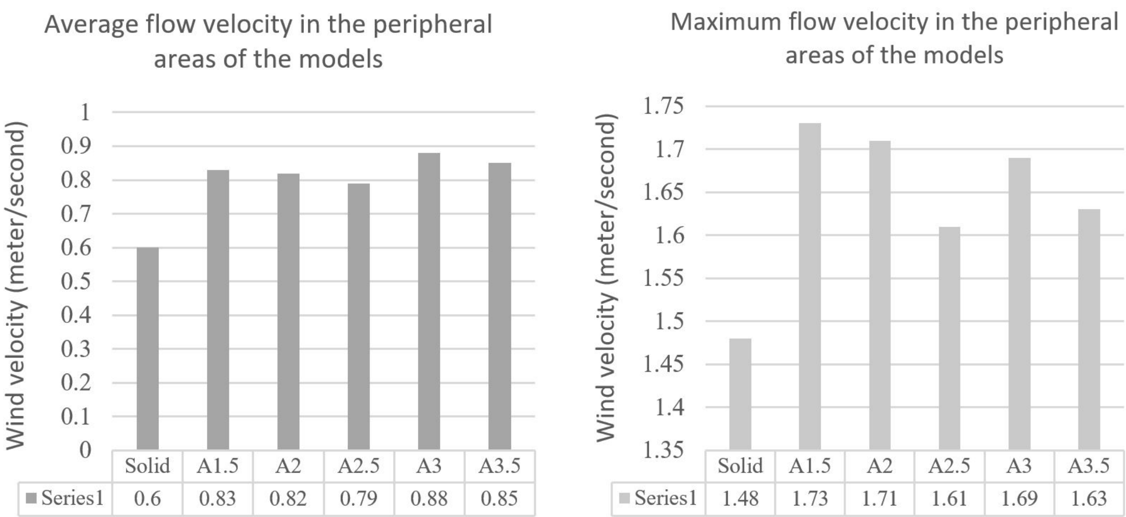

Fig. 11.Graphs of the Average Values Obtained for the Average and Maximum Flow Velocities in the Eight Surrounding Areas of the A1.5-A3.5 Models

A comparative study of the results (Fig. 9) revealed that models A3 and A1.5 have the highest average velocity and maximum flow velocity around the building, respectively. The diagrams indicate that the creation of terraces and recesses throughout the body of the building can have a positive effect on the ambient wind flow. Model A3 increased the natural ventilation potential of the city by increasing the average ambient velocity by 46.66% and model A1.5 by increasing the maximum wind speed by 16.89%. The results revealed that increasing the height of body recesses from 1.5 to 2.5 meters by reducing the average and maximum flow around the building had a negative effect on the efficiency of natural ventilation. It can be acknowledged that there is no direct relationship between the height of body recesses and the efficiency of natural ventilation, and among the five defined models, models A1.5, 2, 3 have higher potential and efficiency than the other two models.

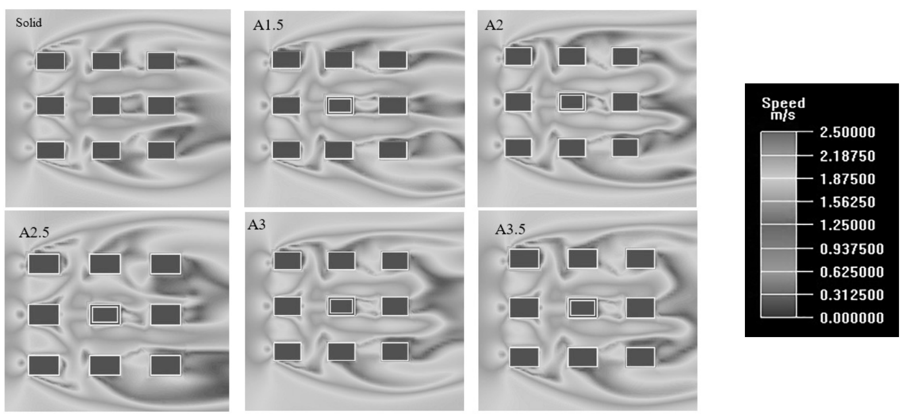

Fig. 12. Graphic Contours of Flow Velocity at the Height of 1.5 m above the Ground in Models A-E and Rigid Buildings

A comparative study of graphic contours (Fig. 12) shows that changes in the height of the terraces have led to changes in the urban wind pattern. It can be concluded that the creation of terraces has led to better flow around the building and especially the areas behind the wind. This aerodynamic behavior improves the peripheral comfort conditions of the building compared to the rigid model. Among the five models tested, A1.5,2,3 are the proposed models to improve the efficiency of natural ventilation around buildings.

6. DISCUSSION

- The simulations revealed that making geometric changes in the form of high-rise buildings can overshadow the speed and pattern of urban wind flow.
- By making geometric changes in the building of origin, the average wind speed in all separated peripheral areas has had positive changes. These results are consistent with the findings of studies by Zhang et al., 2017; Tse et al., 2017; Chew & Norford, 2019; and Du et al., 2018. In the meantime, the positive effects on the windward area of the target building were minimal. Though, the most positive changes are evident in the flow behavior of the area behind the building wind.
- Failure in the longitudinal form of the building by diverting the flow from the direct path and directing it to the area behind the wind of the building has led to an increase in wind speed in this area. The average and maximum flow velocities in this growth area showed about 194.11 and 141.66%.
- From the geometric models simulated in the first step of the research, model A with the highest difference between the mean values and maximum flow velocity with the rigid base model was introduced as the best option to increase the potential of urban natural ventilation. Model B with a similar structure is the most suitable option after Model A.
- The results of the first phase of the simulations attested that the regular distribution of the recess of the body at the height of the building could help ventilate the passages by intensifying the surrounding wind speed. Though, the focus of the recesses on the central part of the building (model C) causes a significant decrease in the flow velocity around the building compared to the rigid model. This part of the results is consistent with the findings of studies by Du et al. (2018) that examine the effect of building porosity on the ambient wind.
- The study of the first stage modeling proved that the creation of terraces around the building as one of the geometric changes of the building has positive effects on the natural ventilation of the perimeter of the building. In this regard, the simulations of the second phase of the research proved the effect of changing the height of terraces and body recesses on the potential of urban natural ventilation.
- By creating terraces all over with different heights, the average speed around the building at the pedestrian level increased compared to the rigid model in all measurement areas. These positive changes are more evident in the back-to-wind area of the building than in the windward area of the building.
- The second stage simulations revealed that the surrounding wind speed has increased compared to the base model. However, this increase is much higher in other areas of 6-7-8 (back to wind area).
- Simulations showed no clear relationship between speed changes around the building and the height of the building terraces. Buildings with recess heights of 1.5, 2, and 3 bodies showed better results than terraced buildings with 2.5 and 3.5.
- A comparative study of all the simulated models in both stages proved that creating geometric changes and cross-sectional shapes of the building at different levels affects the wind flow around the building. This achievement is consistent with the research results conducted by Tsichritzis and Nikolopoulou (2019) and Tse et al. (2017). The best way to increase the speed of urban wind flow is to make changes in the form of regular recesses in the entire height of the building. The focus of this form failure in parts of the building, especially the middle part, has a negative impact on the efficiency of ventilation and wind flow around the building.

7. CONCLUSION

It is essential to pay attention to the building's climatic considerations and aerodynamic behavior along with functional and aesthetic issues in the first steps of architectural design. The 9-storey buildings studied in the first step of this research were five models with different geometric structures and longitudinal sections. Examination of the results of CFD simulations proved the positive effect of these changes on the improvement of urban wind flow compared to the rigid model. These changes resulted in an average increase of 48.33% and a maximum urban wind flow of 16.89% compared to a simple (at best) cubic building. All areas around the target model experienced a positive increase in flow velocity, but in the meantime, the back-to-wind area had the most positive changes with an average increase of 194% and a maximum wind speed of 141%. Making formal changes to intensify the flow of the surrounding passages in the form of the recess of the body should be in the form of a regular distribution of recesses in the entire height of the building. It is not recommended to focus the recess on a specific building elevation, especially in the middle parts.

The second phase of the research, focusing on Group A buildings as the most efficient model of the first phase, investigated the role of changing the height of body recesses on the wind behavior around the building. The simulation results of this stage revealed no direct relationship between the height of the body recess and average and maximum wind speed around the building. By improving the pattern of wind behavior in 8 areas around the building, these models can increase the average flow velocity of the back-to-wind area and the squinch by 80.70% and 47.45% at best. Meanwhile, the A3 model with a height of 3 meters of recessed spaces showed an average increase potential of 46.66%, and the A1.5 model showed a potential increase of 16.89% of the maximum wind speed around the building.

The results of this research can be used as a design aid model to guide the practice of architects in designing buildings that can provide comfort to passers-by in the passages around the building in hot climates by intensifying and strengthening the surrounding currents of the building. Nonetheless, it should be mentioned that as well as the mentioned advantages, the use of continuous terraces in the floors can increase the speed of flow, and in addition to creating air blinds, can cause annoying wind noise in the upper floors. So, in using this solution, all aspects and conditions should be carefully studied and considered.

END NOTE

1. Buildings with a height of 27 meters or more or a building whose number of stories including the ground floor is 8 stories and more or the height of the height of the highest usable floor of the storey is more than 2 meters above the average ground level is called high-rise.
2. In investigating the effect of physics based on aerodynamic behavior, Razjouyan studied the proportions of the building in the form of the length of the obstacle and its elongation to the wind and the ratio of height to the length of the obstacle to the wind (Razjouyan, 2007).
3. Architectural Institute of Japan
4. Solution independence from the network means selecting the best possible network and mesh dimensions to receive the correct answers in the CFD group simulator software.
5. The only exception was the Model C, with a 3.28% reduction in maximum wind speed from baseline.

REFERENCES

- Ai, Z. T., & Mak, C. M. (2013). CFD simulation of flow and dispersion around an isolated building: Effect of inhomogeneous ABL and near-wall treatment. *Atmospheric Environment*, 77, 568–578. https://doi.org/10.1016/j.atmosenv.2013.05.034
- Aliabadi, A. A., Krayenhoff, E., Nazarian, N., Chew, L. W., Armstrong, P., Afshari, A., & Norford, L. (2017). Effects of Roof-Edge Roughness on Air Temperature and Pollutant Concentration in Urban Canyons. *Boundary-Layer Meteorology*, 164. https://doi.org/10.1007/s10546-017-0246-1
- Asfour, O. S. (2010). Prediction of wind environment in different grouping patterns of housing blocks. *Energy and Buildings*, 42(11), 2061–2069. https://doi.org/10.1016/j.enbuild.2010.06.015
- Aynsley, R. (2007). Natural Ventilation in Passive Design. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.7478&rep=rep1&type=pdf
- Bahadori, M. N. (1994). Viability of wind towers in achieving summer comfort in the hot arid regions of the middle east. *Renewable Energy*, 5(5), 879–892. https://doi.org/https://doi.org/10.1016/0960-1481(94)90108-2
- Buccolieri, R., Sandberg, M., & Di Sabatino, S. (2010). City breathability and its link to pollutant concentration distribution within urban-like geometries. *Atmospheric Environment*, 44(15), 1894–1903. https://doi.org/https://doi.org/10.1016/j.atmosenv.2010.02.022
- Chen, K. W., & Norford, L. (2017). Evaluating Urban Forms for Comparison Studies in the Massing Design Stage. *In Sustainability*, 6(9). https://doi.org/10.3390/su9060987
- Chew, L. W., & Norford, L. K. (2019). Pedestrian-level wind speed enhancement with void decks in three-dimensional urban street canyons. *Building and Environment*, 155, 399–407. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.03.058
- Cui, D. J., Mak, C. M., Kwok, K. C. S., & Ai, Z. T. (2016). CFD simulation of the effect of an upstream building on the inter-unit dispersion in a multi-story building in two wind directions. *Journal of Wind Engineering and Industrial Aerodynamics*, 150, 31–41. https://doi.org/https://doi.org/10.1016/j.jweia.2016.01.007
- Dhalluin, A., & Bozonnet, E. (2015). Urban heat islands and sensitive building design – A study in some French cities' context. *Sustainable Cities and Society*, 19, 292–299. https://doi.org/https://doi.org/10.1016/j.scs.2015.06.009
- Du, Y., Mak, C. M., Kwok, K., Tse, K. T., Lee, T. cheung, Ai, Z., Liu, J., & Niu, J. (2017). New criteria for assessing low wind environment at pedestrian level in Hong Kong. *Building and Environment*, 123, 23–36. https://doi.org/10.1016/j.buildenv.2017.06.036
- 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. *Building and Environment*, 117, 84–99. https://doi.org/10.1016/j.buildenv.2017.03.001
- Du, Y., Mak, C. M., & Tang, B. S. (2018). Effects of building height and porosity on pedestrian level wind comfort in a high-density urban built environment. *Building Simulation*, 11, 1215–1228. https://doi.org/10.1007/s12273-018-0451-y
- Fadl, M. S., & Karadelis, J. (2013). CFD Simulation for Wind Comfort and Safety in Urban Area: A Case Study of Coventry University Central Campus. *International Journal of Architecture, Engineering and Construction*, 2(2), 131–143. https://doi.org/10.7492/ijaec.2013.013
- Hagishima, A., Tanimoto, J., Nagayama, K., & Meno, S. (2009). Aerodynamic parameters of regular arrays of rectangular blocks with various geometries. *Boundary-Layer Meteorology*, 132(2), 315–337. https://doi.org/10.1007/s10546-009-9403-5
- Hang, J., Sandberg, M., & Li, Y. (2009). Effect of urban morphology on wind condition in idealized city models. *Atmospheric Environment*, 43(4), 869–878. https://doi.org/10.1016/j.atmosenv.2008.10.040
- Hariri, M. T. R., Khosravi, S. N., & Saadatjoo, P. (2016). The Impact of High-rise Building Form on Climatic Comfort at the Pedestrian Level. *Journal of Architecture and Urban Planning*, 9(17), 61–77.
- Ikegaya, N., Ikeda, Y., Hagishima, A., Razak, A. A., & Tanimoto, J. (2017). A prediction model for wind speed ratios at pedestrian level with simplified urban canopies. *Theoretical and Applied Climatology*, 127(3–4), 655–665. https://doi.org/10.1007/s00704-015-1655-z
- Isyumov, N., & Davenport, A. G. . G. L. W. E. in B. (1975). The Ground Level Wind Environment in Built-up Areas. 4th International Conference on Wind Effects on Buildings and Structures.
- Liu, J., Niu, J., & Xia, Q. (2016). Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort. *Building and Environment*, 105, 185–197. https://doi.org/10.1016/j.buildenv.2016.05.038
- Medhat Osman. (2011). Evaluating and enhancing design for natural ventilation in walk-up public housing blocks in the Egyptian desert climatic design region. University of Dundee.
- Melbourne, W. H. (1978). Criteria for environmental wind conditions. *Journal of Wind Engineering and Industrial Aerodynaemics*, 3(2), 241–249. https://doi.org/https://doi.org/10.1016/0167-6105(78)90013-2

- Mochida, A., Tominaga, Y., Murakami, S., Yoshie, R., Ishihara, T., & Ooka, R. (2002). Comparison of various k-ε models and DSM applied to flow around a high-rise building - Report on AIJ cooperative project for CFD prediction of wind environment. *Wind and Structures An International Journal*, 5, 227–244. https://doi.org/10.12989/was.2002.5.2_3_4.227
- Montazeri, H., Blocken, B., & Hensen, J. L. M. (2015). Evaporative cooling by water spray systems: CFD simulation, experimental validation, and sensitivity analysis. *Building and Environment*, 83, 129–141. https://doi.org/https://doi.org/10.1016/j.buildenv.2014.03.022
- Moonen, P., Defraeye, T., Dorer, V., Blocken, B., & Carmeliet, J. (2012). Urban Physics: Effect of the micro-climate on comfort, health and energy demand. *Frontiers of Architectural Research*, 1(3), 197–228. https://doi.org/https://doi.org/10.1016/j.foar.2012.05.002
- NajafKhosravi, S., Saadatjoo, P., Mahdavinejad, M., & Amindeldar, S. (2016). The effect of roof details on natural ventilation efficiency in single isolated buildings. PLEA 2016 - *Cities, Buildings, People: Towards Regenerative Environments*.
- Ng, E., YUAN, C., Chen, L., Ren, C., & Fung, J. (2011). Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong. *Landscape and Urban Planning*, 101, 59–74. https://doi.org/10.1016/j.landurbplan.2011.01.004
- Rose, L., Horrison, E., & Lavanya Jothi Venkatachalam. (2011). Influence of Built Form on the Thermal Comfort of Outdoor Urban Spaces. The 5th International Conference of the International Forum on Urbanism (IFoU), Oke 1987.
- Saadatjoo, P., Mahdavinejad, M., Khosravi, S. N., & Kaveh, N. (2016). Effect of Courtyard Proportion on Natural Ventilation efficiency. 5, 92–97.
- Saadatjoo, P., Mahdavinejad, M., & Zarkesh, A. (2019). Porosity Rendering in High-Performance Architecture : Wind-Driven Natural Ventilation and Porosity Distribution Patterns. 12(26), 73–87. https://doi.org/10.22034/AAUD.2019.89057
- Saadatjoo, P., Mahdavinejad, M., & Zhang, G. (2018). A study on terraced apartments and their natural ventilation performance in hot and humid regions. *Building Simulation*, 11(2), 359–372. https://doi.org/10.1007/s12273-017-0407-7
- Saadatjoo, P., Mahdavinejad, M., Zhang, G., & Vali, K. (2021). Influence of permeability ratio on wind-driven ventilation and cooling load of mid-rise buildings. *Sustainable Cities and Society*, 70, 102894. https://doi.org/https://doi.org/10.1016/j.scs.2021.102894
- 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 Studies and New Technologies of Architecture and Planning*, 11(3), 67–92. http://bsnt.modares.ac.ir/article-2-50471-en.html
- Saligheh, E., & Saadatjoo, P. (2020). Impact of Central Courtyard Proportions on Passive Cooling Potential in Hot and Humid Regions (Case Study: Single-story Buildings in Bandar Abbas). *Naqshejahan-Basic Studies and New Technologies of Architecture and Planning*, 10(2), 137–152.
- 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. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(10–11), 1749–1761. https://doi.org/10.1016/j.jweia.2008.02.058
- Tsang, C. W., Kwok, K. C. S., & Hitchcock, P. A. (2012). Wind tunnel study of pedestrian level wind environment around tall buildings: Effects of building dimensions, separation and podium. *Building and Environment*, 49, 167–181. https://doi.org/10.1016/j.buildenv.2011.08.014
- Tse, K. T., Zhang, X., Weerasuriya, A. U., Li, S. W., Kwok, K. C. S., Mak, C. M., & Niu, J. (2017). Adopting 'lift-up' building design to improve the surrounding pedestrian-level wind environment. *Building and Environment*, 117, 154–165. https://doi.org/10.1016/j.buildenv.2017.03.011
- Tsichritzis, L., & Nikolopoulou, M. (2019). The effect of building height and façade area ratio on pedestrian wind comfort of London. *Journal of Wind Engineering and Industrial Aerodynamics*, 191, 63–75. https://doi.org/10.1016/j.jweia.2019.05.021
- Uematsu, Y., & Isyumov, N. (1999). Wind pressures acting on low-rise buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 82(1), 1–25. https://doi.org/https://doi.org/10.1016/S0167-6105(99)00036-7
- Willemsen, E., & Wisse, J. A. (2007). Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. *Journal of Wind Engineering and Industrial Aerodynamics*, 95(9), 1541–1550. https://doi.org/https://doi.org/10.1016/j.jweia.2007.02.006
- Wu, Y., Niu, J., & Liu, X. P. (2017). Air infiltration induced inter-unit dispersion and infectious risk assessment in a high-rise residential building. *Building Simulation*, 11. https://doi.org/10.1007/s12273-017-0388-6
- Xu, X., Yang, Q., Yoshida, A., & Tamura, Y. (2017). Characteristics of pedestrian-level wind around super-tall buildings with various configurations. *Journal of Wind Engineering and Industrial Aerodynamics*, 166, 61–73.

https://doi.org/10.1016/j.jweia.2017.03.013

- Yim, S. H. L., Fung, J. C. H., Lau, A. K. H., & Kot, S. C. (2009). Air ventilation impacts of the "wall effect" resulting from the alignment of high-rise buildings. *Atmospheric Environment*, 43(32), 4982–4994. https://doi.org/https://doi.org/10.1016/j.atmosenv.2009.07.002
- Yuan, C., & Ng, E. (2012). Building porosity for better urban ventilation in high-density cities - A computational parametric study. *Building and Environment*, 50, 176–189. https://doi.org/10.1016/j.buildenv.2011.10.023
- 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. *Building and Environment*, 124, 245–257. https://doi.org/10.1016/j.buildenv.2017.08.012
- Zheng, X., Montazeri, H., & Blocken, B. (2020). CFD simulations of wind flow and mean surface pressure for buildings with balconies: Comparison of RANS and LES. *Building and Environment*, 173, 106747. https://doi.org/10.1016/j.buildenv.2020.106747

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