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The Space Opening Number and Volume Effect in the Form of High Buildings Under the Wind Force

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Abstract: Wind force and its response are the main factors dominated the design norms of high buildings. The high buildings form affects the wind movement pattern. The presence of a hole in the form is one of the most common measures of form design. This research investigates comparatively wind flow distribution in a high building with horizontal hole, with the hole variable number and volume and with the aim of finding the space opening effect on wind movement pattern. Numerical study was done by Computational Fluid Dynamics (ANSYS Fluent). In order to validate the results, field studies have been used. The results indicate that the form with more holes is more efficient to reduce the wind force. The wind speed in the middle of the form span with the larger tunnel is 2.436 and in the middle of the volume with the smaller tunnel is 1.249, which is 48.7% greater. In general, with increasing in the tunnels number, the increase in wind speed becomes independent of the tunnels number and the wind speed increases affected by height. In addition, from the locating openings inside the tunnels view point replacing, openings on the leeward wall, in the middle of the wall, is more suitable and if it forced to design the opening on the windward exposure wall, their placement on the first third of the tunnels is more efficient. The design of the space openings reduces the wind speed in the terraces located in the leeward facade, and in relation to the windward exposure facade, the design of the terraces before the space openings is more suitable.

Keywords: *tall building - form - space opening - wind force – CFD*[1]

Introduction

With the increasing progress in design methods and construction technologies and in the rapid urban growth conditions, buildings become more flexible, narrower and higher day by day and create new design challenges for structural engineers. The placement of openings and their efficiency in high buildings, due to the increase in wind speed at altitude, is a challenge that designers are faced. In addition, in order to control the inertial forces

[1] Computational Fluid Dynamics

development caused by earthquakes, there is a need to make buildings lighter. This causes pay more attention to the forces caused by the wind in the building. Therefore, the wind force and the movements caused by the wind generally are dominated on the tall building design. This load directly depends on the exterior shape of the building model and can be significantly reduced with some modifications on the exterior shape (Kumar & Dalui, 2017).

Cubic-shaped buildings are very common for office and residential applications due to their simple form, fast construction capability and simplicity of structural calculations. If the building is in large-scale, these forms have difficulties in providing natural light for the middle spaces. One ways of solving the providing light problem and ventilation in these forms is to use tunnels in the volume that can be horizontal or vertical. The creation of these holes in the volume and facade of the high building affects the wind movement pattern. For a building model with a regular rectangular plan, the leeward facade usually experiences critical pressure distribution, but buildings with an irregular or unusual form and plan sometimes experience critical pressure distribution on other faces as well. The unusual plan buildings response to the wind force is estimated by calculations using wind tunnel or numerical techniques. In this research, with computational fluid dynamics method, the wind force effect on high buildings with space opening is investigated.

background research

In previous researches, in response to unconventional forms and plans effect on the wind behavior pattern, the wind tunnel technique and computational fluid dynamics have been applied. In an article entitled, The Effect of the Geometric Form of High Buildings on the Dispersion of Suspended Particles and Air Pollution in Their Surroundings, Khodakarmi et al., investigated the context around Imam Khomeini Square in Tehran, using Envi-met software. The highest building in this context is the telecommunications building with 50m height. In addition to the real model, different heights from 15 to 45 m have also been modeled and the wind flow distribution pattern results obtained from the software have been compared with each other. By studying the relationship between the height and geometry of this building, with the flow distribution pattern and wind speed around it, it was indicated that with a change in height, the air turbulence patterns around the building changed and this causes a change in the air pollution pattern (Khodakarami & et al,2020).

Yousefian et al. (1396), have examined the form of high complexes effect on the air flow and the obtained results are that the wind speed increases in the building corners, which has a direct relation with the increase in the height. The passage of wind through two buildings acts as a strait and increases the wind speed, and the wind speed increases as the height from the ground level increases. In addition, a building with a smaller width has better conditions in front against the wind than a building with a larger width. The stepped form facing the wind creates a calm zone in the space in front of the staircase, and the integrated blocks have a greater effect in increasing the wind speed than the stepped block. Kwok investigated the effect of the high building shape on the wind flow in the wind tunnel and concluded that modifying the shape of a high building with a rectangular cross-section has an effect on the result of wind excitation, and creating horizontal gaps and beveled corners reduces the wind effect on the building (Kwok, 1998). In two separate articles, Kim et al. have investigated the effect of conical height form against the wind, and it was found that the more conical the cross-section of the building becomes (the apex of the form is sharper), it reduces the wind-induced excitements on the building. This test was done using a wind tunnel (Kim & You,2002, Kim & et al, 2008). Chekraborty et al., compared the wind behavior in a cruciform building with the help of wind tunnel and numerical simulation and the result showed that there is not any difference in the results in both methods except for some faces of the walls and irregular plans such as cruciform, expose to different pressure than the building with a quadrangular plan (Chakraborty & et al,2014). In a similar research, they investigated the distribution of wind pressure on a building with a cross plan with 90° angles and a plan with a cross form with different angles. These studies have been conducted with the help of CFD and it is concluded that the building with a cross plan and different angles is more efficient against the wind force than the cross building with the same angles (Kumar & et al,2017). In a research they examined corners' effect on high building with Y plan, and three corner models were analyzed in this volume. Three different corner models are right corner, beveled and round. To conduct this study, computational fluid dynamics and k-epsilon model were used, and wind tunnel was used to validate the data. The results indicated that the round corner is the most efficient model (Sanyal & et al,2020).

Yi et al., investigated the effect of wind on high buildings and investigated the effect of factors such as random wind direction, surrounding environment and surface soil on a 240-meter building. In this research, the results were extracted by means of wind tunnel and field measurements, and the results coincide with each other to an acceptable extent. The results indicated that with an increase in the ground roughness, the wind force decreases and the interference effects of the surrounding buildings are significantly dependent on the wind direction, and if the surrounding buildings are windward, it causes a decrease in the wind speed (Yi & et al,2015). In another study, they studied the created effect of wind tunnels on wind speed at different heights in high buildings. These tests have been conducted by means of a wind tunnel and the results have indicated that the wind tunnel shape designed in the building and its direction are effective factors in increasing the wind speed. The smaller the wind tunnel, the higher the wind speed in it. In 2018, the effect of a central courtyard presence in quadrangular forms was investigated and the wind flow pattern was compared faced with three forms of central courtyard, U-shaped and quadrilateral without a courtyard. This study has been carried out with the help of computational fluid dynamics and it concludes that in the courtyard and span presence, due to the interference effect, unusual pressure distribution is observed on some walls (Sanyal & et al,2018).

In a research, Kar and his colleagues compared the wind pressure change in the faces of a high building in an octagonal plan with a square plan shape. In addition, in this research, they investigated the effect of wind on these buildings facing the neighboring buildings. The results indicated that by increasing the distance between the buildings, the wind behavior is more recognizable and the wind distribution is symmetric around the building (Kar & et al,2016). In another study, the effect of double skin facade design on the wind flow pattern was investigated. In this research, the facade of double skin facade with and without opening are compared. The results indicate that in the opposite wind direction, the double skin facade with openings significantly reduces the effect of wind on the building, while the double skin facade without openings increases the effect of wind (Hu & et al,2017).

From the research conducted from 1950 to 2010, they conclude that as the height of the building increases, the wind shadow increases and the tension behind the buildings reaches to a minimum value. The wind shadow created behind the building is four times of the height. In addition, the wind speed increases near high buildings, and high buildings create a turbulent wind flow by increasing the unevenness on the facade. Also, the studies showed that building depth increasing does not have much effect on increasing the safe area behind the building (Yin,2010). In a research in 2019, the morphology of the high building was investigated on air pollution and it was concluded that the wind speed and the pollutants amount in the corner of the high forms are at the highest possible form (Yang & et al,2019). Inter-building and intra-building aerodynamic behaviors of connected buildings were investigated by Song et al. (2016). In another research, they presented the analytical and experimental results of pressure distribution on different faces of E-shaped plan in high buildings for different wind angles (Bhattacharya & Dalui, 2018).

The research background shows that the investigation of the space opening effect in the high building form on the movement behavior of the wind has rarely been considered. Also, the results obtained for different climatic conditions show different results, therefore this research has innovation and its results are reliable to benefit from the environmental design of the architecture, in order to achieve suitable air quality and structural design is suitable.

In this research, try to answer the following question according to the gap in the literature of the subject:

Does space opening index have an effect on wind force and its movement pattern? If the answer is positive, what is its effect and which form is the most appropriate?

The authors assume that the presence of holes in the high building disturbs the wind movement pattern, and the smaller these holes are, the tunneling property of the wind and the wind speed increase. Also, it is expected that the wind speed will increase after entering the tunnels. As a result, it is more appropriate to place the openings at the beginning of the space tunnels due to the lower wind speed at the tunnels entrance. In addition, it is expected

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that the creation of semi-open spaces in high building's facade will disturb the wind speed and consequently reduce the wind speed. According to this assumption, the placement of openings inside the terraces brings the wind into the interior spaces at a lower speed than the facades without terraces.

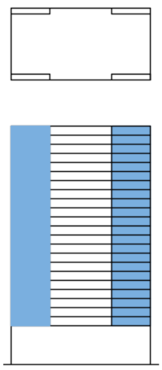
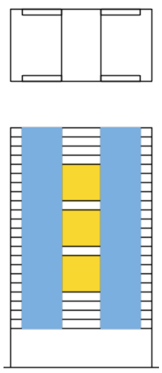
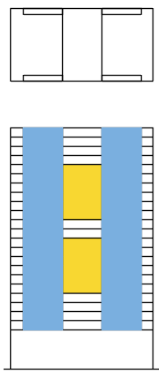
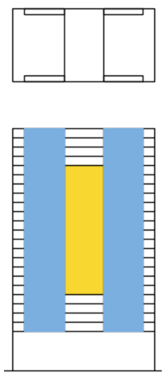
materials and methods

The main tools for urban body evaluating are field measurements, full-scale and reduced-scale laboratory measurements, and numerical simulation methods, including computational fluid dynamics. In this research, the modeling technique with the help of computational fluid dynamics has been used. So that, with field observations, the dominant form of high buildings in Mashhad has been identified, and based on library studies and research background, the investigated index in the research determined and finally the wind direction and speed in the studied area have been extracted as input data of the software. Software model validation has been done through comparison with field studies. For this purpose, the wind speed in the base building different floors has been extracted for comparison with the wind speed extracted from the software in the modeled base building, and finally, after verifying the software correctness, the form modeling has been done with the studied index. Therefore, the used method type is a quantitative method and combined modeling has been used in Mashhad city bed. The current research is placed in applied research category and its results can be used in the design of city development. In the modeling section, the Ansys Design Modeler environment for drawing the geometry, the ICEM environment for the network generation process (an organized network was used to generate it), the Fluent software from the Ansys Fluent family to solve the current field and the software CFD POST and Tecplot software are used to display the results.

Research index

The investigated index is the number and area of space opening, which all three forms, from the fifth to the eighteenth floor, have a volumetric opening, but the number of tunnels created in the facade varies from one to three. In fact, in the first model, a tunnel with a higher opening volume is compared with two other models that have two and three openings but with a smaller volume. In addition, the semi-open spaces (terraces) effect in the high buildings facade of (as a kind of space opening in the facade) on wind force is analyzed. In the following, in both space openings types, i.e. the tunnels in the form and the terraces in the facade, the locating site plot index of the openings, as the gate of the wind entering into the interior spaces, was investigated and the suitable places to the openings design is suggested.

Table1. Selected forms and number of openings (authors)

F_4	F_3	F_2	F_1	
				Forms
No spatial openness	Three openings from the fifth to eighth, tenth to thirteenth	Two openings from the fifth to the tenth and from the	One opening from the fifth to the	Location of space tunnels

F_4	F_3	F_2	F_1	
	and fifteenth to eighteenth floors	thirteenth to the eighteenth	eighteenth residential floor	

Research field

In the urban form modeling field, some researchers used hypothetical geometry (Huang & et al,2019. Wen & Malki Epshtein,2018. Noseka & et al,2018), reality-based geometry (Hassan & et al,2020.Gao & et al,2018.Shen & et al,2017.Karra & et al,2017.Eeftes & et al,2013), and a combination of both methods (Marulanda & et al,2020. Hadavi & Pasdarshahri,2019). In this research, a combined method was used. The investigated field in this article is located in the residential part of Mashhad city. For this purpose, a building with a total height of 92 m with 3 floors for public use and 22 residential floors (Baran Tower 3), in Koh Sangi region, in order to validate the software results by comparing the wind speed in different floors of Baran Tower (reality-based geometry), has been selected with the results of the building modeled in the software (hypothetical geometry). Other investigated models are based on hypothetical geometry, with the variable number of space openings in the high building form.

Model settings (climate data)

In this research, the data of Wind roses drawn at Iowa State University in 2022 have been used. According to the comprehensive report of environmental pollutants monitoring in Mashhad, the fine dust highest amount is related to the June and July months (Wind roses in July) that the highest wind speed is also recorded in this month. According to Wind roses in July 2022, two wind directions with an angle of 30 and 40 degrees, which have the highest frequency and the highest wind speed, have been considered. The average wind speed for these two directions is 12.96 miles per hour, equivalent to 5.8 meters per second. In addition, considering the frequency of winds in Wind roses of July, the wind angle of 34.7 degrees is considered as the wind flow average angle.

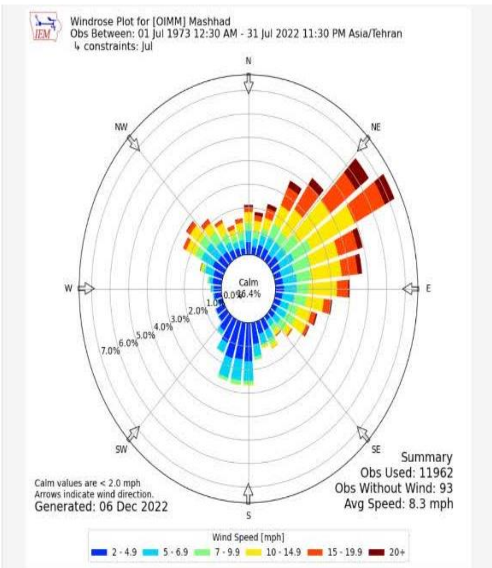


Figure1. Wind roses plot for Mashhad in July 2022

(https://mesonet.agron.iastate.edu/sites/windrose.phtml?station=OIMM&network=IR__ASOS)

Boundary conditions, reticulation and equations solution type

The size of the computational domain used for CFD analysis by considering the minimums mentioned in the studies as well as the model building dimensions (28 * 54 m with a height of 92 m) on one hand and the acceptable convergence of the results on the other hand, was determined. The geometry distance to the entrance boundary and side borders is 150 meters, to the exit boundary is 420 meters, and the height of the domain is 200 meters. CFD solution is also done in a three-dimensional domain.

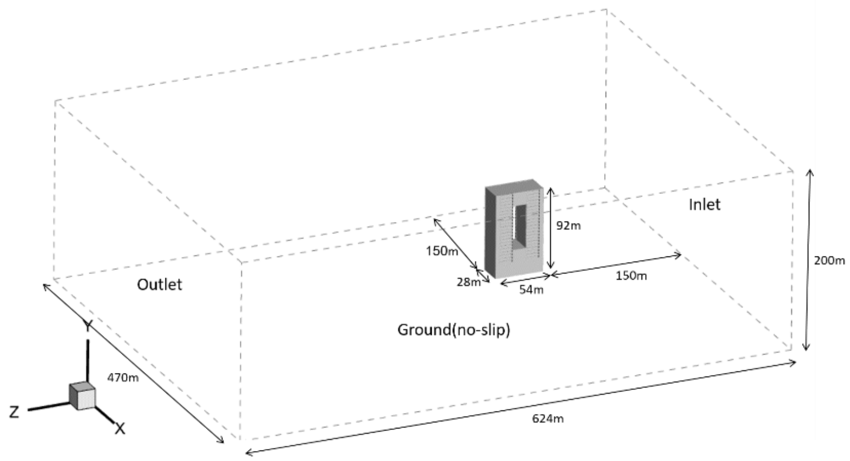


Figure2. Geometry modeled in F1 (authors)

Due to the incompressible flow, the solver type the base pressure has been considered. The solution of the flow has been done in a steady and K-Omega-SST model has been used to model the flow.

The inlet fluid is air, with an inlet velocity of 5.8 m/s, a density of 1.225 kg/m^3, and a viscosity of 1.7894*10^{-5}, in the form of UDF, which represents the effects of Ultrafine Depth Filtration on the velocity profile is considered.

The formula of wind speed vertical input profile u(z), turbulent kinetic energy k(z) and turbulence loss rate £ (z) is specified as follows.

$$u(z)=\frac{u^*}{K}.Ln(\frac{z+z0}{z0})$$

$$u^*=K.\frac{u_{ref}}{ln\,(\frac{H_{ref}+z0}{z0})}$$

$$k(z)=\frac{{u*}^2}{\sqrt{c_\mu}}$$

$$€(z)=\frac{{u^*}^3}{K(z+z0)}$$

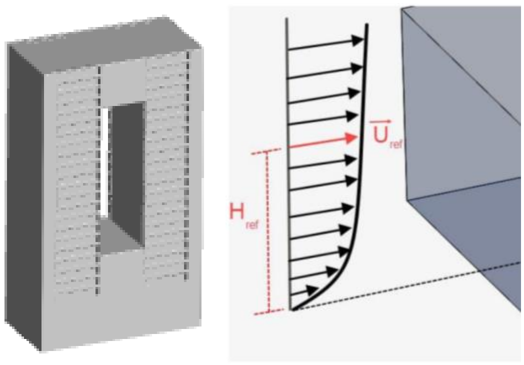


Figure3. Ultrafine depth filtration (authors)

The boundary of the surrounding walls mummy has a no-slip condition and includes the ground surface and all walls of the building. In order to connect velocity and pressure, a simple model has been used, and to discretize the equations of pressure, momentum, turbulent kinetic energy and specific loss rate, the second order upwind direction has been used. The Under-relaxetion have been used for pressure 0.3, for density 1, for momentum 0.7, for turbulent kinetic energy and specific loss rate 0.8, and for turbulent viscosity, a coefficient of 1 has been used. It should be noted that the convergence absolute criterion is considered 10^{-5} for all equations.

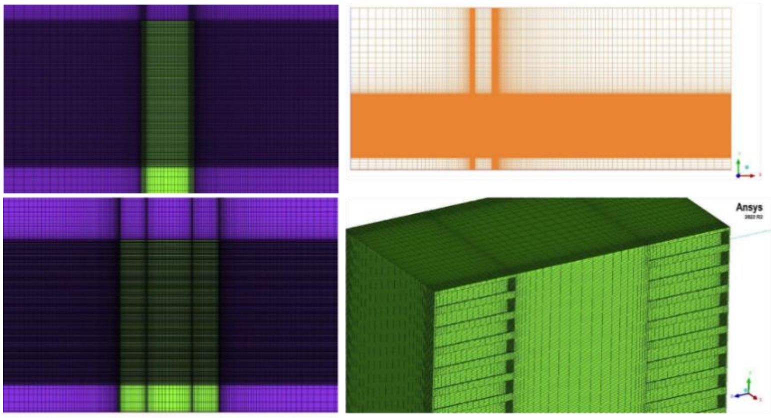


Figure4. Mesh of model F_1 (authors)

Validation

In this research, the field method was used to validate the software results. For this purpose, Wintek anemometer, model WT82, was used. For results with higher accuracy of field studies, on the first, fifteenth and thirtieth days of the month, at 18:00, the value of the wind velocity at a half a meter height from the floor and a distance of 20 cm from the terrace inner wall of floors 3, 6, 9, 12, 15, 18 and 21 have been extracted with the help of anemometer and finally the wind velocity graph on each day was compared with the wind velocity graph extracted from the software results (Fig. 5).

Table2. Comparison of wind speed in different floors in field studies and software studies (authors)

Floor	Height (m)	wind speed (m/s) (Extracted from the software with input speed of 5/8 m/s)	wind speed (m/s) (The first day of the month with input speed of 2.2 m/s)	wind speed (m/s) (The 15th day of the month with input speed of 3/5 m/s)	wind speed (m/s) (The 30th day of the month with input speed of 2.8 m/s)
third floor	26	1/81	0/7	1/07	0/87
sixth floor	36/5	1/88	0/71	1/13	0/9
ninth floor	47	1/85	0/71	1/13	0/89
12th floor	57/5	1/90	0/73	1/15	0/93
15th floor	68	1/96	0/74	1/19	0/95
18th floor	78/5	2/23	0/85	1/38	1/1
21th floor	89	2/48	0/95	1/6	1/2

It is clear that in the simulation research method, due to the complexity of the calculations, some variables are considered constant or are ignored. Therefore, the results obtained from the numerical simulation method and the field method do not completely coincide with each other, but with a certain error percentage, a clear relationship can be found between their results.

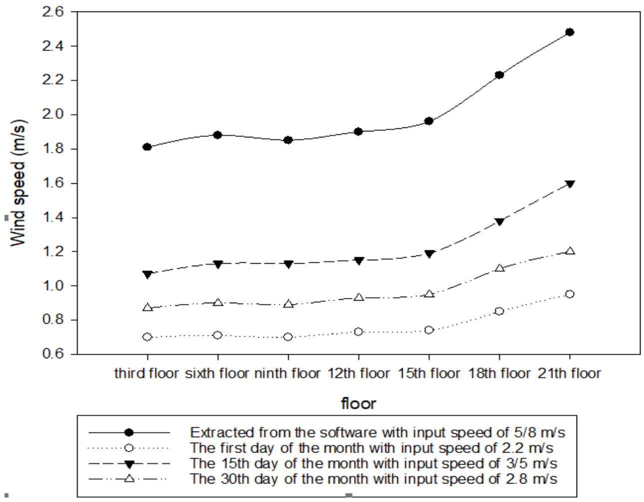


Figure5. Comparison of software results with field studies (authors)

According to the above diagram, the general increasing wind speed trend with increasing height, in two methods of software studies and field studies, are largely consistent. The velocity increased on to the 15th floor gradually, but in higher floors, the increase in height has a greater effect on the wind speed.

Research findings

Wind flow analysis in high building forms (tunnels)

As shown in Fig.10, the wind velocity increases at the facade tunnels entrance, and the amount of this increase has a direct relationship with the tunnels dimensions, and the smaller the tunnels, the lower is the wind speed increasing rate. Inside the tunnels, almost the same behavior of wind movement occurs, so that the wind velocity at the top and bottom of the tunnel vertical range and close to the ceiling and floor walls (completely attached to the walls) reaches to maximum and then at a third of the top and bottom reaches to its minimum amount and the speed increases again in the middle of the tunnel (the speed at the top is lower than at the bottom (except F1)). The lower the number of tunnels, the speed reduction occurs less in the upper third, and the highest velocity reduction in the upper half of each tunnel is related to F3.

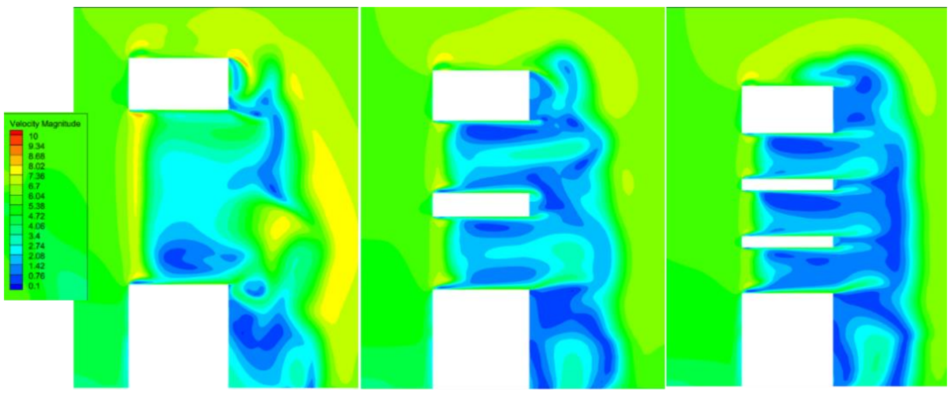


Figure6. Vertical contour (transverse) from the middle of tunnels (authors)

In addition, the wind speed at the tunnel inlet is higher than at one in the outlet. In fact, in all forms (except F1), the lowest wind speed is in the third close to the roof of the tunnel, then in the third close to its bottom, and then in the middle of the tunnel, and finally, the highest wind speed is at its entrance, and the smaller the tunnels and their number are low, the wind speed is lower compared to the bigger tunnel. Obviously, in a longitudinal cross-section of the building, in comparison between the two vertical walls of the tunnel, the wind speed near the leeward wall is lower than the windward exposure wall. In fact, according to the longitudinal section, the wind speed has reached the maximum in the last third windward exposure, and this maximum speed decreases as the tunnels become smaller.

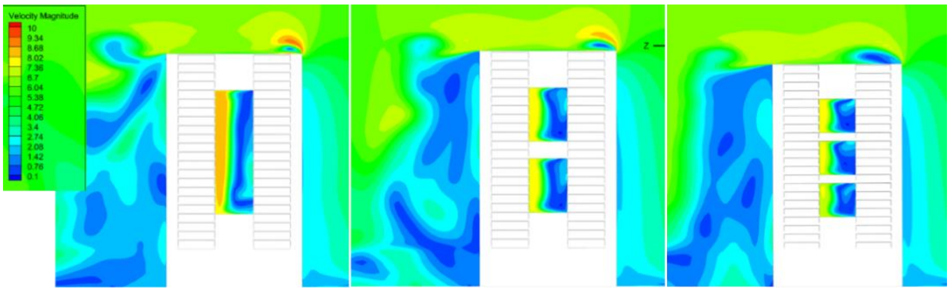


Figure7. Vertical contour (longitudinal) from the middle of tunnels (authors)

The wind speed inside the tunnel is more affected by the dimensions and shape of the tunnel than it changes induced from the height, and it is not possible to compare the wind speed in different floors and heights (variable height examination) inside the tunnel, and it is better to examine the effect of the height in another research, in a simpler form, but in general, with the increase in altitude, the wind speed increases.

In Fig. 12, a section of the end floors and the roof of a high building is shown, which indicates that in the forms with more tunnels and smaller size (F2, F3 and F1, respectively), the wind speed decreases in a wider domain of the roof. In fact, in the F3 form, at a higher level of the roof, we see the wind blowing with a lower speed.

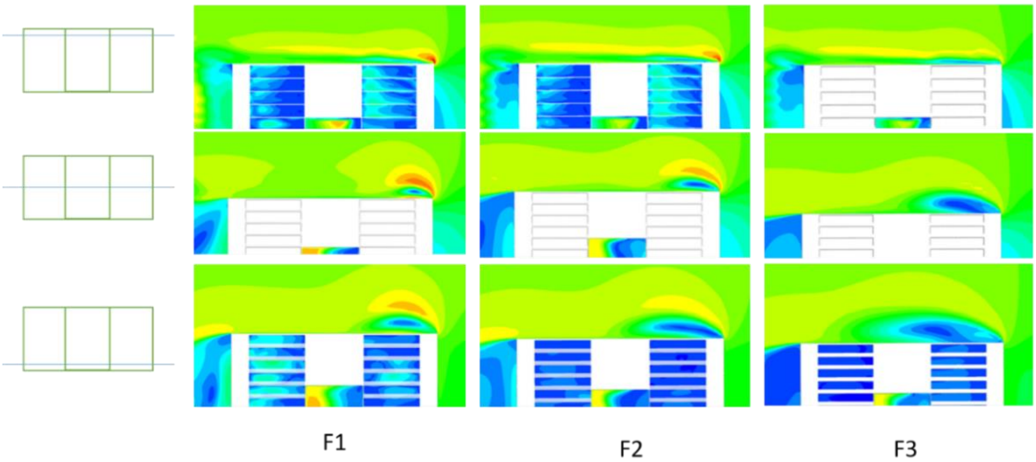


Figure8. Comparison of wind behavior on the roof of a tall building (authors)

Comparing the forms with openings to the base form (without openings), the wind behavior around the facade is comparable. So that, in the basic form, the wind speed in the windward exposure facade is lower than in other forms, and in the leeward facade, the wind speed is higher than the forms F1, F2, and F3 walls, and the maximum speed is in the middle floors. In fact, the presence of an opening in the facade reduces the wind speed in the leeward facade, as well as the roof of the high building, and these openings have a more uniform behavior of the wind flow on the leeward facade.

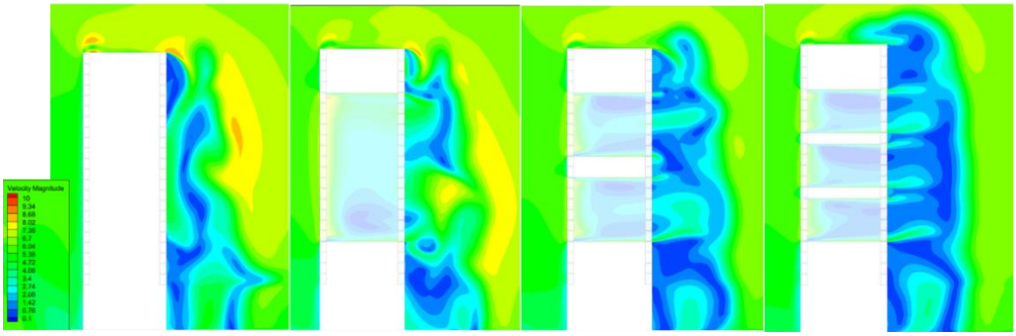
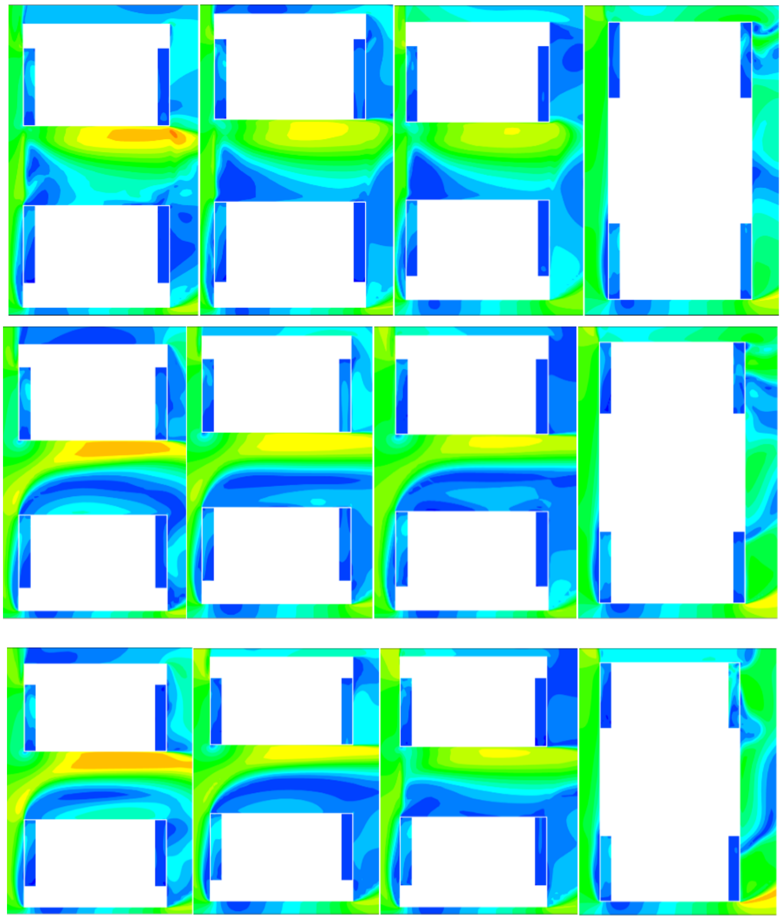


Figure9. Comparison of wind behavior in F1, F2, F3 and F4 (authors)

Analysis of wind flow in high building forms (terraces)

In general, in facades with terraces, the wind speed decreases near the terraces and then inside the terraces, compared to the vertical walls of the facade.



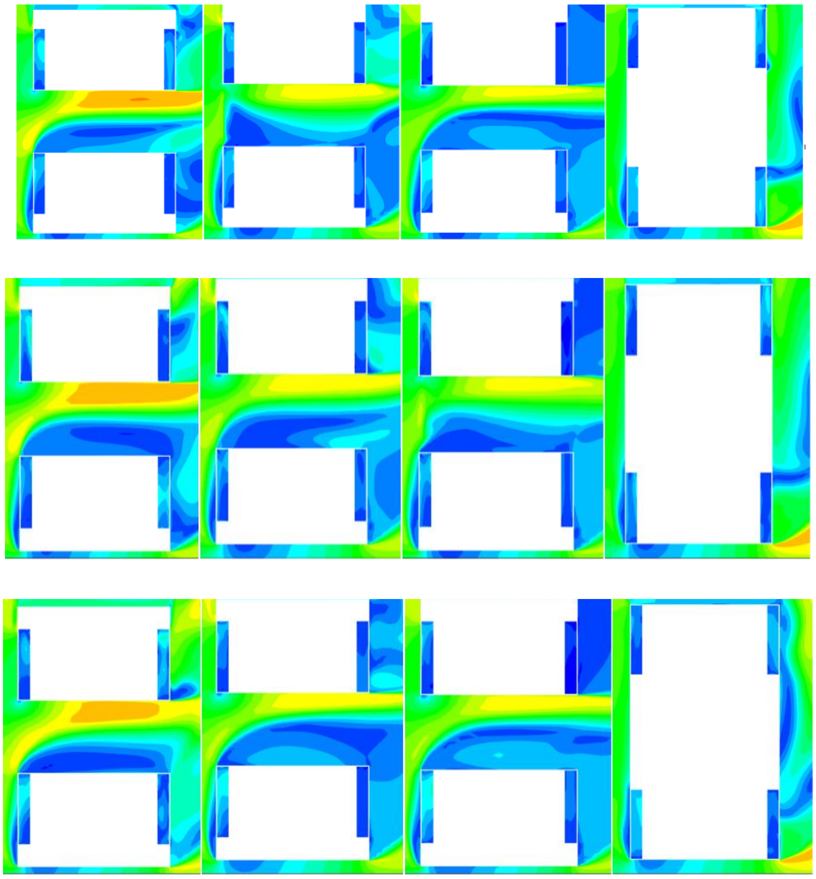


Figure10. Comparison of wind flow in terraces, in four forms in height codes of 29.5, 40, 47, 57.5, 64.5 and 70 meters, from top to bottom (authors)

As it is clear in the above picture, in general, in the leeward front terraces, the wind speed in the forms with openings is lower than the F4 form (without openings). Especially, as the number of facade tunnels increases, the reduction in speed in the leeward front terraces is more noticeable (F3 has the most relax leeward terrace at all heights). Regarding the terraces located on the windward exposure front, in the terraces before the facade tunnels, there is also a different behavior compared to the terraces after the tunnels, and in general, it can be concluded that the presence of openings in the facade reduces the wind speed in the terraces located before the openings to a very small extent, but increases the wind speed in the terraces located after the openings, which of course, the speed increase rate in these terraces in F3 is less than F2 and less than F1. In general, it can be concluded that the presence of a tunnel in the volume decreases the wind speed in the leeward terraces and increases the wind speed in the windward exposure terraces. The number of tunnels has an inverse relation.

Tables 3, 4 and 5 provided in the appendix, the behavior of the wind in the investigated models is given numerically on three separate pages. These three planes are: a plane at a distance of half a meter from the windward exposure wall inside the tunnel (z=34), the middle plane of the tunnel (z=27) and a plane at a distance of half a meter from the leeward wall inside the tunnel (z=20). The wind speed value, in each plane, on the three axes ; of the tunnel beginning of (x=4.66), of the tunnel middle (x=14) and of the tunnel outlet (x=23.34), has been extracted in ten height codes. The results presented in the appendix are comparable in 9 charts for three forms F1, F2 and F3.

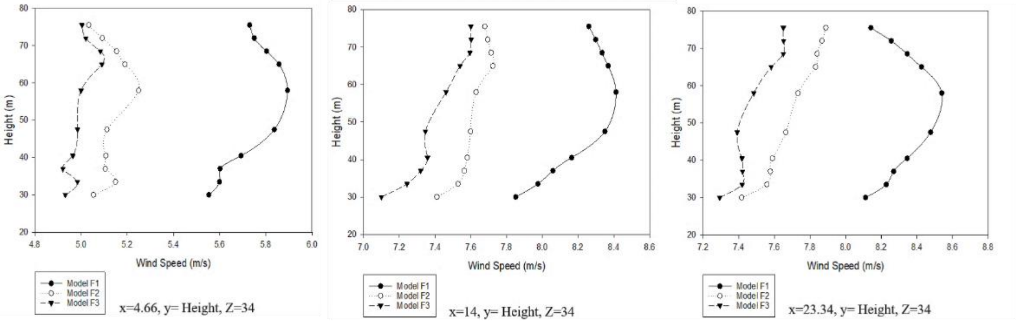


Figure11. Comparison of wind speed at a distance of half a meter from the wall facing the wind, inside tunnels (z=34), from a height of 30 meters to 75.5 meters, in three positions, the entrance of the tunnel (x=4.66), the middle of the tunnel (x=14)) and the exit of the tunnel (x=23.34) for volumes F1, F2 and F3 (authors)

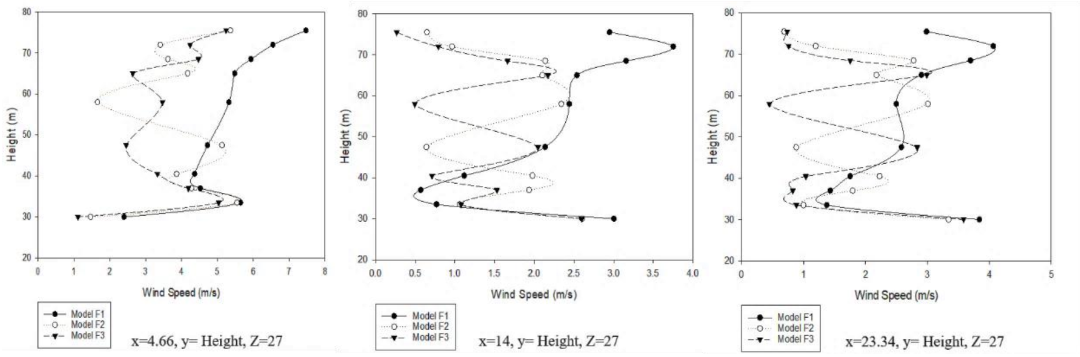


Figure12. Comparison of wind speed in the middle of tunnels (z=27), from a height of 30 meters to 75.5 meters, in three positions, the entrance of tunnel entrance (x=4.66),the middle of tunnel (x=14) and the exit of tunnel (x=23.34) For volumes F1, F2 and F3 (authors)

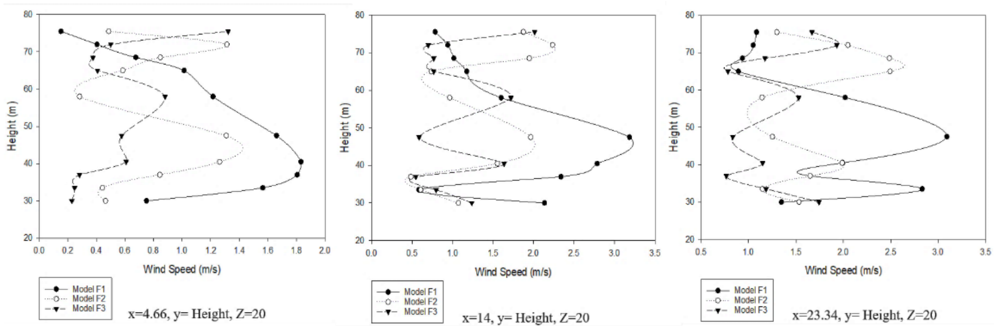


Figure13. Comparison of wind speed at a distance of half a meter from the hidden wall from the wind in tunnels (z=20), from a height of 30 meters to 75.5 meters, in three positions, the entrance of tunnel (x=4.66), the middle of the tunnel (x=14) and the exit of the tunnel (x=23.34) for volumes F1, F2 and F3 (authors)

From the comparison of the graphs drawn in Fig. 14, it is clear that the wind speed in the windward exposure wall inside the tunnel decreases with the increasing in the number of tunnels. In general, in this plane position, the speed in the middle of the tunnels (middle floors) increases in all three forms, and due to the higher overall height of the tunnel in the F1 volume, the change in wind speed occurs more in this form. In fact, the velocity in the middle of the tunnel increases more in this form than in other forms. In form F2 and F3, the wind speed increases with increasing height inside the tunnel, according to a specific pattern, although the speed increase is slightly higher in the middle of the tunnels. But in the F1 form, the highest speed in terms of height is in the middle of the tunnel, and the as we get closer to the roof and floor of the tunnel, the speed decreases again. From the comparison of Figs 15 and 16, it can be observed that the relationship between the number and dimensions of the tunnels, the increase in height and wind speed, is not simple as the movement pattern of the wind in the wind ward exposure plane and is complex. In general, in the middle of the tunnel, the highest wind speed corresponds to the F1 form, although this trend does not remain constant for the entire height of the tunnel, and at its highest height, at all points, the lowest wind speed is related to this form. In addition, one can conclude that in the middle of the tunnel, like the windward exposure plane, the wind speed increases with the increase in height, but under the influence of the floor walls and roof of the tunnels, the speed decreases and again, by getting away from the floor and ceiling of the tunnel it increases. Likewise, the closer we get to the depth of the tunnels, the wind speed increases in all forms.

Regarding the leeward plane (safe region), the highest speed in all forms is related to the tunnel entrance, and after that the speed decreases until it increases about 0.5 m/s at the outlet. In this plane, the relationship between the increase in height and the increase in wind speed is similar to the tunnel middle plane of.

Conclusion

The current study investigates the condition of wind flow in incidence with a high building, with a space opening form and variable dimensions and openings number. This study predicted wind behavior with the K-Omega-SST turbulence model and the results were extracted numerically, graphically and diagrammatically.

The significant results of the current study are summarized as follows:

- The wind speed at the tunnels inlet is higher than the middle and outlet of them, but the more the number of tunnels and the smaller the volume is, the increase in wind speed at the tunnel inlet is lower and the wind behavior in the entire tunnel area is more uniform.
- The wind speed in the third of the tunnel volume, which is windward exposure, is in the highest possible position, as a result, the openings localization in the leeward wall is better than the windward exposure wall.
- In the leeward wall, the wind speed is the lowest in the vertical middle of the wall, so it is the most suitable part for localizing openings.
- Wind speed is the lowest in the first third of the windward exposure wall, and if having to design openings in the windward exposure wall, the most appropriate part is the first vertical third of the tunnel.
- With increasing in the number of tunnels, the increase in wind speed becomes independent of the tunnels number and the wind speed increases under the height influence. As a result, in the form with more opening numbers, it is more appropriate to localize the windows at a lower height of each tunnel, but in the form with less space opening (F1), the upper third and the lower third of the tunnel is the most suitable place to localize the openings.
- The presence of space opening in the form reduces the wind speed in the leeward facade and the roof of high building and creates a more uniform behavior of the wind flow in this facade.
- Comparing the facade with semi-open spaces (terrace) and the facade without semi-open spaces, the presence of terraces reduces the wind speed in the facade, and the localization of openings inside the terraces is more suitable than the facade without a terrace.
- The presence of space openings in the volume reduces the wind speed in the leeward terraces, and the greater the number of space openings, the greater the speed reduction (F3, the most relax terraces in the leeward wall).

- Regarding the windward exposure facade in the examined forms, the presence of space openings slightly reduces the wind speed in the terraces located before the tunnels, but increases the wind speed in the terraces located after the tunnels. The more tunnels, the condition of the terraces located after the tunnel becomes better and the wind speed in them becomes lower. As a result, if there is a space opening in the form, it is more appropriate to localize terraces and openings in the walls before the space openings, and if having to design openings and terraces in the walls after the openings, the form with more space opening number (F3) is more suitable.

the attachment

table3. Wind speed (m/S) at a height of one meter from the floor of each floor in the F1, for three positions at a distance of half a meter from the wall facing the wind, in the middle of the tunnels and at a distance of half a meter from the wall hidden from the wind (authors)

Model	Coordinates	Wind Speed	Coordinates	Wind Speed	Coordinates	Wind Speed
Model F1(The page facing the wind)	(x=4.66, z=34, y=30)	5.553	(x=14, z=34, y=30)	7.851	(x=23.34, z=34, y=30)	8.112
	(x=4.66, z=34, y=33.5)	5.600	(x=14, z=34, y=33.5)	7.975	(x=23.34, z=34, y=33.5)	8.228
	(x=4.66, z=34, y=37)	5.602	(x=14, z=34, y=37)	8.059	(x=23.34, z=34, y=37)	8.269
	(x=4.66, z=34, y=40.5)	5.693	(x=14, z=34, y=40.5)	8.164	(x=23.34, z=34, y=40.5)	8.345
	(x=4.66, z=34, y=47.5)	5.837	(x=14, z=34, y=47.5)	8.351	(x=23.34, z=34, y=47.5)	8.477
	(x=4.66, z=34, y=58)	5.894	(x=14, z=34, y=58)	8.412	(x=23.34, z=34, y=58)	8.540
	(x=4.66, z=34, y=65)	5.857	(x=14, z=34, y=65)	8.368	(x=23.34, z=34, y=65)	8.426
	(x=4.66, z=34, y=68.5)	5.803	(x=14, z=34, y=68.5)	8.334	(x=23.34, z=34, y=68.5)	8.346
	(x=4.66, z=34, y=72)	5.750	(x=14, z=34, y=72)	8.298	(x=23.34, z=34, y=72)	8.256
	(x=4.66, z=34, y=75.5)	5.730	(x=14, z=34, y=75.5)	8.260	(x=23.34, z=34, y=75.5)	8.141
Model F1(Middle plate of the opening)	(x=4.66, z=27, y=30)	2.395	(x=14, z=27, y=30)	3.004	(x=23.34, z=27, y=30)	3.837
	(x=4.66, z=27, y=33.5)	5.644	(x=14, z=27, y=33.5)	0.769	(x=23.34, z=27, y=33.5)	1.373
	(x=4.66, z=27, y=37)	4.523	(x=14, z=27, y=37)	0.570	(x=23.34, z=27, y=37)	1.429
	(x=4.66, z=27, y=40.5)	4.363	(x=14, z=27, y=40.5)	1.118	(x=23.34, z=27, y=40.5)	1.751

Model	Coordinates	Wind Speed	Coordinates	Wind Speed	Coordinates	Wind Speed
	(x=4.66, z=27, y=47.5)	4.724	(x=14, z=27, y=47.5)	2.137	(x=23.34, z=27, y=47.5)	2.578
	(x=4.66, z=27, y=58)	5.320	(x=14, z=27, y=58)	2.442	(x=23.34, z=27, y=58)	2.496
	(x=4.66, z=27, y=65)	5.482	(x=14, z=27, y=65)	2.539	(x=23.34, z=27, y=65)	2.902
	(x=4.66, z=27, y=68.5)	5.934	(x=14, z=27, y=68.5)	3.158	(x=23.34, z=27, y=68.5)	3.695
	(x=4.66, z=27, y=72)	6.547	(x=14, z=27, y=72)	3.752	(x=23.34, z=27, y=72)	4.062
	(x=4.66, z=27, y=75.5)	7.467	(x=14, z=27, y=75.5)	2.950	(x=23.34, z=27, y=75.5)	2.984
Model F1(The page hidden from the wind)	(x=4.66, z=20, y=30)	0.750	(x=14, z=20, y=30)	2.136	(x=23.34, z=20, y=30)	1.347
	(x=4.66, z=20, y=33.5)	1.565	(x=14, z=20, y=33.5)	0.585	(x=23.34, z=20, y=33.5)	2.830
	(x=4.66, z=20, y=37)	1.805	(x=14, z=20, y=37)	2.339	(x=23.34, z=20, y=37)	1.650
	(x=4.66, z=20, y=40.5)	1.832	(x=14, z=20, y=40.5)	2.784	(x=23.34, z=20, y=40.5)	1.992
	(x=4.66, z=20, y=47.5)	1.661	(x=14, z=20, y=47.5)	3.184	(x=23.34, z=20, y=47.5)	3.090
	(x=4.66, z=20, y=58)	1.216	(x=14, z=20, y=58)	1.600	(x=23.34, z=20, y=58)	2.018
	(x=4.66, z=20, y=65)	1.013	(x=14, z=20, y=65)	1.174	(x=23.34, z=20, y=65)	0.893
	(x=4.66, z=20, y=68.5)	0.675	(x=14, z=20, y=68.5)	1.016	(x=23.34, z=20, y=68.5)	0.936
	(x=4.66, z=20, y=72)	0.403	(x=14, z=20, y=72)	0.942	(x=23.34, z=20, y=72)	1.050
	(x=4.66, z=20, y=75.5)	0.151	(x=14, z=20, y=75.5)	0.786	(x=23.34, z=20, y=75.5)	1.085

Table4. Wind speed (m/S) at a height of one meter from the floor of each floor in the F2, for three positions at a distance of half a meter from the wall facing the wind, in the middle of the tunnels and at a distance of half a meter from the wall hidden from the wind (authors)

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Model	Coordinates	Wind Speed	Coordinates	Wind Speed	Coordinates	Wind Speed
Model F2(The page facing the wind)	(x=4.66, z=34, y=30)	5.054	(x=14, z=34, y=30)	7.409	(x=23.34, z=34, y=30)	7.416
	(x=4.66, z=34, y=33.5)	5.149	(x=14, z=34, y=33.5)	7.528	(x=23.34, z=34, y=33.5)	7.558
	(x=4.66, z=34, y=37)	5.105	(x=14, z=34, y=37)	7.563	(x=23.34, z=34, y=37)	7.577
	(x=4.66, z=34, y=40.5)	5.107	(x=14, z=34, y=40.5)	7.579	(x=23.34, z=34, y=40.5)	7.589
	(x=4.66, z=34, y=47.5)	5.112	(x=14, z=34, y=47.5)	7.598	(x=23.34, z=34, y=47.5)	7.664
	(x=4.66, z=34, y=58)	5.249	(x=14, z=34, y=58)	7.629	(x=23.34, z=34, y=58)	7.732
	(x=4.66, z=34, y=65)	5.190	(x=14, z=34, y=65)	7.723	(x=23.34, z=34, y=65)	7.831
	(x=4.66, z=34, y=68.5)	5.154	(x=14, z=34, y=68.5)	7.713	(x=23.34, z=34, y=68.5)	7.840
	(x=4.66, z=34, y=72)	5.092	(x=14, z=34, y=72)	7.694	(x=23.34, z=34, y=72)	7.867
	(x=4.66, z=34, y=75.5)	5.033	(x=14, z=34, y=75.5)	7.678	(x=23.34, z=34, y=75.5)	7.889
Model F2(Middle plate of the opening)	(x=4.66, z=27, y=30)	1.461	(x=14, z=27, y=30)	2.603	(x=23.34, z=27, y=30)	3.340
	(x=4.66, z=27, y=33.5)	5.544	(x=14, z=27, y=33.5)	1.061	(x=23.34, z=27, y=33.5)	0.996
	(x=4.66, z=27, y=37)	4.282	(x=14, z=27, y=37)	1.937	(x=23.34, z=27, y=37)	1.792
	(x=4.66, z=27, y=40.5)	3.862	(x=14, z=27, y=40.5)	1.977	(x=23.34, z=27, y=40.5)	2.225
	(x=4.66, z=27, y=47.5)	5.129	(x=14, z=27, y=47.5)	0.642	(x=23.34, z=27, y=47.5)	0.879
	(x=4.66, z=27, y=58)	1.652	(x=14, z=27, y=58)	2.343	(x=23.34, z=27, y=58)	3.007
	(x=4.66, z=27, y=65)	4.170	(x=14, z=27, y=65)	2.103	(x=23.34, z=27, y=65)	2.176
	(x=4.66, z=27, y=68.5)	3.620	(x=14, z=27, y=68.5)	2.140	(x=23.34, z=27, y=68.5)	2.774

Model	Coordinates	Wind Speed	Coordinates	Wind Speed	Coordinates	Wind Speed
	(x=4.66, z=27, y=72)	3.411	(x=14, z=27, y=72)	0.966	(x=23.34, z=27, y=72)	1.195
	(x=4.66, z=27, y=75.5)	5.359	(x=14, z=27, y=75.5)	0.648	(x=23.34, z=27, y=75.5)	0.684
Model F2(The page hidden from the wind)	(x=4.66, z=20, y=30)	0.463	(x=14, z=20, y=30)	1.072	(x=23.34, z=20, y=30)	1.533
	(x=4.66, z=20, y=33.5)	0.441	(x=14, z=20, y=33.5)	0.607	(x=23.34, z=20, y=33.5)	1.147
	(x=4.66, z=20, y=37)	0.843	(x=14, z=20, y=37)	0.485	(x=23.34, z=20, y=37)	1.649
	(x=4.66, z=20, y=40.5)	1.262	(x=14, z=20, y=40.5)	1.553	(x=23.34, z=20, y=40.5)	1.987
	(x=4.66, z=20, y=47.5)	1.309	(x=14, z=20, y=47.5)	1.965	(x=23.34, z=20, y=47.5)	1.251
	(x=4.66, z=20, y=58)	0.281	(x=14, z=20, y=58)	0.965	(x=23.34, z=20, y=58)	1.142
	(x=4.66, z=20, y=65)	0.584	(x=14, z=20, y=65)	0.736	(x=23.34, z=20, y=65)	2.492
	(x=4.66, z=20, y=68.5)	0.847	(x=14, z=20, y=68.5)	1.948	(x=23.34, z=20, y=68.5)	2.485
	(x=4.66, z=20, y=72)	1.313	(x=14, z=20, y=72)	2.235	(x=23.34, z=20, y=72)	2.047
	(x=4.66, z=20, y=75.5)	0.485	(x=14, z=20, y=75.5)	1.875	(x=23.34, z=20, y=75.5)	1.299

Table5. Wind speed (m/S) at a height of one meter from the floor of each floor in the F3, for three positions at a distance of half a meter from the wall facing the wind, in the middle of the tunnels and at a distance of half a meter from the wall hidden from the wind (authors)

Model	Coordinates	Wind Speed	Coordinates	Wind Speed	Coordinates	Wind Speed
Model F3(The page facing the wind)	(x=4.66, z=34, y=30)	4.932	(x=14, z=34, y=30)	7.099	(x=23.34, z=34, y=30)	7.293
	(x=4.66, z=34, y=33.5)	4.984	(x=14, z=34, y=33.5)	7.242	(x=23.34, z=34, y=33.5)	7.419
	(x=4.66, z=34, y=37)	4.921	(x=14, z=34, y=37)	7.319	(x=23.34, z=34, y=37)	7.421
	(x=4.66, z=34, y=40.5)	4.964	(x=14, z=34, y=40.5)	7.357	(x=23.34, z=34, y=40.5)	7.418

	(x=4.66, z=34, y=47.5)	4.985	(x=14, z=34, y=47.5)	7.345	(x=23.34, z=34, y=47.5)	7.391
	(x=4.66, z=34, y=58)	5.00	(x=14, z=34, y=58)	7.461	(x=23.34, z=34, y=58)	7.484
	(x=4.66, z=34, y=65)	5.090	(x=14, z=34, y=65)	7.539	(x=23.34, z=34, y=65)	7.582
	(x=4.66, z=34, y=68.5)	5.084	(x=14, z=34, y=68.5)	7.594	(x=23.34, z=34, y=68.5)	7.650
	(x=4.66, z=34, y=72)	5.021	(x=14, z=34, y=72)	7.601	(x=23.34, z=34, y=72)	7.652
	(x=4.66, z=34, y=75.5)	5.004	(x=14, z=34, y=75.5)	7.600	(x=23.34, z=34, y=75.5)	7.650
Model F3(Middle plate of the opening)	(x=4.66, z=27, y=30)	1.108	(x=14, z=27, y=30)	2.598	(x=23.34, z=27, y=30)	3.583
	(x=4.66, z=27, y=33.5)	5.034	(x=14, z=27, y=33.5)	1.078	(x=23.34, z=27, y=33.5)	0.881
	(x=4.66, z=27, y=37)	4.188	(x=14, z=27, y=37)	1.531	(x=23.34, z=27, y=37)	0.825
	(x=4.66, z=27, y=40.5)	3.326	(x=14, z=27, y=40.5)	0.712	(x=23.34, z=27, y=40.5)	1.036
	(x=4.66, z=27, y=47.5)	2.454	(x=14, z=27, y=47.5)	2.048	(x=23.34, z=27, y=47.5)	2.834
	(x=4.66, z=27, y=58)	3.466	(x=14, z=27, y=58)	0.496	(x=23.34, z=27, y=58)	0.447
	(x=4.66, z=27, y=65)	2.637	(x=14, z=27, y=65)	2.173	(x=23.34, z=27, y=65)	2.989
	(x=4.66, z=27, y=68.5)	4.470	(x=14, z=27, y=68.5)	1.664	(x=23.34, z=27, y=68.5)	1.751
	(x=4.66, z=27, y=72)	4.238	(x=14, z=27, y=72)	0.793	(x=23.34, z=27, y=72)	0.760
	(x=4.66, z=27, y=75.5)	5.243	(x=14, z=27, y=75.5)	0.268	(x=23.34, z=27, y=75.5)	0.733
	(x=4.66, z=20, y=30)	0.227	(x=14, z=20, y=30)	1.238	(x=23.34, z=20, y=30)	1.743
	(x=4.66, z=20, y=33.5)	0.246	(x=14, z=20, y=33.5)	0.796	(x=23.34, z=20, y=33.5)	1.184
	(x=4.66, z=20, y=37)	0.281	(x=14, z=20, y=37)	0.546	(x=23.34, z=20, y=37)	0.766
	(x=4.66, z=20, y=40.5)	0.607	(x=14, z=20, y=40.5)	1.637	(x=23.34, z=20, y=40.5)	1.148

Model F3(The page hidden from the wind)	(x=4.66, y=47.5)	z=20,	0.575	(x=14, y=47.5)	z=20,	0.587	(x=23.34, y=47.5)	z=20,	0.833
	(x=4.66, y=58)	z=20,	0.880	(x=14, y=58)	z=20,	1.721	(x=23.34, y=58)	z=20,	1.529
	(x=4.66, y=65)	z=20,	0.407	(x=14, y=65)	z=20,	0.768	(x=23.34, y=65)	z=20,	0.784
	(x=4.66, y=68.5)	z=20,	0.375	(x=14, y=68.5)	z=20,	0.768	(x=23.34, y=68.5)	z=20,	1.173
	(x=4.66, y=72)	z=20,	0.499	(x=14, y=72)	z=20,	0.702	(x=23.34, y=72)	z=20,	1.930
	(x=4.66, y=75.5)	z=20,	1.321	(x=14, y=75.5)	z=20,	2.012	(x=23.34, y=75.5)	z=20,	1.669

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