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Evaluation of wind comfort with computational fluid dynamics simulations for pedestrian sidewalks around buildings

Alper Aydemir*, **Fikriye Ezgi Karahüseyin**, and **Yaşar Can Yılmaz**

Nuh Naci Yazgan University, Engineering Faculty
Civil Engineering Department
Nuh Naci Yazgan University Campus Kocasinan,
38050 Kayseri, Turkey

**Corresponding author E-mail: aydemir@nny.edu.tr*

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Abstract— Wind power could be one of the most clean and powerful renewable resources for electrical energy production, but on the other hand, uncontrolled wind flow especially in urban places could cause undesired situations as damage to buildings, decrease in pedestrian comfort, environmental damage, or even life loss. Construction of high-rise buildings, widely spread structures within cities, and environmental changes forces, engineers to find quick, reliable, and also economically viable solutions during design stages, but wind comfort of sidewalks generally not considered enough even if they are located in crowded areas. The web-based computer aided engineering (CAE) program named Simscale which runs on the basis of sophisticated graphical interface was used as computational fluid dynamics (CFD) software to determine wind speeds under influence of buildings in the Nuh Naci Yazgan University campus. Also, field measurements carried out in campus area for a short term period were compared with long term hourly wind speed data obtained from the Turkish State Meteorological Service (MGM) station located in Kayseri to identify most optimal wind speed data for the research area. Results of analysis showed that wind speed increased in the mostly used paths of campus, which means that the layout of buildings negatively affected the wind comfort. CFD analysis softwares could be used to determine the possible consquences of wind with less economic investment in a short time, and they could be used in accordance with comfort criterias as well as safety regulations.

Key-words: wind, pedestrian wind comfort, wind analysis, computational fluid dynamics

1. Introduction

Wind is defined as a weather event that is determined in relation to the earth, generally it develops horizontally and has environmental effects (MGM, 2021). Wind direction and speed stand out as important determining criteria. Measurements related to wind gain importance, especially when investigating its effect on different surfaces. Although earth winds can be measured at different heights, measurements made 10 meters above the earth are used as reference data.

Wind power could be one of the most clean and powerful renewable resources for electricity production, but uncontrolled wind flows around urban places could cause undesired situations such as damage to buildings, pedestrian comfort loss, environmental damage, or even life loss. Also, effects of wind around sidewalks generally not considered enough by engineers, so pedestrian wind comfort is one of the important subjects especially for the last years. The computational fluid dynamics programs, experimental studies generally made in wind tunnels, and field measurements are most common solutions to overcome this wind effect problem.

The wind tunnel testing, the techniques of computational fluid dynamics (CFD) have also been increasingly exploited by academic researchers and industrial practitioners in various ways (*Hu* and *Wang*, 2005). Buildings or obstacles around buildings could be well modeled with CFD, as well as parts or elements of structures could be modeled in the same manner. For example, wind loads on solar photovoltaic collectors can be modeled by using both CFD and wind tunnel experiments with smoke visualization observations (*Meroney* and *Neff,* 2010). Obstacles such as trees around pedestrian roads were also examined, and numerical results with field measurements of wind velocity and turbulent energy around trees were compared (*Mochida et al*., 2008). There are many studies in literature for both experimental and CFD analyses, while comparison studies show good correlation, so in some cases solely CFD analysis could be used to define wind analysis. The Architectural Institute of Japan (AIJ) conducted experiments on high-rise buildings and compared findings with CFD results obtained by the ANSYS Fluent software, and results that show the simulation by all two-equation turbulence models have good agreement with experimental results (*Behrouzi et al*., 2013). However, the complexity of the investigated problem effects the accuracy of results. For example, results of a study showed that the CFD model underestimated the pollutant concentrations on the leeward (also overestimated on windward) walls inside the street canyon in the presence of trees, while the simulated pattern and magnitude of pollutant dispersion were similar to those in the wind-tunnel measurements (*Kang et al*., 2017). Another study focused on the influence of an upstream building on a downstream target building. When the interfering building is located downstream of the target building, it may strengthen the leeward reverse flow of the target building, which may induce higher pollutants re-enter ration on the leeward side of the target building (*Cui et al.*, 2016).

Main constraints for wind studies especially for the one such as pedestrian comfort are high-cost of analysis and time-consuming wind flow analysis processes. Developments in technology lead new solutions for wind-based researches. Computational fluid dynamics (CFD) analysis programs are the most suitable ways for wind flow simulations, because they are relatively low-cost compared to wind tunnel experiments and need less time depending on computational hardware. Technological developments lead to faster computers as well as to online based CFD softwares running on online servers, which allow users to reach projects from all over the world by using internet. Investigations of the urban flow in a complex morphological street network that is coincidentally similar to the ancient Algeria city Ghardaïa were investigated, and a CFD model was suggested to simulate the air flow behavior in this urban area (*Houda et al.*, 2012). High wind speed condition simulations with 3D steady RANS and the realizable k–ε model for 12 wind directions with surface roughness parameterization and specification were performed. The simulation results of mean wind speed and wind direction are generally within 10–20% of the corresponding measurement values (*Blocken et. al.*, 2015). Wind studies about pedestrian comfort include three aspects: (1) statistical meteorological data, (2) aerodynamic information, and (3) a comfort criterion (*Blocken* and *Persoon*, 2009). Another study investigated turbulent flow fields over two typical urban elements, a row of trees with low packing density and an isolated building with high packing density with a modified k - ε model and a large eddy simulation (LES) model (*Qi* and *Ishihara*, 2018).

Urban areas should be designed to ensure the comfort, health, and safety for inhabitants and users around them, so this makes wind comfort and wind safety for pedestrians as an important requirement for urban areas (*Blocken et al.*, 2012). This comfort could be arranged with detailed engineering studies based on regulations for pedestrian wind comfort criteria. Changes in urban areas such as construction of higher buildings, city plans without wind analysis, changes in wind speeds, and climate change effects influence the wind flows. Higher height buildings resulted changes for wind flows around urban blocks. These changes could be simulated with CFD and also by experimental using of wind tunnel experiments in a turbulent boundary layer *(Yoshie et al.*, 2006). Effects of high-rise buildings on pedestrian level wind (PLW) comfort could be reduced with using some obstacles in the wind flow way. For example, a canopy or a podium can significantly reduce the area-averaged PLW speed (up to 29%) and the maximum PLW speed (up to 36%) around the high-rise building (*Van Druenen et al.*, 2019). Studies of wind comfort and wind safety involve combining statistical meteorological data, aerodynamic information, wind comfort, and safety criteria (*Blocken et al.*, 2012). Changes in wind speeds should be very variable depending on the measurement period. Seasonal wind changes and topography are main reasons of this variation. The semi-closed U-type street canyon has been widely used in the high-density trans-oriented development of urban design for providing private space. However, U-type canyon exhibits a lower wind speed at the pedestrian level than that of the parallel canyon both inside and in the vicinity of the street canyons, especially under parallel wind direction (*Cui et al*., 2019). Many countries publish written regulations about wind safety or wind comfort. In the Netherlands, the wind code is not another legal building requirement, but a helping hand to include wind comfort in a building program, and it explicitly regulates the technical procedures and quality control (*Willemsen* and *Wisse*, 2007). Statistical analysis using long time period data could help researchers to find required wind speeds for studies, but if there are safety regulations, these restrictions force researchers to find different solutions. Also, it could be suggested to measure field data for a long time period before the planning stage and to use it during the design stage, but in most cases, it could not be possible because of tight construction schedule of civil engineering projects or the high economic investment costs for these kinds of measurements could be high.

Complex problems including wind loads on structures could be solved both with wind tunnels and CFD. These methods could be well used in extraordinary shaped buildings such as telescopes (*Mamou et al*., 2008). There are basically two types of parameters that act as sources of error in CFD results. First, there are modeling errors that arise from the turbulence models used and the physical boundary conditions applied. The other errors stem from the numerical modeling (*Franke et al.*, 2004). Most of the studies about wind conditions in passages between parallel side-by-side buildings focus on pedestrian-level winds. Two main categories can be distinguished: (1) Fundamental studies, which are typically conducted for simple, generic building configurations to obtain insight in the flow behavior, to study the influence of different building dimensions and passage widths, and to provide input for knowledge-based expert systems (KBES) and/or for model validation. (2) Applied studies, which provide knowledge of the wind environmental conditions in specific and often much more complex case studies (*Blocken et al*., 2007). *Du* and *Mak* made a research about Hong Kong, and their results indicated that the lift-up design can improve the wind comfort in building surroundings, and its influence is highly dependent on the incident wind direction (*Du* and *Mak*, 2017). Studies involved with wind flow simulation require detailed examination even if it is wind tunnel experiment or CFD. Accuracy of these methods mostly changeable depending on many factors. There are some uncertainties inherent in wind tunnel experiments (such as measuring instrument errors, incidental errors, errors in the position where the sensor is installed, etc.), but there are no such uncertainties in CFD, and furthermore, it is very difficult to have an arbitrary approach flow in the wind tunnel, while this can be freely done in CFD (*Yoshie et al*., 2007). In single building models, which are considered to give the highest accuracy in the experiment, the CFD analysis results were consistent with experimental results within an accuracy about 10% in the strong wind region *(Yoshie et al.*, 2007). The results of pedestrian wind comfort analysis could be well applied to different projects such as autonomous control systems. Assessment of wind around passages for Silvertop Towers in Antwerp showed that traditional remedial studies gave unsatisfactory results, so an automatic control system has been designed and analyzed to modify the wind climate in the passages. The measurements are performed in upper through-passages above the passage canopies and the control system is estimated to leave doors open for about 50% to 70% of the time (*Blocken et al*., 2004).

In this study, pedestrian wind comfort analysis has been performed with Simscale CFD software by using wind flow data obtained from the Turkish State Meteorological Service (MGM). Section 2 describes statistical analysis of wind data and information used in CFD software about the university campus. Results of the wind comfort analysis given in Section 3, and Section 4 comprises conclusion of the whole investigation with suggestions to guide future studies in the subject of the pedestrian wind comfort.

2. Material and method

2.1. Material

Nuh Naci Yazgan University (NNY University) is a non-profit private university supported by industry and charity, and it has active collaboration with industry that leads to high quality in both local and international student placements (NNY, 2021). NNY University is officially founded by the Kayseri Higher Education and Social Aid Foundation (KHESAF) in 2009. Location of university is in the northwestern side of Kayseri province in Turkey. This makes the university campus buildings, roads, and sidewalks vulnerable for high-speed winds coming from south direction. Situation plan and general view of university campus are given in *Figs. 1* and *2*, respectively. The terrain of surroundings near the university campus is given in *Fig. 3,* where a red circle indicates the campus. It can be seen that the north side of the area is surrounded by relatively high hills from the north direction, while fully open field from the south direction.

Fig. 1. Nuh Naci Yazgan University Campus situation plan.

Fig. 2. General view of university campus.

Fig. 3. Terrain around campus area.

2.2. *Wind data*

Measurements of wind speeds are carried out by the Turkish State Meteorological Service (MGM) in Turkey. In this study wind speeds have been obtained from the Kayseri Regional Directorate of MGM. While Nuh Naci Yazgan University located in the Erkilet district, the closest wind measurement station is located in the city center. Distribution of wind speeds change in seasonal, monthly, daily, and even hourly periods. Hourly wind speeds including direction for long time period (2009–2018) obtained from MGM was used in this study. Wind flow direction changes in very short periods because of various reasons, nevertheless, prevailing wind direction is vital for wind flow based studies. Distributions of wind events for the observation period are given in *Fig. 4*.

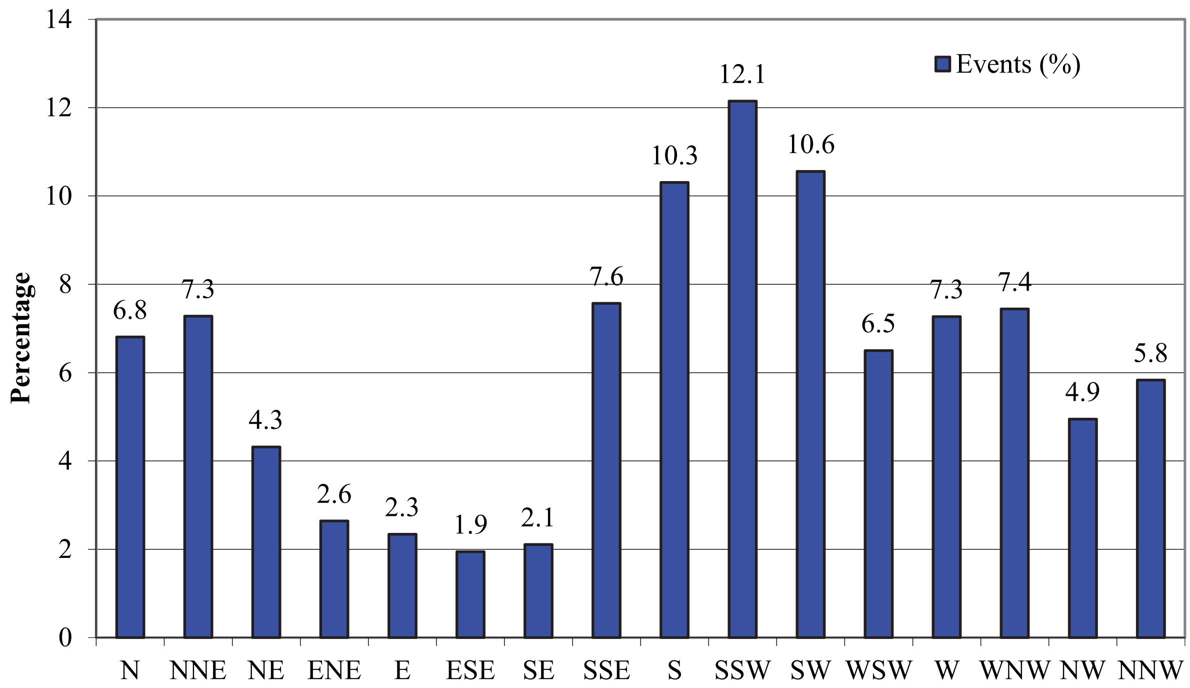

Fig. 4. Distribution of wind directions.

Besides wind directions, it is also important to define wind speeds. Changes in wind speeds must be definitely considered during the analysis because turbulence, obstacles (such as buildings), and pressure differences obligate changes in both wind direction and speed. Wind speeds grouped in 6 speed classes, and the distribution based on these classes are given in *Fig. 5*.

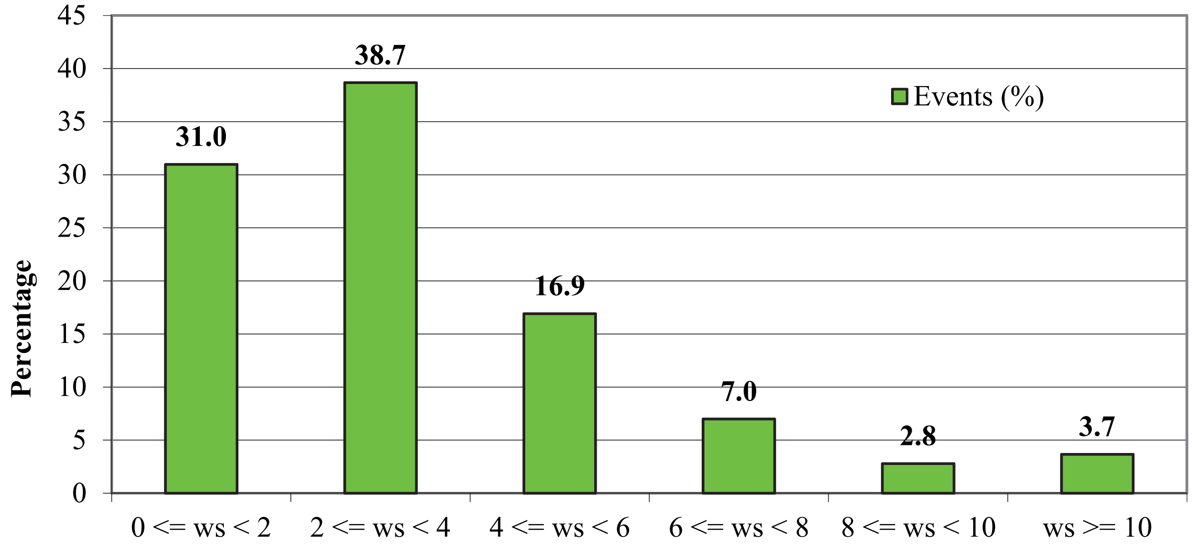

Fig. 5. Wind speed class distribution.

Wind roses are used to find the prevailing direction and also wind speed distribution for a specific area. The wind rose for Kayseri is given in *Fig. 6*, and it could be concluded that the prevailing wind direction is south-southwest (SSW).

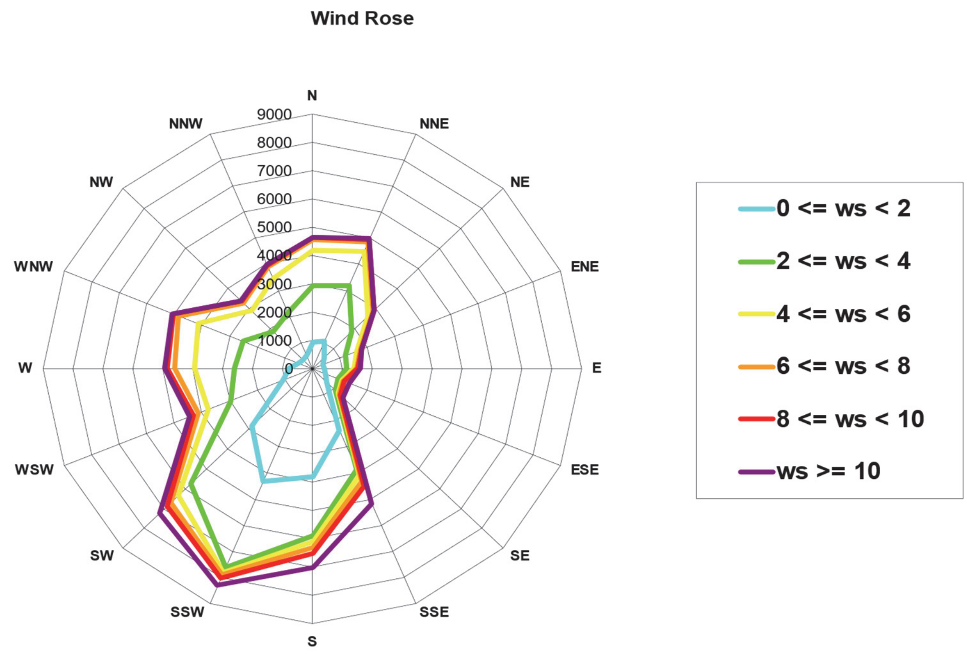

Fig. 6. Wind rose drawn with Kayseri long-term wind speed data.

Distribution of winds based on classes could give a clue about the consequences of wind effects around the investigated buildings, but for a detailed CFD analysis it is important to select and use the most suitable wind speed according to the special requirements of the project. In this study, average wind speeds according to the frequency analysis are selected to reflect a normal daily life situation. Number of wind events and average speeds sorted with the EnviroComp Consulting Wind Tool are given in *Table 1* (*Enviroware*, 2018).

Table 1. Frequency analysis of wind speed data

Direction	**0≤ws<2**	**2≤ws<4**	**4≤ws<6**	**6≤ws<8**	**8≤ws<10**	**ws≥10**	**Average speed (m/s)**	**Number of events**	**Events (%)**
N	951	2004	1233	379	71	11	4.9	4649	6.8
NNE	1076	2122	1285	378	90	20	5.9	4971	7.3
NE	559	1303	748	250	67	21	5.0	2948	4.3
ENE	375	841	404	123	34	26	3.6	1803	2.6
E	409	741	252	97	42	57	3.1	1598	2.3
ESE	458	445	142	64	52	167	3.6	1328	1.9
SE	672	419	94	70	67	117	3.6	1439	2.1
SSE	2393	1484	225	202	209	657	2.9	5170	7.6
S	3824	2063	239	204	186	522	3.2	7038	10.3
SSW	4294	3301	198	110	120	273	3.1	8296	12.1
SW	2863	2882	609	330	216	311	2.5	7211	10.6
WSW	1074	1887	807	356	202	114	1.9	4440	6.5
W	777	1827	1347	674	220	120	2.0	4965	7.3
WNW	516	1999	1636	690	178	64	3.3	5083	7.4
NW	419	1434	1040	393	80	13	3.7	3379	4.9
NNW	496	1659	1296	452	69	12	4.9	3984	5.8
Number of events	21156	26411	11555	4772	1903	2505			
Events (%)	31.0	38.7	16.9	7.0	2.8	3.7			

Wind speed could be measured in many different time scales. The MGM wind data of Kayseri province has been statistically investigated as given previous sections of this study. For wind comfort modeling, it is crucial to find wind speeds in the examination area for realistic results. Mini weather stations are widely used in small regions to measure and record weather events. A mini weather station funded from the TUBITAK (The Scientific and Technological Research Council of Turkey) project was placed in the campus area to find hourly wind speeds. A selected sample for wind speeds measured with mini weather station located near Engineering Faculty of Nuh Naci Yazgan University are given in *Fig. 7*.

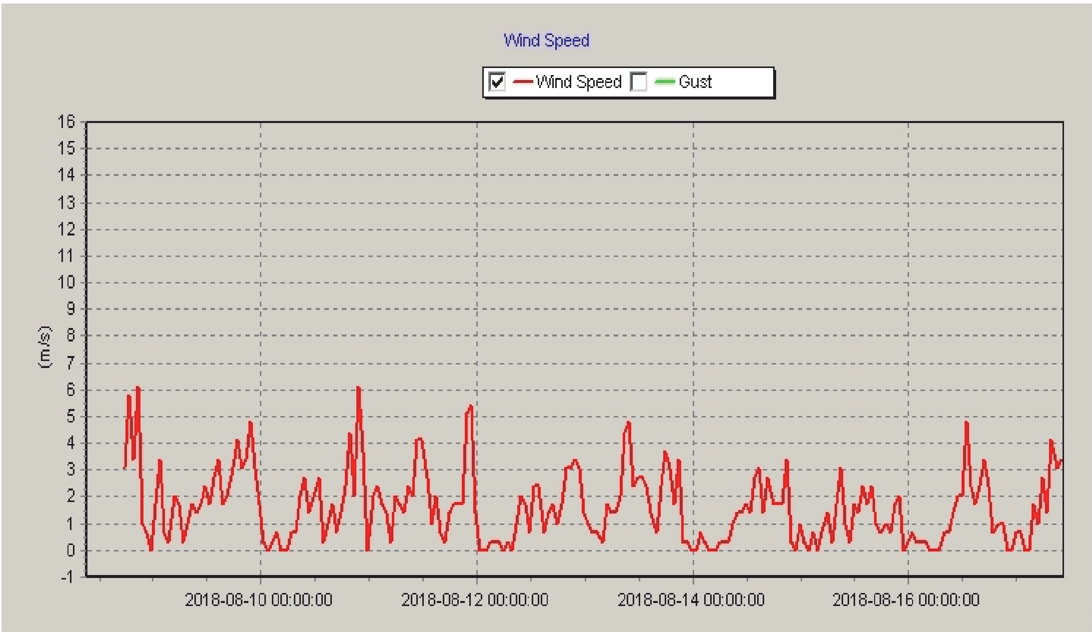

Fig. 7. A sample of wind speed data obtained from field measurements.

Measurements of wind speeds in the campus area data were recorded in a very short period when compared with MGM data, but it was seen that wind speeds were very variable, especially in the hourly periods, during night-day changes which was reasonably expected. It was also found that the measured wind speed values in the campus area are close but always a little bit lower than the MGM values in the same month's same day, and so MGM values are selected as primary wind data in this study.

Measurements of wind speeds are taken at 10 m height from the ground surface as a standard in worldwide. Nevertheless, the pedestrian level wind comfort analysis needs to be made in a proper height. This height should be a suitable height in meters for every person in public. In this pedestrian wind comfort study, the university campus was selected as case study, and the investigations showed that the proper height value which is suitable for most students was around 1.5 meters, and so authors decided to use this value as reference point. The main obstacle during wind speed calculations is the wind speed profile which is in a logarithmic form. There are many studies about the wind speed variation with height, but the main conflict about the subject is the surface roughness of the investigation area. From those wind profile models, the most convenient one was selected as power law profile, because it is a widely used model, and it would allow to find the vertical wind speed profile. The power law profile in a basic form is given as:

$$\frac{U_{(z)}}{U_{(z_r)}} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

where $U_{(z)}$ is the velocity of wind in desired height, $U_{(zr)}$ is the reference wind speed at height z_r, z is the height of wind speed calculation, z_r is the reference wind speed height (10 meters in meteorological measurements), and α is the power law exponent.

It has been found, that the power law exponent varies with such parameters as elevation, time of day, season, nature of the terrain, wind speed, temperature, and various thermal and mechanical mixing parameters, and many researchers have developed methods using the log law for calculations (*Manwell et al.*, 2006). A decisively influencing factor during the determination of the pedestrian wind comfort is the wind speed. In this study, the MGM values have been degraded from 10 meters to 1.5 meters using the wind logarithmic profile (or log law). The study area is a university campus that makes a dilemma for the selection of wind speed data time period. Working hours during daytime are the highest pedestrian density time period for the university, so the maximum value of wind speeds based on hourly measurement periods has been sorted. Based on this criterion, the maximum wind speed was found as 24 m/s with direction of SSW. This speed has been measured at 10 meters above the surface level, so by using this value in the wind power law equation it was transformed into the 1.5-meter height level as 9.87 m/s. Air flow in the atmosphere has both speed and direction, and this is represented mathematically by a vector. A south-southwest wind means that the wind comes from the SSW, so the wind barb (flag) would be pointed SSW, but the wind arrow would be pointed to north-northeast (*Doty*, 2015). Meteorological wind directions were converted into CFD suitable directions as input data to the software.

2.3. Turbulence models

Osborne Reynolds investigated the motion of fluids in contact with solid surfaces and found, that the relation between them depends on the relation between a physical constant of the fluid and the product of the linear dimensions of the space occupied by the fluid and the velocity (*Reynolds*, 1883). While the laminar flow determines low speeds and parallel and smoothly moving fluid flow patterns, turbulent flow patterns are irregular and the streamlines intersect each other. It is crucial to model the turbulence with high reliability, because speed variations could be revealed by numerical investigations made behind CFD modeling software. There are many turbulence models found in literature, but it should be considered that all models have advantages and constraints when compared with each other. So, it is important for engineers to find the suitable model for every project. The most widely used turbulence models and their applications are given in *Table 2 (Bakker* and *Marshall*, 2004).

Table 2. Comparision of turbulence models

Turbulence model	**Application area of the model**
Standard K-epsilon	The most widely used model, it is robust, economical, and time-tested. The Reynolds stresses are not calculated directly, but are modeled in a simplified way by adding a so-called turbulent viscosity to the molecular viscosity. Its main advantages are a rapid, stable calculation, and reasonable results for many flows, especially those with a high Reynolds number. It is not recommended for highly swirling flows, round jets, or for flows with strong flow separation.
RNG K-epsilon	A modified version of the K-epsilon model, this model yields improved results for swirling flows and flow separation. It is not well suited for round jets, and is not as stable as the standard K-epsilon model.
Realizable K-epsilon	Another modified version of the K-epsilon model, the realizable K-epsilon model correctly predicts the flow in round jets, and is also well suited for swirling flows and flows involving separation.
Spalart-Allmaras	The Spalart-Allmaras model was developed for external flows in aerospace applications. It provides good answers for attached flows and flows with mild flow separation. It is not commonly used for process industry applications.
RSM	The full Reynolds stress model provides good predictions for all types of flows, including swirl, separation, and round and planar jets. Because it solves transport equations for the Reynolds stresses directly, longer calculation times are required than for the K-epsilon models.
LES	Large eddy simulation is a transient formulation that provides excellent results for all flow systems. It solves the Navier-Stokes equations for large scale turbulent fluctuations and models only the small-scale fluctuations (smaller than a computational cell). Because it is a transient formulation, the required computational resources are considerably larger than those required for the RSM and K-epsilon family of models. In addition, a finer grid is needed to gain the maximum benefit from the model and to accurately capture the turbulence in the smallest, sub-grid scale eddies. Analysis of LES data usually requires some degree of planning in advance of building the model.

Turbulence models are still in development, and many studies investigate new formulas to define the secret procedure in turbulence. One of the newest k-omega model-based turbulence model is the shear stress transport (SST) model. This model has the ability to account for the transport of the principal shear stress in adverse pressure gradient boundary-layers. In this study, k-omega SST model is used to model the turbulence effects on wind flow around the study area. The mathematical representation of k-omega SST Model expressed by the following equations.

The turbulent energy κ is given by:

$$κ = \frac{3}{2}(UI)^2 \quad , \tag{2}$$

where U is the mean flow velocity and I is the turbulence intensity.

The turbulence intensity gives the level of turbulence and can be defined as follows:

$$I = \frac{u'}{U} \quad , \tag{3}$$

where u' is the root mean square of the turbulent velocity fluctuations that could be found with the following equation:

$$u' = \sqrt{\frac{1}{3}({u'}_x^2 + {u'}_y^2 + {u'}_z^2)} = \sqrt{\frac{2}{3}k} \quad . \tag{4}$$

The mean velocity U can be calculated as follows:

$$U = \sqrt{U_x^2 + U_y^2 + U_z^2} \quad . \tag{5}$$

The specific turbulent dissipation rate can be calculated using the following formula:

$$\omega = C_\mu^{\frac{3}{4}} \frac{\kappa^{\frac{1}{2}}}{l} \quad , \tag{6}$$

where C_μ is the turbulence model constant which usually takes the value 0.09, κ is the turbulent energy, l is the turbulent length scale. The turbulence length scale describes the size of large energy-containing eddies in a turbulent flow. The turbulent viscosity v_t is, thus, calculated as:

$$v_t = \frac{\kappa}{\omega} \quad . \tag{7}$$

2.4. CFD Software

Computational fluid dynamics softwares or any kind of special softwares are programmed only to analyze wind flow work based on computational methods used for flow modeling in fluid dynamics. In this study, the Simscale software was used for CFD analysis. Simscale is a web-based computer-aided engineering (CAE) program that runs on the basis of sophisticated graphical interface to analyze designs and solve complex engineering problems such as finite element analysis (FEA), computational fluid dynamics (CFD), thermal analysis, multibody dynamics, and optimization (*Simscale,* 2021).

A CFD analysis generally includes following steps which are similar in all CFD software:

a) CAD preparation (pre-processing): CAD programs used to draw 2- or 3-dimensional forms of objects.
b) Simulation setup: CFD models such as turbulence models, time periods selected and operated.
c) Post-processing: results taken in graphic, tabular, or visual forms.
d) Visualization: Examination of visual outputs of CFD analysis.
e) Error estimation (re-run simulation if needed): if there are errors so simulation steps could be restarted from any step depending on user's experience.

2.5. NNY Campus CFD Analysis

The university campus is modeled with CAD software at the selected level of scale, which has enough detail to show the perspective of buildings but does not include every tiny details of buildings, especially the ones without any possible effect on wind. This procedure was used for each building in the campus area and *Fig. 8* shows computational grid.

The mesh of the campus based on CAD model has been created by using the Simscale mesh operation. There are 5 detail levels in the software, but higher detail levels need more simulation time. Grid detail level selected as 3 (moderate level) to gain enough quality without sacrificing the simulation performance. The mesh of the Engineering Faculty building as an example part of the whole grid is given in *Fig. 9*.

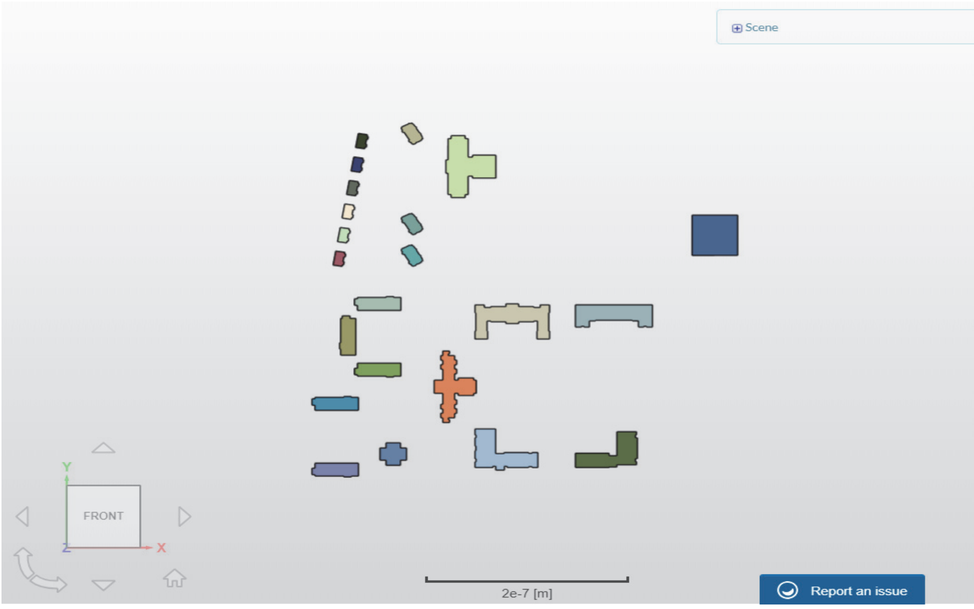

Fig. 8. Campus geometry.

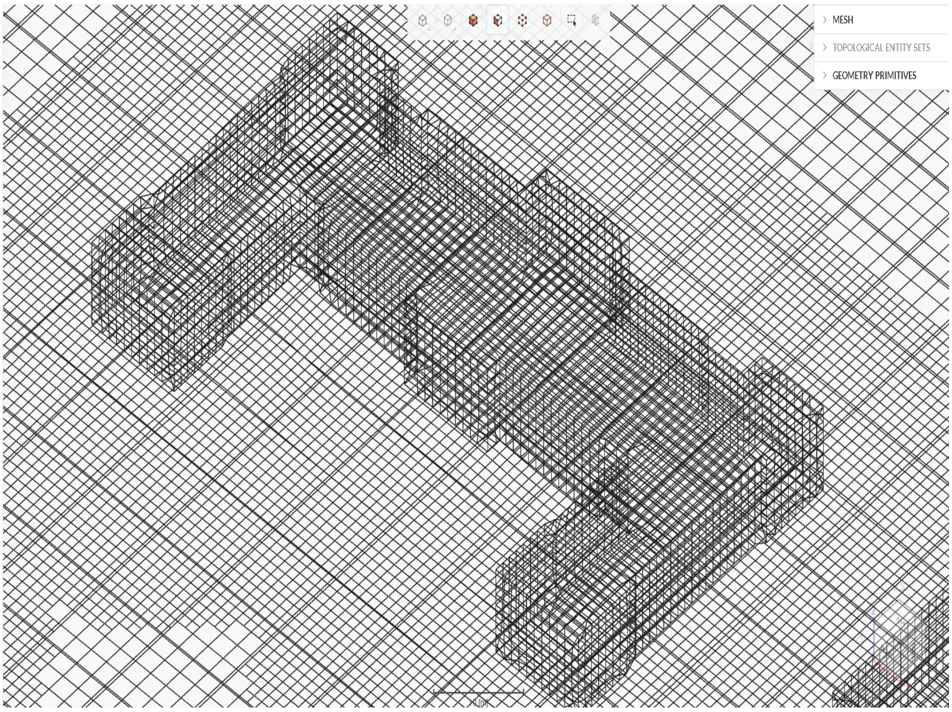

Fig. 9. Computational grid of the NNY Engineering Faculty building.

Boundary conditions include the surfaces of awind tunnel, because wind comfort studies simulate wind tunnel experiments. This kind of modeling could be affected by roughness of walls for both experimental and numerical solutions.

According to the recommendations on the use of CFD in predicting pedestrian wind environment publication, dimensions of the wind tunnel must be selected by using the height of the tallest building (H_{max}) in the domain (*Franke et al*., 2004). Dimensions for the ideal analysis are suggested as: height of tunnel is 6 H_{max}, distance from buildings (left, right, and front) is 5 H_{max}, and distance of rear tunnel wall from the last building is 15 H_{max}. In this study the wind tunnel dimensions were selected based on these criteria, and suitable values according to suggestions were given as input tunnel size parameters to the software.

3. Results

High speed winds cause many effects in the surroundings. These effects can change due to obstacles in the front of the wind flow, and possible consequences of wind damage should be separated as sea and land based on the flow environment. Outcomes of wind speeds have been defined with speed intervals to clarify the possible consequences and this is called Beaufort scale which is widely used in wind researches as given in *Table 3* (US Department of Commerce, 2021).

Table 3. Beaufort Scale

Force Speed (m/s) Speed (knots) Description	**Specifications for use at sea (First row) Specifications for use on land (Second row)**
0 0-0.3 0-1 Calm	Sea like a mirror. Calm; smoke rises vertically.
1 0.4-1.7 1-3 Light air	Ripples with the appearance of scales are formed, but without foam crests. Direction of wind shown by smoke drift, but not by wind vanes.
2 1.8-3.1 4-6 Light breeze	Small wavelets, still short, but more pronounced. Crests have a glassy appearance and do not break. Wind felt on face; leaves rustle; ordinary vanes moved by wind.
3 3.2-5.3 7-10 Gentle breeze	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses. Leaves and small twigs in constant motion; wind extends light flag.
4 5.4-8.1 11-16 Moderate breeze	Small waves, becoming larger; fairly frequent white horses. Raises dust and loose paper; small branches are moved.
5 8.2-10.9 17-21 Fresh breeze	Moderate waves, taking a more pronounced long form; many white horses are formed. Small trees in leaf begin to sway; crested wavelets form on inland waters.

Table 3. Continue

Force Speed (m/s) Speed (knots) Description	Specifications for use at sea (First row) Specifications for use on land (Second row)
6 11.0-13.3 22-27 Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere.
	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7 13.4-16.9 28-33 Near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
	Whole trees in motion; inconvenience felt when walking against the wind.
8 17.0-20.0 34-40 Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.
	Breaks twigs off trees; generally, impedes progress.
9 20.1-23.7 41-47 Severe gale	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility
	Slight structural damage occurs (chimney-pots and slates removed)
10 23.8-27.9 48-55 Storm	Very high waves with long overhanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes on a white appearance. The tumbling of the sea becomes heavy and shock-like. Visibility affected.
	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11 28.0-31.9 56-63 Violent storm	Exceptionally high waves (small and medium-size ships might be for a time lost to view behind the waves). The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.
	Very rarely experienced; accompanied by wide-spread damage.
12 32.0-33.3 64-71 Hurricane	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.

Results of the CFD analysis conducted on the Nuh Naci Yazgan University campus are given in *Fig. 10*.

The CFD analysis results showed that the shape as well as spatial settlement building are important parameters for the directional deflection of the wind flow. Sharp edges at all sides force wind speed to increase, meanwhile points positioned behind buildings are under the influence of variable wind speeds. Highest wind speeds were found around buildings located in the south of the university campus.

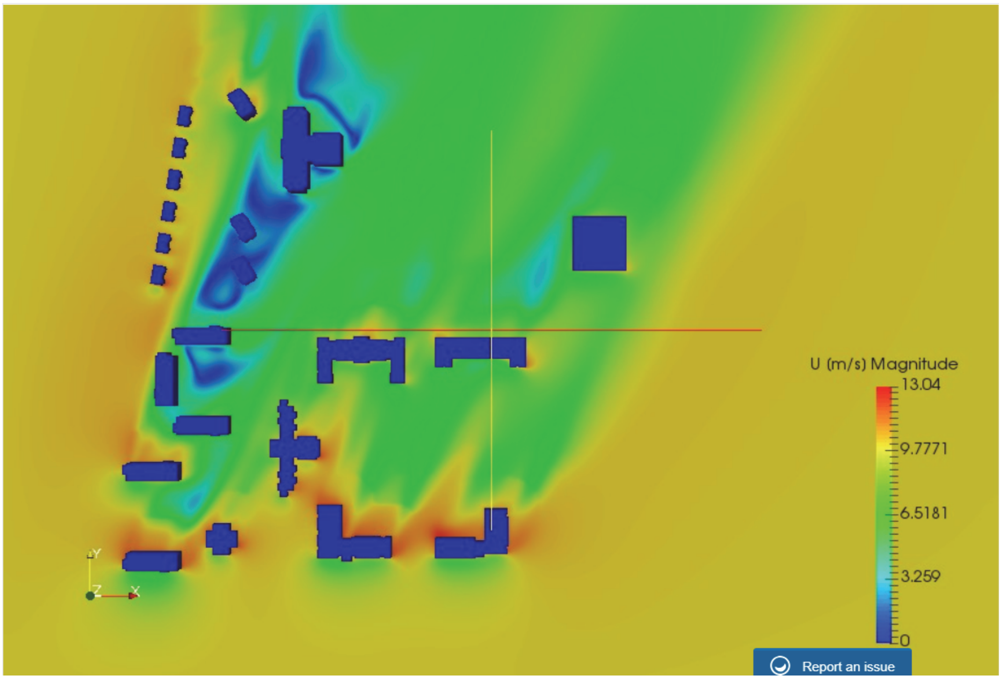

Fig. 10. Results of the CFD wind comfort analysis

4. Conclusion

In this study, a university campus pedestrian level wind comfort analysis has been conducted by using the CFD software. For this purpose, wind speed data were used during the analysis, and results showed that the position of buildings caused the increase in wind speeds, and if we consider possible changes in the campus area such as new buildings, this process would lead to higher damages in different areas. Results of the analysis indicated that, planning of a city or even more smaller regions such as a university campus should be designed with the CFD wind analysis tools in order to evaluate wind comfort analysis. Also, it could be concluded, that the intensity of pedestrian traffic should be under consideration during the planning stages. Meanwhile, pedestrian wind comfort guidelines including region specifications could guide designers about design criterias, and this would help to find the optimum solutions against undesirable wind effects. The wind speed increased to 13.04 m/s in some places, and according to the Beaufort scale this amount of wind speed creates these spesifications on land: "Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty". This result was obtained with CFD, and input wind speed data was found by statistical investigation of historical data measured around the research area. This means, that climate change effects that would create a change for wind data in future or relatively small obstacles (such as lamppost, bus stop, etc.) around buildings were not taken into account in the calculations, and so the wind flow could more dramatically change if the effects of these parameters are considered. However, for rural pedestrian wind comfort studies, this kind of possible changes could be taken into account to determine possible consquences of wind speed variationsduring CFD calculations, and could be used in wind comfort evaluations in accordance with comfort criterias as well as safety regulations.

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References

Bakker, A. and *Marshall, E.M.,* 2004: Computational Fluid Dynamics. In (Ed. Lee, S.), Encyclopedia of Chemical Processing. New York: Marcel Dekker Inc. 1–23.

B*ehrouzi, F., Azwadi, N.O.R., Che, B.I.N., Nakisa, M.,* and *Witri, A.,* 2013: Numerical prediction of wind flow around the high-rise buildings by two equations turbulence models for urban street canyon. *Comput. Method. Sci. Engineer 13,*152–156.

Blocken, B., Janssen, W.D.D., and *van Hooff, T.,* 2012: CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus. *Environ. Model. Software 30*, 15–34. https://doi.org/10.1016/j.envsoft.2011.11.009

Blocken, B. and *Persoon, J.,* 2009*:* Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard. *J. Wind Engineer. Indust. Aerodynam. 97*, 255–270. https://doi.org/10.1016/j.jweia.2009.06.007

Blocken, B., Carmeliet, J., Stathopoulos, T., Carmeliet, J., and *Stathopoulos, T.,* 2007*:* CFD evaluation of wind speed conditions in passages between parallel buildings—effect of wall-function roughness modifications for the atmospheric boundary layer flow. *J. Wind Engineer. Indust. Aerodynam. 95*, 941–962. https://doi.org/10.1016/j.jweia.2007.01.013

Blocken, B., Roels, S., and *Carmeliet, J.,* 2004: Modification of pedestrian wind comfort in the Silvertop Tower passages by an automatic control system. *J. Wind Engineer. Indust. Aerodynam. 92*, 849–873. https://doi.org/10.1016/j.jweia.2004.04.004

Blocken, B., van der Hout, A., Dekker, J., and *Weiler, O.,* 2015: CFD simulation of wind flow over natural complex terrain: Case study with validation by field measurements for Ria de Ferrol, Galicia, Spain. *J. Wind Engineer. Indust. Aerodynam. 147*, 43–57. https://doi.org/10.1016/j.jweia.2015.09.007

Cui, D., Hu, G., Ai, Z., Du, Y., Mak, C. M., and *Kwok, K.,* 2019*:* Particle image velocimetry measurement and CFD simulation of pedestrian level wind environment around U-type street canyon. *Build. Environ. 154*, 239–251. https://doi.org/10.1016/j.buildenv.2019.03.025

Cui, D.J.J., Mak, C.M.M., Kwok, K.C.S., and *Ai, Z.T.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. *J. Wind Engineer. Indust. Aerodynam. 150*, 31–41. https://doi.org/10.1016/j.jweia.2016.01.007

Doty, M.B., 2015: Wind: u and v Components. Access date: 20.07.2022 Retrieved from http://colaweb.gmu.edu/dev/clim301/lectures/wind/wind-uv

Du, Y. and *Mak, C.M.* 2017: Effect of lift-up design on pedestrian level wind comfort around isolated building under different wind directions. *Procedia Engineer. 205*, 296–301. https://doi.org/10.1016/j.proeng.2017.09.979

Enviroware, 2018: Enviroware-tools wind data tool. Access Date: 12.08.2018. Retrieved from https://www.enviroware.com/tools/

F*ranke, J., Hirsch, C., Jensen, A. G., Krus, H.W., Schatzmann, M., Miles, P.S.W.* and *S. D., Wright, N. G., 2004:* Recommendations on the Use of CFD in Wind Engineering. Cost Action C14, (May), 1–11. https://doi.org/10.1007/BF02800469

Houda, S., Zemmouri, N., Hasseine, A., Athmani, R., Belarbi, R., and Flow, U., 2012: A Cfd Model for Simulating Urban Flow in Complex, *2*(1), 1–10.

Hu, C.H. and *Wang, F.,* 2005: Using a CFD approach for the study of street-level winds in a built-up area. *Build. Environ. 40*, 617–631. https://doi.org/10.1016/j.buildenv.2004.08.016

Kang, G., Kim, J.J., Kim, D.J., Choi, W., and Park, S.J., 2017*:* Development of a computational fluid dynamics model with tree drag parameterizations: Application to pedestrian wind comfort in an urban area. *Build. Environ. 124*, 209–218. https://doi.org/10.1016/j.buildenv.2017.08.008

Mamou, M., Benmeddour, A., Khalid, M., Fitzsimmons, J., Sengupta, R., Cooper, K. R., and *Sengupta, R.,* 2008: Correlation of CFD predictions and wind tunnel measurements of mean and unsteady wind loads on a large optical telescope. *J. Wind Engineer. Indust. Aerodynam. 96*, 793–806. https://doi.org/10.1016/j.jweia.2007.06.050

Manwell, J., Mcgowan, J., and *Rogers, A*. 2006: Wind Energy Explained: Theory, Design and Application, Second Edition. 10.1260/030952406778055054.

Meroney, R.N. and *Neff, D.E.,* 2010: Wind Effects on Roof-Mounted Solar Photovoltaic Arrays: CFD and Wind-Tunnel Evaluation. *T*he Fifth International Symposium on Computational Wind Engineering, (May), 1–8.

Mochida, A., Tabata, Y., Iwata, T., and *Yoshino, H*., 2008: Examining tree canopy models for CFD prediction of wind environment at pedestrian level. *J. Wind Engineer. Indust. Aerodynam. 96*, 1667–1677. https://doi.org/10.1016/j.jweia.2008.02.055

MGM, Turkish State Meteorological Service, 2021: Meteoroloji Sözlüğü. Access date: 07.07.2021, Retrieved from https://www.mgm.gov.tr/genel/meteorolojisozlugu.aspx? (In Turkish)

NNY, Nuh Naci Yazgan University, 2021: NNY University. Retrieved July 20, 2021, from https://www.nny.edu.tr/?p=contact

Qi, Y. and *Ishihara, T.,* 2018: Numerical study of turbulent flow fields around of a row of trees and an isolated building by using modified k-ε model and LES model. *J. Wind Engineer. Indust. Aerodynam. 177*, 293–305. https://doi.org/10.1016/j.jweia.2018.04.007

Reynolds, O., 1883: An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosoph. Transact. Roy. Soc. London*, *174*, 935–982. https://doi.org/10.1098/rstl.1883.0029

Simscale, 2021*:* SimScale Documentation | Online Simulation Software | SimScale. Retrieved February 26, 2021, from https://www.simscale.com/docs/

US Department of Commerce, 2021: N. N. W. S. Beaufort Wind Scale. NOAA's National Weather Service, Access Date: February 20, 2021, Retrieved from https://www.weather.gov/mfl/beaufort

Van Druenen, T., van Hooff, T., Montazeri, H., and *Blocken, B.,* 2019: CFD evaluation of building geometry modifications to reduce pedestrian-level wind speed. *Build. Environ. 163*, 106293. https://doi.org/10.1016/j.buildenv.2019.106293

Willemsen, E., and *Wisse, J.A.,* 2007: Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. *J. Wind Engineer. Indust. Aerodynam. 95*, 1541–1550. https://doi.org/10.1016/j.jweia.2007.02.006

Yoshie, R., Mochida, A., Tominaga, Y., Kataoka, H., Harimoto, K., Nozu, T., and *Shirasawa, T.,* 2007: Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. *J. Wind Engineer. Indust. Aerodynam. 95*, 1551–1578. https://doi.org/10.1016/j.jweia.2007.02.023

Yoshie, R., Mochida, A., Tominaga, Y., Kataoka, H., and *Yoshikawa, M.,* 2006: CFD Prediction of Wind Environment around a High-rise Building Located in an Urban Area. *Jwe*, *1*(108), 129–132.