

# Evaluation of Pedestrian Wind Comfort in Contemporary Residential Complexes. Residential Complex Sample in Hebron – Palestine

Abdallah Dweik, Abdelrahman Halawani and Maria Germana<sup>1</sup>

**Abstract**—Open public spaces in Residential complexes are essentials. The role of architects and urban planners is to design them with adequate standards of thermal comfort conditions and pedestrian wind comfort.

The aim of the study is to assist architects and urban planners in using a valid simulation software by performing a pedestrian wind comfort study on a selected case study based on Lawson comfort criteria in different scenarios. The used software was Ansys® Discovery Live software. In order to validate simulation results, wind velocity on-site measures were executed in three different days in order to compare them with the simulated wind velocity. Results show similarity between measured and simulated wind velocities in most of the selected points, where the root mean square error calculated for all simulated results was 0.78 m/s. Results showed that some points were considered uncomfortable regarding Lawson wind comfort criteria in King Abdullah Ben AbdulAziz residential complex.

## I. INTRODUCTION

Wind speed is essential in assessing human thermal comfort, whereas wind comfort refers to wind condition that is comfortable for pedestrians based on certain activities, e.g., sitting, standing, walking running, cycling, etc. (Yang et al., 2013). It describes the mechanical force of the wind that affects pedestrians based on their status and activities. There are different outdoor comfort criteria, e.g.: Lawson criteria, Isyumov and Davenport criteria and Dutch Standard NEN8100. The criteria have different considerations regarding wind velocity and occurrence probabilities of each velocity value and pedestrian.

A growing number of contemporary architects and urban planners are trying to integrate wind analysis into their designs, but are confronted with the complexity of the underlying physics, creating a gap between engineering knowledge of wind behavior and the implementation into design strategies (Passe & Battaglia, 2015). Computations fluid dynamics (CFD) simulation software which is a field of fluid mechanics that simulates, analyzes, and solves fluid flow problems using computer-based numerical analysis and algorithms (Tryggvason, 2016) could be considered as a simple and accurate tool to be used in the early design stage for new contemporary residential complexes and in providing

solutions for existing problems regarding pedestrian wind comfort level.

Buildings heights, shapes, setbacks, street orientations, vegetation and many other factors have a significant effect on wind behavior. In order to study wind behavior in an urban content, architects and urban planners use tools such as Computational Fluid Dynamics (CFD) simulation software. In this study, a focused simulation-based study was made on a residential complex located in Hebron city in Palestine, i.e. King Abdullah Ben Abdul-Aziz residential complex.

## II. LITERATURE REVIEW

### A. Wind comfort criteria

Wind has a major effect on outdoor human comfort. Comfort criteria is a combination of a discomfort limit and the maximum probability of discomfort that is acceptable. There are many different comfort criteria that were suggested in the past where a previous study compared 30 different criteria (Blocken & Carmeliet, 2008).

The differences between these criteria are related to wind speed averaging period and its probability of occurrence to the significance of its magnitude, taking into account the expected pedestrian activities.

(Koss, 2006) studied wind comfort criteria at different European cities, where results showed that using an hourly mean wind speed may give a better pedestrian wind comfort code. (Sanz-Andres & Cuerva, 2006) showed that human perception or acclimatization considered has a major effect on comfort criteria.

The Beaufort wind force scale is mainly used to classify wind speed based on observed resulting conditions. The scale was originally used to standardize wind condition on ships, but it was adjusted later on to include land observation. Wind speed can be measured nowadays, but Beaufort scale is still being referred to in order to give weather warnings to public (Stathopoulos, 2009).

Beaufort scale shows the effect of different wind speeds on the human body (Table I). Keeping in mind that the physiological effects are more complicated since it's linked to other factors.

<sup>1</sup> \*Abdallah Dweik, Instructor in Palestine Polytechnic University; Email: [a.dweik@ppu.edu](mailto:a.dweik@ppu.edu).

Abdelrahman Halawani, Assistant Professor in Palestine Polytechnic University; Email: [arahman@ppu.edu](mailto:arahman@ppu.edu)

Maria Germana, associate Professor, Palermo University, Italy. Email: [marialuisa.germana@unipa.it](mailto:marialuisa.germana@unipa.it)

TABLE I.

BEAUFORT SCALE

Beaufort Number	The Beaufort wind force scale		
	Descriptive Term	Speed (m/s)	Specification for Estimating Speed
0	Calm	0-0.2	Smoke rises vertically.
1	Light Air	0.3-1.5	Direction of wind shown by smoke drift but not by wind vanes.
2	Light Breeze	1.6-3.3	Wind felt on face; leaves rustle; ordinary vane moved by wind.
3	Gentle Breeze	3.4-5.4	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate Breeze	5.5-7.9	Raises dust and loose paper; small branches are moved.
5	Fresh Breeze	8.0-10.7	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong Breeze	10.8-13.8	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near Gale	13.9-17.1	Whole trees in motion; inconvenience felt in walking against the wind.
8	Gale	17.2-20.7	Breaks twigs off trees; generally, impedes progress.
9	Strong Gale	20.8-24.4	Slight structural damage occurs e.g. to roofing shingles, TV antennae, etc.
10	Storm	24.5-28.4	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	Violent Storm	28.5-32.6	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	> 32.7	Considerable and widespread damage to vegetation and a few windows broken.

In general, pedestrian wind comfort criteria are evaluated keeping account of the magnitude of wind speed and its frequency of occurrence, according to the activity expected in an outdoor space. For instance, when the magnitude of wind speed ranges from 6-8m/s, it is considered to be acceptable to someone who's strolling in a public open space but it is

considered disturbing to someone who's sitting in a public space and trying to read the newspaper.

Meanwhile, criteria set by (Bottema, 2000) describes the effect of wind speed (Table II).

TABLE II. OBSERVED WIND EFFECTS ON PEOPLE

Wind Speed (m/s)	Observed wind effects on people
	Wind Effect
4	Clothing flaps
5-6	Hair is disturbed/ Hair disarranged
10	Irregular footsteps, walking difficult to control
11	Difficult to hold umbrella (wind tunnel)
12	Violent flapping of clothes
13-14	Appreciably slowed into the wind
15	Walking difficult; dangerous for elderly person Impossible to hold umbrella (wind tunnel)
16	Blown sideways
17	Appreciably slowed into the wind
18	Almost halted in the wind
19	Uncontrolled tottering walking downwind
20	Great difficulty with balance in gusts
23	People blown over by gusts
24	Unbalanced, grabbing at supports

In the research of (Janssen et al., 2012) a comparison and evaluation between four criteria, given by Isyumov and Davenport, Melbourne (Melbourne, 1978), Lawson (Lawson, 1978) and the Dutch Standard NEN8100 was made. The research concluded that Lawson was the most restrictive criteria, therefore the assessment of pedestrian wind comfort in this study will be based on Lawson criteria (Table III)

TABLE III. LAWSON GENERAL COMFORT CRITERIA

Lawson general comfort criteria			
Wind Speed		Percentage of occurrence	Pedestrians activities
1.8	m/s	< 2%	Sitting Longley
3.6	m/s	< 2%	Sitting Shortly
5.3	m/s	< 2%	Walking Leisurely
7.6	m/s	< 2%	Walking Fast
7.6	m/s	>=2%	Uncomfortable

### III. RESEARCH METHODOLOGY

#### A. On-site measurement points

Wind velocities were measured using (CEM DT-619) thermo anemometer tool (Figure 1) The used thermo- anemometer measures wind speed with the range of 0.40-30.00 m/s, and has an error ratio of  $\pm 3\%$  (0.20 m/s). The on-site wind speed measurements were recorded by taking the average wind speed of two minutes at different points selected in site at 1.5 meters height, since in general, taking a 1.5m height is considered a good choice for the pedestrian level (Reiter, 2010).



Figure 1. Thermo Anemometer (CEM DT-619).

#### B. Simulation Software

The software used in simulating wind velocities was Ansys® Discovery Live 2019. The software was released in 2018, it creates interactive design exploration and fast product invention, it provides instantaneous simulation results and has a modeling engine. To observe real-time changes in performance, users may quickly adjust geometry, material types, or physics inputs, its simple user interface and relatively quick simulation results give a great advantage for urban planners in predicting wind behavior in their early design stage (fluidcodes.com, n.d.).

- *The assignment of the domain boundaries*

Based on (Blocken, 2015; Liu et al., 2017) the domain boundaries were set  $15H_{max}$  away on four directions of the selected urban model, where  $H_{max}$  is the height of the tallest building in the simulated urban area. In King Abdullah Complex,  $15H_{max} = 15 \times 18 = 270m$ , making the overall dimensions of the domain 655.4 m X 708 m. The blockage ratio was set as 2.5% (less than 3%) and therefore the height of the domain was set to be 126.8m.

- *The assignment of the ambient wind velocity in the simulation process*

Since terrain roughness and the built context may change the value of the average wind speed in the site compared with metrological station records, the following formula may be applied (Reiter, 2010).

$$U_0 = K z^a U_{10,m} \dots\dots\dots(1)$$

Where:

- $U_{10,m}$  represents the average wind velocity at the height of 10 meters, measured at the meteorological wind station.
- $U_0$  represents the average wind velocity, measured at the pedestrian level, taking into consideration the roughness of the site but without considering the built form.
- $z$  is the height of the wind speed evaluation on the site. In general, considering  $z = 1.5m$  is a good choice for the pedestrian level.
- $K$  and  $a$  are parameters for a suburban zone equals 0.4 and 0.235 respectively (Reiter, 2010).

The affecting wind velocity can be calculated using the previous formula result is as follows

when  $U_{10}$  was 14 m/s

$$U_0 = 0.4 (1.5)^{0.235} \times 14 = 6.15m/s$$

And when  $U_{10}$  was 4 m/s

$$U_0 = 1.76 m/s$$

It should also be noted that the contour levels of King Abdullah residential complex has a 30% slope, while in simulation, the model considered to be flat, this assumption came after several attempts to include the topography by using different techniques to create CFD simulation, all wind speed values were unreasonable and the visualization of the results had proven to be problematic. Also, since most CFD software show results as 2D slices, it can't give a continuous picture of the wind speed at pedestrian level.

#### C. wind speed for simulation

In Lawson criteria (Lawson, 1978) a minimum wind frequency of occurrence for the value of 2%. Based on metrological data from Hebron City, wind speeds that were analyzed were 2.0-3.5 m/s and 3.5-5.5m/s, the highest values were simulated (3.5 and 5.5 m/s). Wind speeds that are higher than 5.5 m/s were neglected since its frequency of occurrence

is less than 2% of the time, whereas wind speeds with lower values (0-2.5m/s) may not cause discomfort conditions for pedestrians and can also be excluded. Meanwhile, ambient wind directions that were simulated were northwest, west and southwest directions since these directions are the dominant wind directions.

#### IV. CASE STUDY ANALYSIS

##### 1) Case study description

King Abdullah Ben Abdul-Aziz residential complex (located in Hebron) is selected in this study. It was established in 2007, containing four main blocks, each has 3-4 attached or detached buildings that have four floors each. The total number of apartments are 100, with an area of 125 m<sup>2</sup> for each apartment. Figure 2 show a 3D perspective image of the residential complex.



Figure 2. A 3D image of the residential complex.

It should be noted that the activities of pedestrians in the residential complex were set by observation based on several visits to the site, where occasional sitting, walking, cycling and playing basketball are the main activities that were assigned in the residential complex. Figure 3 shows the location of each activity, which will be focused on in the simulation cases later on.



Figure 3. Pedestrians activities with the proposed sitting area circled in red.

The site was designed to contain vegetation and trees planted between the building blocks, where sitting activities were expected near those locations, but due to reflectance and lack of vegetation these locations were improperly used. Therefore, such areas are proposed to become sitting areas where they are circled in red.

##### 2) CFD simulation for the selected case study

The locations of measuring points were selected based on expectation of having different values of wind speed caused by the effect of buildings heights, setback and orientation of the main streets on wind behavior or because of observed high change in wind velocities while taking measurements in the residential complexes (Figure 4). The wind speed value recorded on site at each point was the average wind velocity measured in two minutes.



Figure 4. On-site measurement points distributed in King Abdullah Ben Abdul-Aziz residential complex.

Table IV shows details the wind speed in the selected point when ambient wind was 14m/s from the east direction:

TABLE IV. MEASURED WIND VELOCITIES IN KING ABDULLAH BEN ABDUL-AZIZ RESEDEBTIAL COMPLEX

Point	Table Column Head	
	Date & time (dec 27 <sup>th</sup> 2020)	Ambient wind speed
K1	14:13-14:15	4.5
K2	14:17-14:19	4
K3	14:20-14:22	2.5
K4	14:23-14:25	4.5
K5	14:26-14:28	2
K6	14:29-14:31	4
K7	14:33-14:35	2
K8	14:35-14:37	1.5
K9	14:38-14:40	4

Simulation results may be presented in different forms and measurements of wind velocities at certain points is possible which gives more accurate results of wind velocity values.

The comparison between measured and simulated wind velocities are presented in Figure 5 and table V, where the calculated root mean square error for the simulation results was 0.89.

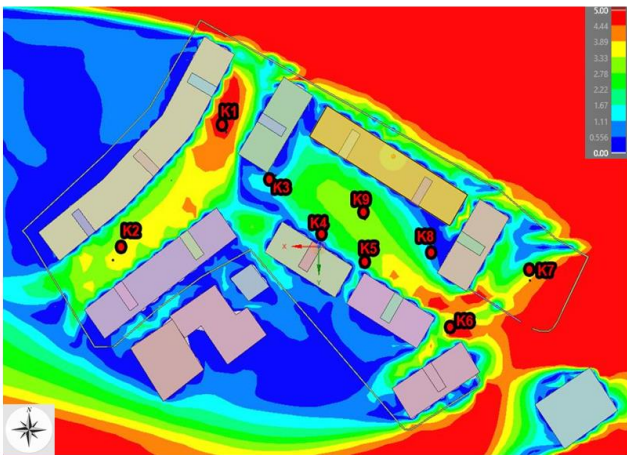


Figure 5. CFD simulation results for 14m/s wind velocity from the east using Ansys Discovery Live software

TABLE V. MEASURED AND SIMULATED VALUES OF WIND VELOCITY IN KING ABDULLAH BEN AABDUAZIZ RESIDENTIAL COMPLEX AT 14M/S WIND SPEED FROM THE EAST.

software	Wind Velocity (m/s)	
	Measured	Simulated
Ansys@ Discovery Live	4.5	4.5
	4	3.5
	2.5	1
	2.1	1.65
	2	1.9
	4	3.6
	2	3.8
	1.5	1.2
4	3	

### 3) Evaluation of pedestrian wind comfort level using CFD simulation

Different wind speeds and directions affects Hebron city. Since Lawson criteria (Lawson, 1978) is based on a minimum wind frequency of occurrence for the value of 2%, the value of wind speed that will be focused on is 5.5m/s, the highest value will be simulated (5.5 m/s). Higher wind speed values will be neglected since its frequency of occurrence is less than 2% of the time, whereas wind speed with lower magnitude (0-2.5m/s) may not cause discomfort conditions for pedestrians and can also be excluded. Meanwhile, the selection of ambient wind directions that will be simulated will be directed from the northwest, west and southwest directions based on the weather data analysis.

The residential complex had two simulation cases performed and each case had two scenarios, the first case had the existing buildings heights, the second case was performed after adding additional floors to the existing buildings reaching the maximum number of floors allowed based on the building regulations applied in Palestine. In King Abdullah Ben Abdul-Aziz residential complex, the maximum number of floor reached was seven floors for all apartment buildings.



Figure 6. Simulated points and its relations to activities

By calculating the wind velocity affecting the case study considering the residential complexes located in a sub-urban zone, the 5.5 m/s wind speed was simulated as 2.4 m/s.

Several points were assigned in the residential complex models in order to have an exact wind velocity value at each selected point, these points were selected based on the observed activities for pedestrians in the residential complexes, note that some activities were suggested based the design of the site in King Abdullah Ben Abdul-Aziz residential complex. Points KS1-6 represent sitting for a long-time activity, KW1-9 were set along the path where pedestrians either walk or cycle, and KP1 was located in the basketball playground (Figure 6). All results were compared to Lawson general comfort criteria

#### a) Case I: Pedestrian wind comfort in King Abdullah Ben Abdul-Aziz residential complex for original buildings heights

Figures 7 - 9 show the simulation results when ambient wind velocity was 5.5m/s where wind directions were from the northwest, west and southwest respectively.

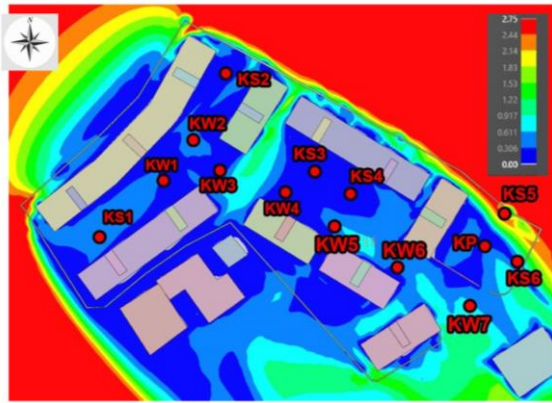


Figure 7. Simulation of the wind velocity in the residential complex when ambient wind velocity is 5.5 m/s from the northwest direction.

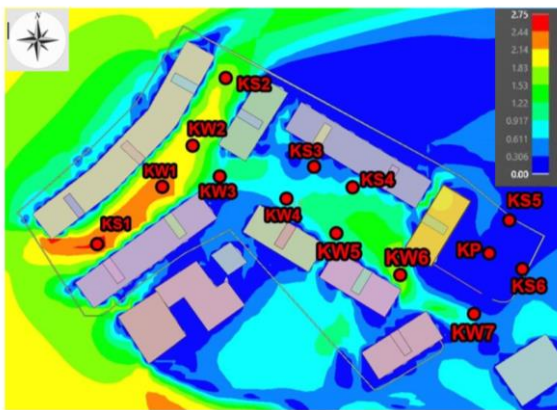


Figure 8. Simulation of the wind velocity in the residential complex when ambient wind velocity is 5.5 m/s from the west direction.

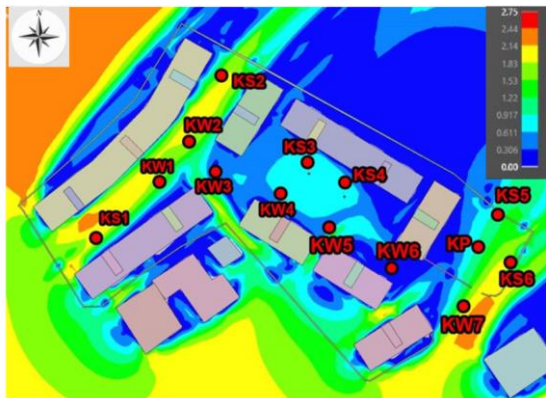


Figure 9. Simulation of the wind velocity in the residential complex when ambient wind velocity is 5.5 m/s from the southwest direction.

Simulation results have shown various differences in wind velocities at different locations in the residential complex. When the ambient wind direction was from the northwest direction, there were no significant high wind velocities recorded at the selected points, whereas the highest effect on wind comfort was recorded when ambient wind direction was from the west and the southwest directions, where corner

effect near Block 1 and the smooth edge design of the street located between Block 1 and Block 2 with the absence of vegetation and street furniture have caused an acceleration of wind near points KS1, KW1 and KW2 for the cases, all results are considered acceptable for the assigned pedestrians activities except point KS1, since the acceptable wind speed value should be less than 1.8 m/s based on Lawson criteria.

Table VI illustrates the value of wind velocity at all selected points in King Abdullah Ben Abdul-Aziz residential complex, where the green colored values are considered comfortable based on Lawson comfort criteria and the red colored values are considered uncomfortable. It can be noted that the only uncomfortable point was KS1 when wind speed and directions were 5.5 m/s from the West and Southwest direction.

TABLE VI. WIND VELOCITY VALUES AT THE ASSIGNED POINTS FOR THE ORIGINAL BUILDING'S HEIGHTS

Pedestrian Activities	Wind Velocity & Directions			
	Points	5.5m/s NW	5.5m/s W	5.5m/s SW
Sitting Longley	KS 1	0.3	2.5	2
	KS 2	0.1	1.7	1.7
	KS 3	0.1	0.4	0.9
	KS 4	0.1	0.6	0.7
	KS 5	0.5	0.1	1.2
	KS 6	0.4	0.1	1.5
Walking leisurely	KW1	0.2	2.2	1.6
	KW2	0.2	2	1.8
	KW3	0.2	1	0.1
	KW4	0.2	0.8	0.7
	KW5	0.1	1	0.4
	KW6	0.3	1.6	0.1
	KW7	0.3	0.9	1.7
Running	KP	0.4	0.1	1

a) Case 2: Pedestrian wind comfort in King Abdullah Ben Abdul-Aziz residential complex for maximum permitted buildings heights

In order to study the effect of future vertical expansion, three more floors were added to the original design reaching the maximum allowed number of floors based on the local building regulations (Figure 10).

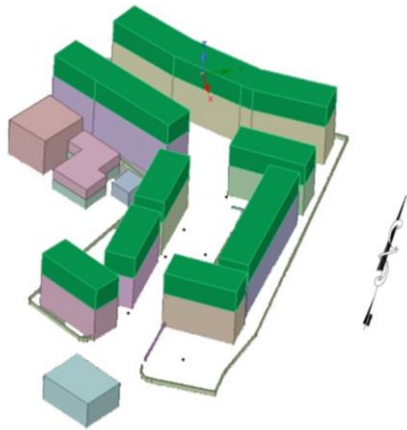


Figure 10. 3D model after adding the maximum permitted number of floors

When considering a dominant wind velocity value to be 5.5 m/s, table VII shows the simulation results when the simulated wind directions were from the northwest, west and southwest directions.

TABLE VII. WIND VELOCITY VALUES AT THE ASSIGNED POINTS FOR THE THE MAXIMUM BUILDING'S HEIGHTS

Pedestrian Activities	Wind Velocity & Directions			
	Points	5.5m/s NW	5.5m/s W	5.5m/s SW
Sitting Longley	KS 1	0.2	2.7	2
	KS2	0.12	1.8	1.8
	KS 3	0.67	0.6	0.6
	KS 4	0.5	0.95	0.5
	KS 5	0.37	0.23	1.3
	KS 6	0.18	1.1	1.6
Walking leisurely	KW1	0.12	2.3	1.74
	KW2	0.2	1.8	1.8
	KW3	0.4	1	1
	KW4	0.5	0.075	0.56
	KW5	0.77	0.75	0.43
	KW6	0.4	1.4	0.08
	KW7	0.45	0.3	1.7
Running	KP	0.3	0.2	1.1

The differences between wind velocities when comparing the both cases shows limited changes in wind velocities. The average difference between both cases was 0.08m/s, and the highest wind velocities recorded were also at point KS1 with a value of 2.7m/s and 2 m/s when ambient wind was 5.5 m/s from the west and the southwest directions respectively.

## V. CONCLUSION

The use of pedestrian wind comfort criteria may assist planners and urban designers in creating comfortable outdoor spaces. In this research, Lawson general wind comfort criteria was adapted since it is considered a restrictive criterion compared with other criteria (Janssen et al., 2012).

By applying this criteria and by using Ansys Discovery Live software for creating CFD simulation of King Abdullah Ben Abdul-Aziz residential complex, results illustrated the effects of different building forms and urban layouts on air movement, where the design of a long building block perpendicular to dominant wind direction had a significant role in reducing wind velocity in the residential complex, e.g. when ambient wind was affecting from the northwest direction, wind velocity was reduced for up to 80% in average for most of the measurement points locations due to the shape and size of building block1. However, attention should be given to corner effect and the smooth edge street in such a case, where the highest wind velocities were recorded around the corners of building block 1 with the value of 2.5m/s, which is considered uncomfortable based on Lawson general pedestrian wind comfort criteria for sitting activity. In the second assumption where four additional floors were added to the buildings to reach the maximum allowed number of floors based on local regulations, Results had shown a limited change in wind velocity where the average difference between both cases was 0.21m/s.

## REFERENCES

- [1] F. Yang, F. Qian, and S. Lau, "Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai," *Build. Environ.*, vol. 70, pp. 122-137, Dec. 2013.
- [2] U. Passe and F. Battaglia, *Designing spaces for Natural Ventilation: an Architect's Guide*, 1<sup>st</sup> ed. New York: Routledge, 2015.
- [3] G. Tryggvason, "Computational Fluid Dynamics," in *Fluid Mechanics*, Academic Press, 2016, pp. 227-297.
- [4] B. Blocken and J. Carmeliet, "Pedestrian wind conditions at outdoor platforms in a high-rise apartment building: Generic sub-configuration validation, wind comfort assessment and uncertainty issues," *Building Physics and Systems*, Technische University Eindhoven, vol. 1 no. 11 pp. 51-70, 2008.
- [5] H. Koss, "On differences and similarities of applied wind comfort criteria," *J. Wind Eng. Ind. Aerodyn.*, vol. 94, pp. 781-797, 2006.
- [6] A. Sanz-Adres and A. Cuerva, "Pedestrian wind comfort: Feasibility study of criteria homogenization," *J. Wind Eng. Ind. Aerodyn.*, vol. 97, pp. 799-813, 2006.
- [7] T. Sathopoulos, "wind and comfort," in *proc. Int. Conf. Wind Eng.*, Florence, Italy, 2009.
- [8] M. Bottema, "A method of optimization of wind discomfort criteria," *Build. Environ.*, vol. 35, pp. 1-18, 2000.
- [9] W. Janssen, B. Blocken, and T. vanHooff, "Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on a whole-flow field data for a complex case study," *Building Environ.*, vol. 59, pp.547-562, Oct. 2012.
- [10] W. Melbourne, "Criteria for environmental wind conditions," *J. Ind. Aerodyn.*, vol. 3, pp. 241-249, 1978
- [11] T. Lawson, "the wind content of the built environment," *J. Ind. Aerodyn.*, vol. 3, pp. 93-105, 1978.
- [12] S. Reiter, "Assessing wind comfort in urban planning," *Environ. Plan. Des.*, vol. 37, pp. 857-873, 2010