EVALUATING URBAN VENTILATION IN THE URBAN GRID OF BARCELONA AND BERLIN: A COMPARATIVE STUDY ON THE RELATIONSHIP BETWEEN WIND DIRECTION AND URBAN MORPHOLOGY

Abstract

Natural ventilation is an effective strategy to reduce energy consumption of the building and improve air quality for the building occupants. However, natural ventilation is highly affected by external factors. The required air conditions for natural ventilation rely on the building's location in the urban context. Therefore, it is important to study the air around the building. Airflow in the urban context has a different behavior from the prevailing wind due to various factors, such as urban morphology. Urban morphology can affect the behavior of air around the building and make it unpredictable. Urban morphology causes the urban street canyon, so that the airflow in the urban street canyon is turbulent. Therefore, predicting the airflow of the building is dependent on urban morphology and the airflow behavior in the urban street canyon. This study investigates how the airflow conditions, such as temperature and velocity, change on the ground level with the changing wind direction in different types of urban contexts.

Author

Homeira Mirhosseini
Penn State University

Keywords

Urban ventilation, CFD simulation, urban morphologies

Introduction

Buildings in the modern urban context of cities consume substantial energy for mechanical ventilation and air conditioning systems. Passive cooling is a method that helps reduce energy consumption by reducing heat gain. Oropeza-Perez and Østergaard (2018) define passive cooling as "technologies or design features developed to cool buildings without or with minimal energy consumption in order to improve their energy efficiency."

Natural ventilation is a passive cooling strategy that helps to reduce the energy required for cooling and ventilation of buildings, while improving indoor environmental conditions. Providing outside air is a necessity for delivering natural ventilation. Due to the growth of the population, most cities are leaning toward dense urban contexts (Zhai et al., 2016). The objective of natural ventilation is to provide thermal comfort and indoor air quality for the building occupants. To provide good indoor air quality, the building must have fresh air coming in from the inlets. However, the air condition in the building could be different based on where it is located in the urban context. In other words, studying the natural ventilation for an isolated building is not practical, as the quality, temperature, pressure, humidity, and other factors of the incoming air depend on the situation of the building in its urban context. Because of that, it is also important to investigate urban ventilation. Investigating urban ventilation helps to provide fresh air, which is a crucial factor for having natural ventilation in the building (Ng, 2009; Ghiaus & Allard, 2012).

Previous research shows that naturally ventilated buildings can effectively decrease sick building syndrome. Indoor air quality of the buildings relies heavily on the local outdoor microclimate. For example, in the summer, decreasing the wind speed from 1.0 to 0.3 m/s results in a 1.9°C temperature increase. The air condition around the building in urban areas depend on various factors. As today's urban development trends are toward high-density compact cities, urban morphology can have substantial effects on the local urban climate. Denser urban contexts with complex urban morphologies can produce heat islands and affect urban air ventilation (Xu et al., 2017).

Natural ventilation in urban environments, and particularly in street canyons, is not as effective as in rural environments (Ghiaus et al., 2006). Street canyon is defined as a narrow street with buildings along both sides (Vardoulakis et al., 2003). Spatial configuration of the buildings in the urban context has significant effects on the required energy for cooling and heating the buildings (Rahimian et al., 2018). The spaces must be evaluated with respect to their street canyon proportion and wind direction to understand the potential for the application of natural ventilation in urban spaces (Passe & Battaglia, 2015). Even though the natural ventilation of buildings in the street canyon has generally proven to be ineffective, the appropriate wind data should be considered in urban spaces to improve the effectiveness of using natural ventilation in urban buildings. The air temperature in the areas with high density is higher than in the rural areas; therefore, a "heat island" exists in areas with higher densities. High urban temperatures can cause higher electricity demands for air conditioning in buildings (Passe & Battaglia, 2015). Similarly, the presence of the buildings leads to reduced potential for natural ventilation (Vardoulakis et al., 2003). Low wind speeds, high temperatures, noise, and pollution are some of the challenges in the application of natural ventilation in urban environments (Santamouris, 2013).

Additionally, the air flow in urban canyons is turbulent. While it is difficult to define turbulent flows, their main characteristics can be recognized. Turbulent flows are random in time, diffusive, rotational and three dimensional, dissipative, and unique. They also have random physical characteristics (Ghiaus et al., 2006). The majority of natural ventilation strategies involve turbulence in the air movement. As mentioned earlier, it is hard to predict the time and space in which the turbulence happens. Although the air flow in the urban street canyon is not predictable, air turbulence might provide the potential to effectively use natural ventilation. As well as prevailing wind profiles, overall air velocity is dependent on the geometry of the urban environment. Manipulating the city morphology and street geometry can modify urban air movement. Wind patterns in the pedestrian-level of high-density cities are affected by urban geometry. Therefore, parametrizing the urban geometry and studying factors like aspect ratio of building height to street width or urban street canyons are necessary for studying the wind patterns of urban environments (Yang et al., 2013).

Consequently, for providing comfortable air conditions for pedestrians in an urban environment and providing suitable air conditions for natural ventilation of buildings, exterior microclimate parameters need to be studied. Factors like shape of the buildings affect the airflow around the building (Edussuriya et al., 2011). This study investigates the effects of some urban morphology parameters and prevailing wind direction on the air conditions around the building in the urban areas of Berlin and Barcelona. Although Berlin and Barcelona have the same average building height, they are different in other aspects of urban morphologies. Simulations have been performed using various wind directions to study the effects of urban morphology on air around the building. Computational Fluid Dynamics (CFD) using Star CCM+ software has been employed to study the movement of air, velocity, and temperature around the buildings.

Figure 1: Images of urban contexts–Berlin (top) and Barcelona (bottom). (Source: Google Earth.)

Methods

APPROACH

This study compares the effects of urban morphology on the air around the building in the cities of Berlin and Barcelona by considering various wind directions. The two cities have about the same average building height, which results in eliminating the factor of building height from the urban morphology and reduces the complexity of the study. The generic 3D geometries of the two cities were modeled based on the information on the dimensions of the blocks in the urban context of Berlin and Barcelona (Passe & Battaglia, 2015). Nine blocks are chosen as the target grid for this study in the urban context of each city.

Barcelona has an urban context with symmetrical blocks of the same size, while the blocks in Berlin are varied in length, width, and length to width aspect ratios. This will make the two urban contexts different in receiving airflows. Figure 1 shows the urban context of Berlin and Barcelona. In addition, the edges of the blocks in the urban context of Barcelona are chamfered, which can have an effect on airflows. To investigate the influence of the chamfered edges on the airflow around the blocks in Barcelona, an additional urban context is defined for the city of Barcelona in which the chamfered edges of the blocks are flattened. Thus, three different urban contexts will be investigated in this study. Figure 2 represents the defined urban context for Berlin, and Figure 3 represents the various urban contexts defined for Barcelona.

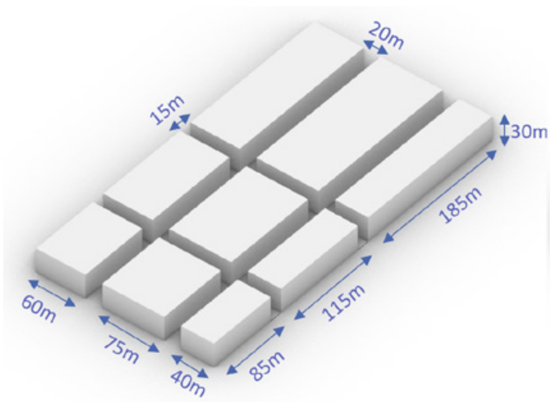

Figure 2: Defined geometry for Berlin.

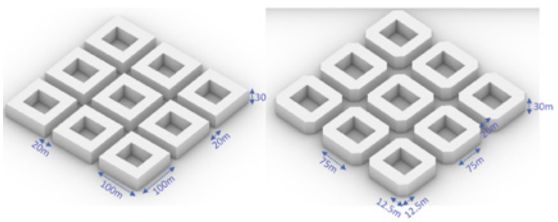

Figure 3: Defined geometries for Barcelona.
Left: Without chamfered edges. Right: With chamfered edges.

SIMULATION CASES

Different cases of CFD simulation will be performed on the defined urban contexts of Berlin and Barcelona. Wind directions of 0º, 45º, and 90º in relationship to the directions of the urban structures are chosen for the simulation cases of Berlin to recognize the effects of prevailing wind direction on the air around the buildings in Berlin. Since the urban context of Barcelona is symmetrical, the wind directions for the simulation cases of Barcelona are considered 0º and 45º. It is assumed that the results of the simulation for the wind direction of 90º would be the same as 0º because of the symmetry of the geometries. To change the wind direction for the simulation cases, the geometries of urban contexts are kept constant, and the wind tunnel is rotated to provide wind in the desired direction. Table 1 summarizes all different simulation cases in this study.

Simulation Case	Geometry	Wind Direction
1	Barcelona chamfer	0°
2	Barcelona chamfer	45°
3	Barcelona no chamfer	0°
4	Barcelona no chamfer	45°
5	Berlin	0°
6	Berlin	45°
7	Berlin	90°

Table 1: Simulation Matrix.

SIMULATION DOMAIN

For setting up the wind tunnel for each simulation case, the following dimensions are considered. The variables L, W, and H respectively represent the overall length, width, and height of urban context geometries.

- Wind tunnel length = 25L
- Wind tunnel width = 20W
- Wind tunnel height = 10H
  (The height needs to be at least 5H.)

Figure 4 represents the relative location of urban context geometries in the wind tunnel for simulation cases.

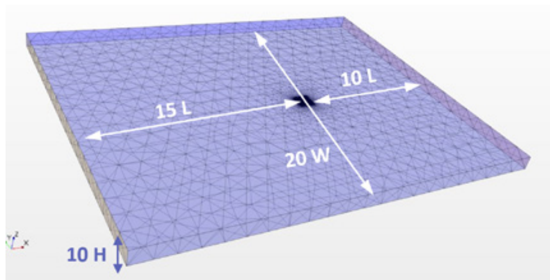

Figure 4: The geometry of wind tunnel in the simulation cases based on the dimensions of the target urban grid.

The geometries of the blocks and wind tunnel are scaled 1:20 to be compatible with the simulation environment of the Star CCM+ software.

SIMULATION PARAMETERS

The original velocity considered for the simulations is 5 m/s. However, since the geometries are scaled, based on the Reynolds Number formula (Re = uL/v) in which L is the linear dimension of the characteristics and u is the velocity, when the geometry is scaled 1:20, the velocity must be multiplied by 20 to keep the Reynolds Number value constant. Therefore, in the simulation case, the velocity for the inlet of the wind tunnel is set to 100 m/s.

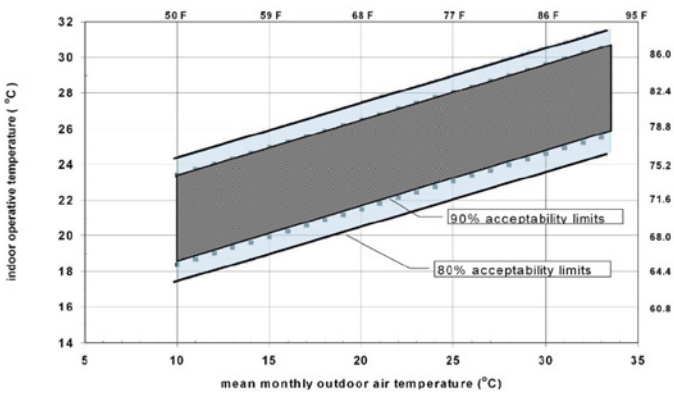

Figure 5: Acceptable operating temperature ranges for naturally ventilated spaces. (Source: Yasa, 2016.)

Wind tunnel inlet temperature is chosen based on the average temperature of Berlin and Barcelona in the months that outdoor temperature provides the possibility for natural ventilation. Based on this information, the temperature for the inlet of the wind tunnel is set to 16.1°C. Figure 5 represents the acceptable operative temperature range for natural ventilation based on ASHRAE standards, and Table 2 shows the average outdoor air temperature during the year in Berlin and Barcelona.

	Berlin	Barcelona
Jan	1.7	7.8
Feb	0	8.9
Mar	5	11.1
Apr	7.8	12.8
May	13.9	16.7
Jun	17.2	20.6
Jul	18.9	23.3
Aug	18.3	23.9
Sep	14.4	21.1
Oct	10	17.2
Nov	3.9	11.7
Dec	2.2	9.4

Table 2: Average outdoor air temperature in Berlin and Barcelona (°C). The highlighted fields represent the months that the temperature provides the possibility for natural ventilation based on Figure 5. The numbers are taken from Climate Consultant software.

The selected mesh models are Surface Remesher, Trimmer, and Prism Layer Mesher. The mesh size of the wind tunnel surfaces is set as 20 m and the mesh surface size for the nine buildings in each urban context in this study is set as 0.2 m. The physics models for the simulation cases of this study are considered as follows:

- Three dimensional
- Steady/gas/segregated flow/constant density/ segregated fluid temperature
- Turbulence/ turbulence/SST Mentor
- All y+ wall treatment/gravity

Turbulence/ $K-\omega$ turbulence/ SST Mentor $K-\omega$

In the simulations, for studying velocity, vector scenes were analyzed and for studying temperature, scalar scenes were analyzed. Also, the residuals in the simulations were convergent and the simulation results had mass balance. Additionally, mass flow monitor and heat transfer monitor verified the accuracy of the results.

Cases	Cells	Faces	Vertices
Barcelona-0	186671	549895	229040
Barcelona-45	179945	530904	22749
Barcelona-no chamfer-0	195798	575620	240398
Barcelona-no chamfer-45	187351	552185	232981
Berlin-0	139188	413673	170285
Berlin-45	141441	419885	173485
Berlin-90	139666	415165	171119

Table 3: Number of cells, faces, and vertices of generated mesh for each simulation case.

Discussion

SIMULATION RESULTS

Temperature and velocity are studied in all seven cases of CFD simulation. Three cases are studied in the urban context of Berlin and four cases are studied in the urban context of Barcelona. Figures 6 and 7 show the temperature and velocity in the urban context of Berlin. Figure 8 represents the temperature in the urban context of Barcelona in both urban contexts with and without chamfered edges. Figure 9 represents velocity for Barcelona. As mentioned above, the cases of Barcelona were simulated at 0º and 45º.

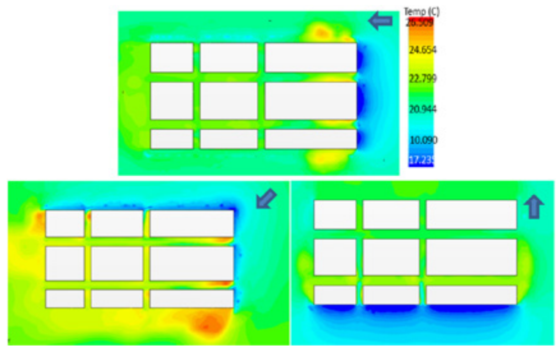

Figure 6: Changes of temperature in different wind directions in Berlin: 0° (top), 45° (bottom left), 90° (bottom right).

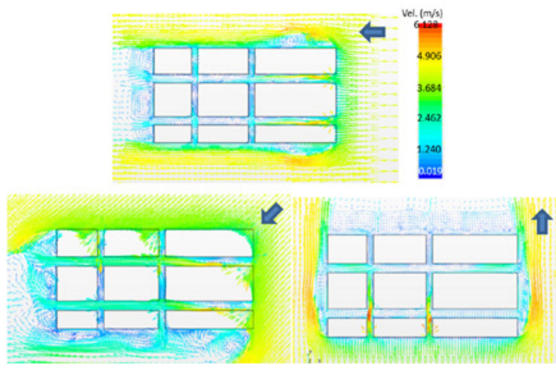

Figure 7: Changes of velocity in different wind directions in Berlin: 0° (top), 45° (bottom left), 90° (bottom right).

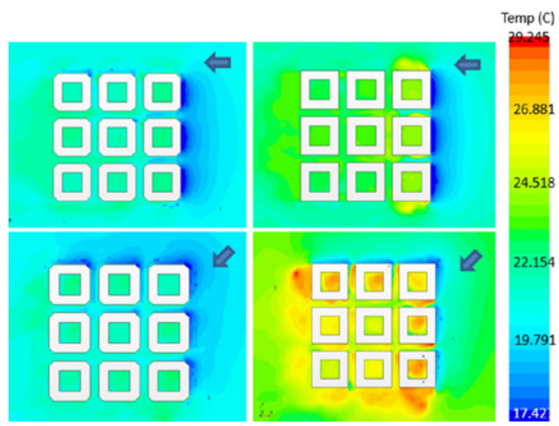

Figure 8: Changes in temperature in different wind directions: 0° (top) and 45° (bottom), with chamfered edges (left) and without chamfered edges (right).

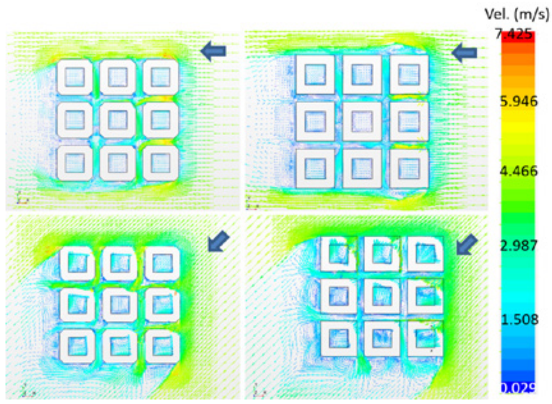

Figure 9: Changes of velocity in different wind directions: 0° (top) and 45° (bottom), with chamfered edges (left) and without chamfered edges (right).

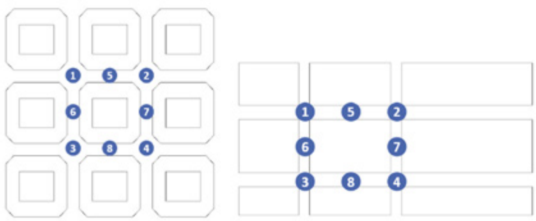

Figure 10: Eight points that are measured in each urban context-Barcelona (top) and Berlin (bottom).

To compare the results of simulations, eight points around a target block in the middle of each urban context are chosen at the pedestrian level. The middle building is chosen because it seems to have the most unpredictable airflow behavior around it. For having comparable results, all of the points were chosen at the pedestrian level (2 m above the ground). These points are measured to represent the air conditions around the buildings in the urban context. Figure 10 shows the eight points that will be measured for each urban context.

The results of the velocity and temperature in the measured points around the buildings are shown in Table 4 for Berlin and Table 5 for Barcelona. The temperature and velocity in each of the eight points in the urban context are measured based on the results of the CFD simulations and are represented in the tables.

		Velocity			Temperature		
		0	45	90	0	45	90
	Point 1	0.78	2.52	1.982	21.3	20.7	21
	Point 2	1.78	2.745	0.29	20.6	20.5	21.8
	Point 3	1.62	2.272	4.405	21	20.9	19.2
	Point 4	1.575	2.357	3.48	21	21	20.8
	Point 5	0.63	2.76	0.46	21.5	20.5	21.7
	Point 6	0.36	0.305	3.042	21.3	21.85	20.3
	Point 7	0.86	0.985	0.39	21.15	21.6	21.9
	Point 8	0.21	2.285	0.96	21.6	21	22.5

Table 4: Velocity and Temperature in eight points around the block in the urban context of Berlin.

	Velocity				Temperature			
	0 w. chamfer	0 w/o chamfer	45 w. chamfer	45 w/o chamfer	0 w. chamfer	0 w/o chamfer	45 w. chamfer	45 w/o chamfer
Point 1	2.8	1.275	0.67	2.21	19.5	21.3	20.45	20.9
Point 2	2.105	1.01	1.165	2.227	20.3	22	20.55	20.4
Point 3	1.98	1.16	1.235	1.6	20.9	21.45	20.95	21
Point 4	1.08	0.84	2.325	1.48	20.9	22.3	20.5	21.2
Point 5	1.27	0.675	2.935	2.485	21.4	22	19.8	20.7
Point 6	2.02	0.895	1.91	0.49	20.65	21.4	20.8	21.9
Point 7	3.055	1.112	3.265	0.77	20.5	22.1	19.9	21.6
Point 8	0.54	0.555	1.75	0.44	21.8	22.15	20.95	21.6

Table 5: Velocity and Temperature in eight points around the block in the urban context of Barcelona.

Then, the results are represented on the line charts. Figure 11 compares the temperature and velocity in different simulation cases for Berlin. Figure 12 compares the same results for Barcelona. Each line in Figures 11 and 12 shows the results of one simulation case for the cities of Berlin and Barcelona. The results of the simulation for each point around the target block can be compared using the charts.

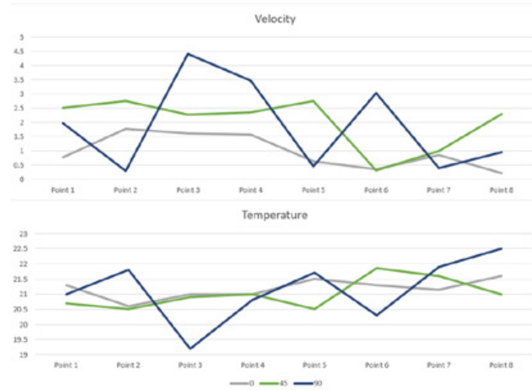

Figure 11: Comparison of Velocity and Temperature in the points around the block for different wind directions in Berlin.

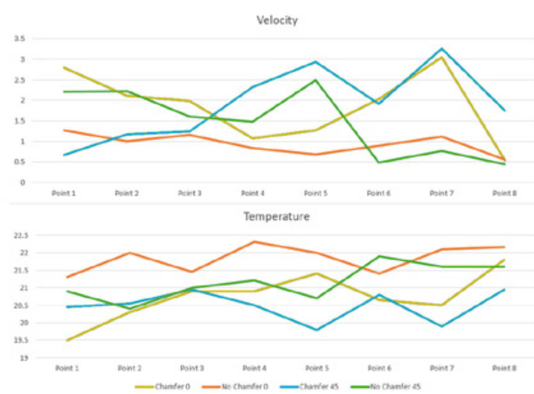

Figure 12: Comparison of Velocity and Temperature in the points around the building for different wind directions in Barcelona.

Conclusion

After comparing the results of measured points at the pedestrian level in the urban context of Barcelona, it seems that an urban context with chamfered block edges has relatively lower temperature and higher velocity around the block. Therefore, when in an urban context where the velocity is not adequate for providing natural ventilation for the buildings, manipulating the urban context and chamfering the edges of the blocks seem to be a solution that helps to provide natural ventilation. In addition, the temperature and velocity results show more fluctuations in the asymmetrical urban context of Berlin, while the results are more predictable in the symmetrical urban context of Barcelona.

Regarding the influence of wind direction on the air around the building, it seems that the temperature tends to be lower with a wind direction of 45º in both Berlin and Barcelona. Although studies on both cities show almost the same results, the results are more evident in the symmetrical urban context of Barcelona. In addition, it is observed in both cities that the velocity is higher with the wind direction of 45º. This result could be used to determine the orientation of the buildings in the urban context for the future development of the cities.

More research must be performed on other aspects of urban morphology, such as building height, urban street canyon width, height to width aspect ratio of the buildings, and so on. As mentioned, for the best results of natural ventilation, it is necessary to study the airflow around the building and the factors that might affect it.

Future Work

This study uses a parametric approach to obtain urban ventilation performance. The buildings in this study have generic configurations in opposed to many research studies that focus on wind performance in real urban morphologies. More research needs to be done on defining urban typology. A couple of examples are mentioned in this proposal. In the next steps of this research, different cases of urban typology in high density cities need to be identified to investigate the effects of urban morphologies on air conditions around the buildings in the pedestrian level. These cases need to be defined considering different aspects of urban morphology in high density cities such as height of the buildings, length and width of the buildings, orientation, street canyon width.

After specifying the urban contexts, CFD simulations could be performed on the urban contexts of high-density cities to recognize the variables that impact urban ventilation the most at the pedestrian level. The results of these simulations then could be used to propose improvements in the urban ventilation of pedestrian level in existing urban context of those high-density cities like Shanghai and Hong Kong. The proposed improvement strategies could be used as guidelines for the architects to provide a suitable environment in the process of developing the urban context of future cities.

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