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The Impacts of Air Pressure Differences on Microclimatic Wind Comfort among Low-Rise Buildings in the Historical Urban Landscape of the Bay of Kotor Region, Montenegro

Enes Yasa and Kadir Özdemir

Abstract

Urban design and urban form can affect ventilation potential by causing flow turbulences around and at the top of buildings, which result in higher wind velocity. The air velocity is either increased or decreased by building blocks, and the solar energy is trapped in the urban canyons formed by buildings on both sides of the streets. The aim of this study was to investigate the effect of building orientation and forms, and street orientations in terms of pedestrian-level microclimatic within the dense structure of the city of the case study area, which is considered the historical texture of the Montenegro region. The another aim was to answer the questions on the relation of the prevailing wind with the wind behavior in the built-up area. This is a multidisciplinary study between urban architecture, and urban physics. The data collection analysis and its interpretation are the numerical part of the study. When the results of the analyses on all prevailing wind directions and flows are examined in detail, building layouts can be revised and optimized to allow sufficient pressure on the facades of buildings with the lowest pressure values around each group of buildings. Otherwise, buildings with insufficient wind flow and therefore buildings with low-pressure values will exposed the insufficient natural ventilation performance.

Keywords: historical texture in urban context, urban design, air exchange rate, pedestrian level wind microclimatic condition, the effect of building orientation

1. Introduction

Due to the rapid increase in urbanization in recent years, urban microclimate studies are gaining popularity. In the meetings held by the United Nations in recent years, “making cities and human settlements climate-resistant and sustainable” has started to be promoted as one of the sustainable development goals [1]. Especially after the Covid-19 pandemic, which emerged all over the world in 2019 and caused the death of thousands of people by affecting their health, researches

on sustainable healthy cities-habitats with the issue of natural ventilation of the city and buildings gain importance and will continue to gain importance in the coming years.

Approaches that emphasize microclimatic comfort sensitivity as part of the urban planning processes implemented to date are rarely included in the design process because there is a general lack of knowledge on how to do this among urban planning practitioners. Many studies conducted so far have documented that urban microclimate can affect building energy performance and occupant thermal comfort balance, especially its effects on human health [2–6]. Urban comfort, which is the most important topic in the field of urban physics, deals with the relationship between wind/thermal comfort of pedestrians and pollutants and wind, which examines the urban air quality to ensure a healthy and happy life for the residences living in the city. Should the importance of urban form in urban design is developed in accordance with the context of urban microclimatic comfort, it can improve the quality of life of millions of people living in cities. The importance of climatically sensitive urban design is very important on the concept of sustainability, which has been a popular decision of recent years. Appropriate urban design enables the use of renewable energy sources for passive natural ventilation at city scale and passive heating and cooling at building scale while increasing pedestrian comfort and efficiency.

2. The characteristics of wind in a built environment

The average wind speed profile near the ground (interface layer) is governed by pressure differences due to the presence of buildings, vegetation, and topography. The nature of the obstacles regulates the turbulence level. When the wind velocity is greater than 10 m/s, the influence of surface friction is predominant in distorting and generating a turbulent flow. Flow disruption depends on the shape and height of the obstacles. The wind does not reach a full speed up to a certain height above the ground (called gradient wind); this height depends on local obstacles and is called surface roughness. Surface roughness and obstacles usually reduce wind speed, but can also have an acceleration effect on the wind. It occurs when airflow passes through a smaller cross-section (for example, passing through a building). It can also happen near tall buildings. Many features of the built environment and atmosphere affect wind speed. Wind speed in the built environment, therefore, exhibits a very complex behavior that is difficult to model.

3. Pedestrian level comfort in urban texture

In recent years, the number of studies on pedestrian comfort levels around buildings has increased in urban textures where building densities have increased. Due to the necessity of analyzing the negative comfort conditions that may occur at the pedestrian level, pedestrian health, and safety conditions very well, the urban texture and buildings have started to be analyzed in detail. The wind is the most important microclimatic parameter that affects pedestrian level comfort around the building. Wind movement manifests itself in basically two ways at the pedestrian level: it can either be felt like a wind speed that affects the heat exchange between people and the environment, or it can be felt as a force from the sum of the pressure field on the human body [7]. Urban wind flow has many effects on pedestrian level comfort, including heat transfer via convection, penetration of rain, dilution of pollutants, noise, or dust removal. In this study, only the mechanical effects of wind on pedestrian comfort are discussed. Pedestrian thermal comfort threshold at pedestrian level

corresponds to wind speeds of about 4.50 m/s [8]. Pedestrian comfort conditions between buildings depend on several parameters. Among these parameters, biological factors such as wind speed, local climate, ambient temperature, precipitation amount, humidity, the activity level in public spaces, clothing, age, and psychological states of people come to the fore. A preliminary assessment of wind behavior at ground level and around buildings can prevent excessive wind speeds [9]. Pedestrian level outdoor microclimatic comfort between buildings can be achieved by applying the right design strategies of building groups together with open/semi-open and closed spaces within the urban texture. For this reason, in advance, meteorological analysis, evaluating the data according to the microclimate of the settlements, and planning the building form and settlement will increase the quality of life.

4. Urban physics and microclimatic comfort analysis with CFD

When both the applications and the literature are examined, it is seen that the number of research studies and applications that take into account the wind, which is the most important parameter of the microclimatic comfort parameter in urban design, is inadequate. Although most of the literature studies generally focus on the details and technical aspects of wind simulation used in the analysis, there are not many studies for urban planning practitioners on how they can apply wind simulation to improve their designs. This naturally means that wind simulation is not used enough in city planning at the moment, which reduces the quality of the outdoor urban area, and unqualified designs are produced.

The application of wind simulation in urban planning in conceptual design, schematic design, and detail design processes in the urban planning process can be preferred especially in schematic and detail design processes since the conceptual design phase is not very detailed by nature. During the schematic design phase, wind behavior between buildings can be considered on a rather macro scale. In the detail stage, wind analyzes may not be very effective in the wind-design relationship, since it is a scale that can be handled at the scale of the building envelope, and at this stage the settlement, shape-form decisions are determined.

There are four methods for analyzing wind speeds and directions. The first is on-site measurements. These provide detailed information, but extensive field measurements are time-consuming and expensive. They only work when analyzing current situations, so their use in predicting the impact of changes on the built environment is limited.

The second is the testing of scale models in wind tunnels. The modeling process itself is fairly simple and sensors can be used to get precise data on wind speeds, but it has two drawbacks. First, measurements are only made where the sensors are located, so their placement becomes critical to the results. Second, a wind tunnel is a specialized piece of equipment and not everyone has physical and financial access to it, which may be seen by urban planners as a barrier to its adoption.

The third method consists of simplified calculation methods. Rather than simulating the actual physical processes that together determine wind behavior, they use simplified, empirical mathematical models to predict wind speed based on surrounding urban geometry. These techniques have a relatively low computational cost but are also less accurate. There is also a lack of user-friendly software for the implementation of these techniques, making them less suitable for practitioners [10].

The fourth method of analyzing wind is computational fluid dynamics (CFD). This is using a computer-based model to simulate real physical processes that together determine the behavior of the wind. CFD provides a complete picture of wind behavior across the entire model and is well established in a variety of fields,

making it more accessible than field measurements, wind tunnel experiments, or simplified mathematical models in general. CFD is also becoming more applicable due to advances in computer technology [11].

Considering all the advantages and disadvantages, wind analyzes, whether alone or comprehensively as a part of microclimate analysis, cannot be used sufficiently in urban planning processes at present [3]. The barriers for CFD are lower than for other techniques, so CFD is the focus of this chapter. When we look at the historical background of urban microclimate studies, they have mostly been done with observational methods such as field measurements. In recent years, with advances in computational resources, numerical simulation approaches have become increasingly popular. Nowadays, especially CFD is frequently used to evaluate the urban microclimate. Computational simulations in urban physics and urban design studies can be used to study urban microclimate at different scales, from meteorological macro–micro scale to building scale [12–14]. Most of the CFD urban physics for microclimate studies have focused on parameters related to temperature, wind flow, thermal comfort, and heat transfer. CFD has repeatedly demonstrated its predictive ability in validation studies focusing on different parameters. CFD provides the possibilities of detailed indoor and outdoor comfort modeling of each building by evaluating inter-building microclimatic parameters at an urban scale. In the past, articles have been published that provide extensive reviews of meteorological micro-scale CFD studies [15, 16].

Advances in the application of computational simulations in recent years have allowed them to develop best practice guidelines in urban microscale studies, so the popularity of the use of CFDs has continued to grow steadily [13, 17, 18]. Micro-scale CFD studies in urban design, pedestrian level comfort between buildings, wind flow around buildings [19–23] pedestrian wind comfort [24, 25] pedestrian thermal comfort [26] the effect of wind-induced rain on buildings [27, 28]. It includes the distribution of urban air quality [29–32] etc. In the literature, there are studies on natural ventilation studies and convective heat transfer coefficients CFD studies for the analysis of the microclimate at the pedestrian level around the buildings at the building scale [12, 13, 15, 16, 21, 26, 33–36]. The smallest-scale studies using CFD on microclimatic analyzes at urban scale are the ones dealing with the indoor microclimatic comfort conditions of the building, where the horizontal distances between buildings are approximately 10 m and the focus is on the indoor climate. CFD has been used primarily for indoor ventilation studies and HVAC design issues in studies on this scale [22, 37–42]. In the last decade, the popularity of topics such as urban settlement/location, urban street canyons, building blocks, courtyards, and urban microclimate has been increasing year by year in studies with CFD on the microclimatic scale of urban physics [43–53]. Most of the studies on real urban areas appear to have been conducted in mid-latitude climates [54].

In the literature, CFD studies on urban physics and microclimatic comfort studies appear as validated and unvalidated studies. CFD studies on the unvalidated real urban area are mostly comparative studies comparing current real comfort conditions of different urban configurations, design parameters, neighborhoods, and districts within the same urban area. Most of these studies target to achieve best-case scenarios based on optimization of a target parameter (e.g. outdoor thermal comfort) [55–58]. Most of the CFD urban microclimate studies are conducted without verification. The percentage share of unvalidated studies seems to have remained fairly stable in recent years. However, it is imperative that CFD urban microclimate studies include much more frequent validation to provide the desired reliability and predictive capability. The most common reason for the lack of validation in CFD microclimate studies may be the lack of relevant and well-documented measurement data [54].

When the field measurements method is used in microclimate studies in real urban areas, meteorological measurements such as field measurements of wind and

air temperature around the street and building are made, this method is relatively simple. However, this methodology may not be possible to use in all urban studies. However, there may be certain limitations in the use of these data for scientific purposes and, in particular, their suitability for validation purposes. This is because the meteorological conditions in the measured urban area are complex and constantly changing, and not only requires careful measurement of a large number of parameters (to be used as boundary conditions in simulations), but also a fairly complete reporting of the urban area, measurement systematics, at the same time, a detailed and comprehensive validation study of the urban area, measurement scheme, measurement accuracy, etc., would not be possible without them [55–58].

When the related articles studies in the literature are examined, in addition to experimental wind tunnel tests and field measurements studies, numerical analysis studies with CFD have been increasing in recent years to examine pedestrian level comfort wind conditions in urban areas. Compared to both wind tunnel tests and field measurements, CFD has some advantages. One of the major advantages of CFD over wind tunnel testing is that it gives detailed flow area data of associated parameters across the entire calculation area.

Another advantage of CFD over wind tunnel measurements is that, in general, wind tunnel measurements are performed at only a few selected points in the model, while CFD provides a more detailed analysis of wind flow around the building(s) by providing data on relevant parameters at all points of the calculation areas [59–61].

This study aims to investigate the effect of building orientation and forms, and street orientations in terms of pedestrian level microclimatic comfort and natural ventilation of pedestrian level comfort conditions in the urban area within the dense structure of the city of the case study area, which is located in the historical texture of Montenegro region. The aim is to answer the questions on the relation of the prevailing wind and the wind behavior in the built-up area. For this purpose, in the case study area of Montenegro, which is a historical settlement area, wind analyzes were carried out in 10 different directions (North, South, East, West, North-East, North-West, South-East, South-West, North- North-East, East- North-East) using the highest wind speed of 30.5 m/s, considering the worst scenarios in the light of meteorological data, as well as cardinal and intercardinal directions as boundary conditions.

This study focuses on the role of wind, which is the most important parameter affecting urban microclimatic comfort, which should be considered in the urban design process. Wind affects primarily urban air pollution and air pressure, as well as the energy exchange of buildings and users with the effect of convective heat transfer. Thus, it becomes one of the main driving forces of urban physics and urban microclimate. To evaluate the natural ventilation potential in the hot-humid climate of the Bay of Kotor region of Montenegro, the air exchange coefficients of the buildings in the case study region were examined. In the study of Moreau and Gandermer [62], on the evaluation of natural ventilation and pedestrian level comfort conditions in the urban area, a table is given about the air exchange rates

Level of natural ventilation efficiency	ΔC_p range
ACH too low	$\Delta C_p < 0.17$
ACH enough	$0.17 \leq \Delta C_p < 0.39$
ACH good	$0.39 \leq \Delta C_p < 0.53$
ACH very good	$0.53 \leq \Delta C_p$

Table 1.
Guidelines for natural ventilation potential [62].

of the buildings in the urban texture and the relationship between natural ventilation (**Table 1**). Guidelines are based on the pressure coefficient differential ΔC_p between upwind and downwind sidewalls of a building.

5. Characteristics of case study area

This study was carried out in the region of the Bay of Kotor Region, Montenegro, located in the historical texture of Montenegro with traditional stone buildings and painted shuttered windows on the edge of the Bay of Kotor. This residential area of this coastal city of Montenegro is located on the Bay of Kotor (**Figure 1**). It is one of the youngest cities on the Adriatic, formerly part of the Ottoman Empire and the Republic of Venice; it characterizes architecture that reflects a mix of Venetian and picturesque architectural styles (**Figure 2**).

Montenegro the Bay of Kotor region has a hot-humid climate with much more precipitation in winter than in summer. Its distinctive topography and high mountains make it one of the wettest places in Europe. This residential area is sunny about 200 days a year. Local meteorological data for this region as relative air humidity is the highest 80% indicator in autumn. It is seen in the summer period with the lowest level of 63%. The average temperature throughout the year is 15°C. The lowest recorded temperature (monthly average) of the studied region was measured at -1°C in January 2017, and the highest temperature (monthly average) was measured in July 2015 at 29°C (**Figure 3**).

Annual average local atmospheric wind conditions for the Bay of Kotor Region, Montenegro are shown in the wind rose plotted in **Figure 3**. It is clear that northerly

Figure 1. The bay of Kotor region, architectural and urban characteristic and settlement pattern of the region where the study was conducted (https://elevation.maplogs.com/poi/bijela_montenegro.436217.html).

Figure 2.
The façade architecture and street façade texture characteristic of the region where the study was conducted (<https://tr.depositphotos.com/275544506/stock-photo-narrow-streets-in-the-old.html>).

Figure 3.
Meteorological measurement data of 1951–2017, average temperature values, and wind rose for the bay of Kotor region, Montenegro.

winds prevail throughout the year. Also, in **Table 2**, maximum wind speeds are given for all directions.

The Bay of Kotor Region, Montenegro, the case study area located in the heart of Boka Bay, is close to the two historic medieval towns of Perast and Kotor and the Adriatic Coast. The area of Kotor has been classified as a UNESCO World Heritage Site since 1979 due to its historical and cultural significance (**Figure 4**).

6. Methodology and numerical modeling

CFD software is the most popular tools used to calculate the wind flow to balance the microclimate within the built environment in the urban texture. These allow easy understanding and interpretation of the flow characteristics of the wind around buildings in any urban area. For urban designers and architects, the wind flow velocity and pressure values obtained as a result of CFD analysis during the design process are used to optimize the urban texture draft project in terms of layout approaches, location, and orientation of buildings to provide the correct microclimate. It also facilitates the detailed evaluation of the comfort conditions in the texture and the wind comfort condition for pedestrians.

Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Maximum wind velocity (m/s)	18.7	30.5	30	21	18.9	15.5	17	12	12	14.4	10	12.3	17	10	6	18

Table 2.
Wind direction & velocities for Montenegro.

Figure 4.
 Plan and landscape view of the case study area.

In this study, CFD Fluent was preferred to simulate pedestrian level comfort conditions and wind condition environments due to both the bureaucratic and economic constraints encountered for field measurements and the more comprehensive analysis parameters provided by numerical simulation. The CFD simulations were performed using CFD code Fluent and the 3D steady RANS equations. The closure was provided by the realizable (k- ϵ) turbulence model. The choice of this turbulence model was based on recommendations by Franke et al. [63] and earlier validation studies for pedestrian-level wind conditions [64]. Sensible modeling of the atmospheric boundary layer in CFD is one of the most important criteria in external aerodynamic analyzes around the building. Many of the analysis software conduct flow analysis for materials with a low roughness coefficient, and therefore the roughness coefficient is defined as 0 in the CFD. Depending on the region where the structure is located, the roughness coefficient should also be defined. Since it is an open zone surface, the surface roughness is defined as 0.2 m [9].

Pressure differences occur on the surfaces of buildings exposed to wind. Due to the pressure difference in the building envelope caused by the wind and the density difference between the indoor and outdoor air, it causes air exchange around the building and in the buildings. Pressure coefficients largely depend on the shape of the buildings and the influence of neighboring buildings. The pressure field in a complex urban area can be analyzed to reveal the potential for natural ventilation in the urban texture. Modeling of wind flow and velocity around buildings in urban texture has traditionally been applied with full-scale measurements and wind tunnel tests when studies in the literature are examined. However, the creation and adaptation of atmospheric flow conditions in wind tunnel tests is a serious problem. Numerical simulations based on CFD are quite common as a tool to support the assessment of airflow around buildings in urban texture. CFD solves the problem of establishing and adapting atmospheric flow conditions encountered in a wind tunnel by providing both the actual wind flow velocity of the study area and the distribution of turbulence over the entire study area. The case study area of wind modeling, which takes into account regional terrain conditions and meteorological period average data of the region, includes surface roughness modeling in an atmospheric boundary layer [60, 65, 66].

Although RANS remains very popular in research projects, especially in the areas of wind flow and comfort between buildings, urban air pollutants and pollution dispersion, urban thermal performance, urban natural ventilation, and indoor airflow, the application of the large eddy simulation (LES) technique allows taking into account the characteristics of the wind at the atmospheric scale. The LES provides a deeper insight into the unstable flow properties. Many situations that are

interesting for urban planning applications still seem to be beyond the reach of such simulations today [60].

Pressure fluctuations occurring on building surfaces depending on the average wind speed lead to both laminar and turbulent flow through leaks from the surface and between buildings [67]. High-frequency fluctuations around buildings create a turbulent distribution of air across inter-building openings containing eddies of similar or smaller size. The frequency-domain analysis of wind speed and wind pressure on the building facades is effective on the rate and amount of air exchange.

Wind-induced air change rate ACH (1/h) is given by the following equation.

$$ACH_d(t) = \left(\frac{3600}{V} \right) \sum_{j=1}^n (K_{d,j}(V_q)) A_j \quad (1)$$

$$\left[0.5\rho(Cp_{d,j}^{ext} - Cp_{d,j}^{int})V_d^2(t) + 0.04z_j\Delta T(t) \right]^{0.5} \quad (2)$$

This equation describes the calculated air exchange rate for different building components that are exposed to a positive pressure difference or a negative pressure difference caused by the wind blowing from d at time t .

$K_{d,j}$ in the formula; a leakage function presented as a linear function of V_q regarding the flow rate from the building openings to the area of the building component j and the corresponding pressure drop across the openings for the wind blowing from there, $d(\sqrt{m^3/kg})$; v_q —“frictionless flow rate” (m/s) through openings; n —the number of elements of the building envelope facing only positive or only negative pressure difference; V —volume (m^3); A_j —area of j th element (m^2); ρ air density (kg/m^3); $Cp_{d,j}^{ext}$; assumed external pressure coefficient (–) for facade j exposed to wind from direction d ; $Cp_{d,j}^{int}$; assumed internal pressure coefficient for facade j exposed to wind from direction d (–); $v_d(t)$ —wind blowing from direction d (m/s); z_j —the vertical distance from the neutral pressure layer to the center of the j th building element (m); $\Delta T(t)$ —10-min mean temperature difference between outside and inside (K) treated later on as slowly changing 1-hour mean.

Pressure differences and fluctuations in wind flow caused by turbulence around buildings affect airflow through openings and cracks in the building envelope and between buildings. The character of the wind flow depends on the scale of the wind flow length and the geometrical properties of buildings and their cracks in relation to the Reynolds number for airflow [68, 69].

7. Computational domain settings-parameters and meshing system

A solid model of the case study area was created with the information obtained from the 2-D architectural project and site plans of the buildings. Three-dimensional model of the project is illustrated in **Figure 5**. The definition of wind direction is illustrated in **Figure 3**. The CFD model represents buildings set along with the real topography of their location. The 1000 m × 1000 m topography, where the case study buildings are situated has been obtained from the Google Earth software. For the atmospheric boundary layer to be formed correctly, a denser grid was used in regions with rapid changes in geometry and near the surface. As a result, the quality of the grid affects the precision when the results are compared with the experimental values. Using the grid tuning twice during the analysis caused the grid

Figure 5.
3D model view of the case study.

to become denser where necessary and the flow solution to converge in the continuous flow regime. It was applied automatically in every 300 iterations depending on the average pressure changes on the predetermined surfaces in the buildings. The design of buildings must account for wind loads, and these are affected by wind gradients. The respective gradient levels, usually assumed in the Building Codes, are 500 m for cities, 400 m for suburbs, and 300 m for flat open terrain [70].

The approaching wind was created from a power-law model to approximate the mean velocity profile:

$$U = U_r + \left(\frac{Z - d}{Z_r} \right)^\alpha \quad (3)$$

where; U = mean wind speed, Z_r = reference height, U_r = wind speed at reference height Z_r , d = zero plane displacement, and α = power-law exponent. The exponent α varies according to the type of terrain; $\alpha = 0.14$, 0.25 , and 0.33 for open country, suburban, and urban exposures, respectively. At the inlet condition, the power-law equation is used to simulate a mean wind velocity of 30.5 m/s at the building height according to an exponent α , which depends upon the surface roughness of the terrain surrounding the building model. The input parameters for wind density, ρ , and wind dynamic viscosity, η are based on the real wind characteristic.

Mean wind velocity 30.5 m/s was used as inlet boundary conditions at ten directions. A total of 30.5 m/s maximum wind velocity was used as inlet boundary conditions at ten directions as shown in **Table 1**, so that the worst scenarios could be considered.

The accuracy of simulation results is highly dependent on the appropriate computational modeling, such as domain size, grid size, and grid discrepancy. Therefore, the CFD simulation modeling for the validation approach discussed in this study complies with the AIJ (Architectural Institute of Japan) guidelines, which is one of the standards in the literature for the urban pedestrian wind environment. AIJ guidelines are based on a series of cross-comparisons between CFD, wind tunnel experiments, and field measurements. In contrast, another popular guideline, cost recommendations, is based on a literature review [71]. The calculation area size for the validation experiment is 500 m $\times$ 500 m $\times$ 50 m ($W \times L \times H$). The domain is divided into 125,170 grid points. Pressure velocity coupling was taken care of by the simple algorithm. Second-order discretization schemes were used for viscous terms of the governing equations. Simulations were performed for ten wind directions as seen in **Table 3**. The iterations were terminated when the scaled residuals showed a very little further reduction with an increasing number of iterations. The following minimum values were reached:

Description of the terrain	Power law exponent, α	Gradient height, z_g
For open country, flat coastal belts, small islands situated in large bodies of water, prairie grasslands, tundra, etc.	(0.14)	900 ft. (274 m)
For wooded countryside, parkland, towns, outskirts of large cities, rough coastal belts	(0.29)	1300 ft. (396 m)
For centers of large cities	(0.40)	1700 ft. (518 m)

Table 3.
Power law exponents for various descriptions of terrain.

Figure 6.
Computational domain mesh numerical grid system.

For x , y , z -velocity components: 10^{-8} . For $(k - \epsilon)$: 10^{-7} . For continuity: 10^{-6}

Four layers (layer height: 0.5 m) are arranged below the assessment height (2.25 m above ground) to comply with AIJ guidelines. In the first step, a flow volume is created around the buildings. This area is called the computational area. This area is knitted with the network structure while creating the mathematical model. Then, boundary conditions are defined. After these definitions are made, the equations are solved and the result is reached. In all simulations, a denser network structure has been created in areas where velocity and pressure gradients are predicted to be high.

The first step is to discretize a part of the continuous space around the considered building. This part of space is named the computational domain. The domain was divided into a finite volume. For each volume of the computational domain, the basic equations were set up. Subsequently, the equations are solved given a set of initial and boundary conditions. For all performed simulations a mesh is used which is denser in regions where velocity gradients or pressure gradients will be high. An example of the mesh used is illustrated in **Figure 6**. The computational domain mesh consisted of about 12 million polyhedral and hexahedral cells.

8. Results and discussion

Pressure differences occur on the surfaces of buildings exposed to wind. Due to the pressure difference in the building envelope caused by the wind and the density difference between the indoor and outdoor air, it causes air exchange in/around the buildings. Evaluation of the effect of wind on the air exchange rate is generally limited to analysis of hourly average wind speed. The wind pressure and the pressure coefficient in the leeward area mostly depend on the form characteristics of the building according to the wind direction. The frequency-domain analysis of wind speed and wind pressure on the building facades is effective on the rate and amount of air exchange. Thus, due to the changing rate and amount of air exchange around

the building, the amount of air exchange around the building will vary in the urban texture, and both the urban air quality and the pedestrian level will be effective on microclimatic comfort values. Air exchange in buildings and around the buildings is caused by the pressure difference in the building envelope caused by the wind and the density difference between the outside and indoor air. So, the minimum and maximum wind pressure difference on buildings causes air exchange around and inside the building [69]. For this reason, in this study, the minimum and maximum pressure values that affect the amount of air exchange around the buildings in the urban texture were examined. Evaluation of the effect of wind on the air exchange rate is generally limited to analysis of hourly average wind speed.

It was observed that the region with the highest pressure difference occurred in the region where the C01-C05-SPA buildings and TOWER buildings are located (Figures 7 and 8). In the case of northerly wind flow, the highest air exchange rate between buildings was observed in the region where the C01-C05-SPA-TOWER buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in Table 1, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C01-C05-SPA buildings are located (Figures 9 and 10). In the case of southerly wind flow, the highest air exchange rate between buildings was observed in the region where the C01-C05-SPA is located. When the ACH around the buildings is evaluated according to the ΔC_p values in Table 1, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

Figure 7. Maximum & minimum pressure on building facades for wind direction: North (N).

Figure 8. Velocity streamlines and pressure gradient for wind direction: North (N).

Figure 9. Maximum & minimum pressure on building facades for wind direction: South (S).

Figure 10. Velocity streamlines and pressure gradient for wind direction: South (S).

It was observed that the region with the highest pressure difference occurred in the region where the C01-ML-SPA-MP buildings are located (**Figures 11 and 12**). In the case of East wind flow, the highest air exchange rate between buildings was observed in the region where the C01-ML-SPA-MP are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C01-C04-ML-P2-SPA buildings are located (**Figures 13 and 14**). In the case of west wind flow, the highest air exchange rate between buildings was observed in the region where the C01-C04-ML-P2-SPA buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C01-ML-SPA buildings are located (**Figures 15 and 16**). In the case of North–East wind flow, the highest air exchange rate between buildings was observed in the region where the C01-ML-SPA buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C02-P2-P3-SP buildings are located (**Figures 17 and 18**).

Figure 11.
Maximum & minimum pressure on building facades for wind direction: East (E).

Figure 12.
Velocity streamlines and pressure gradient for wind direction: East (E).

In the case of North-West wind flow, the highest air exchange rate between buildings was observed in the region where the C02-P2-P3-SP buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C01-C05-P2-TOWER buildings are located (**Figures 19 and 20**). In the case of South-East wind flow, the highest air exchange rate between buildings was observed in the region where the C01-C05-P2-TOWER buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are

Figure 13.
Maximum & minimum pressure on building facades for wind direction: West (W).

Figure 14.
Velocity streamlines and pressure gradient for wind direction: West (W).

Figure 15.
Maximum & minimum pressure on building facades for wind direction: North-East (NE).

Figure 16.
Velocity streamlines and pressure gradient for wind direction: North-East (NE).

other building groups other than the building groups where the lowest and highest pressure differences are seen.

It was observed that the region with the highest pressure difference occurred in the region where the C01-ML-SPA-SP buildings are located (**Figures 21 and 22**). In the case of South–West wind flow, the highest air exchange rate between buildings was observed in the region where the C01-ML-SPA-SP buildings are located. When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

Figure 17.
Maximum & minimum pressure on building facades for wind direction: North–West (NW).

Figure 18.
Velocity streamlines and pressure gradient for wind direction: North-West (NW).

When the maximum and minimum wind pressure values resulting from the wind flows coming from different directions on the roof surfaces of the buildings in the study area were observed, the lowest pressure values were caused by the wind flows coming from the NE and NNE directions (**Figure 23**).

In this study, a total of ten wind directions, four cardinal directions, and six intercardinal directions were discussed on the settlement pattern in the historical Montenegro region, which was considered as a case study. In this chapter, the results of four main directions and four intermediate directions are evaluated in detail. Air exchange in and around buildings is caused by the pressure difference of the wind on the building envelope and the density difference between the outside and indoor air. Therefore, in this study, pressure differences on buildings, which are one of the sources of air changes occurring around the building, are discussed in detail. In this context, the wind directions that cause the most air change on the buildings in the

Figure 19.
Maximum & minimum pressure on building facades for wind direction: South-East (SE).

Figure 20.
Velocity streamlines and pressure gradient for wind direction: South-East (NW).

Figure 21.
Maximum & minimum pressure on building facades for wind direction: South-West (SW).

Figure 22.
Velocity streamlines and pressure gradient for wind direction: South-West (SW).

urban texture, which is considered first, are the wind flows coming from the NE and NNE directions.

According to the relationship between the rates of change in the surface pressure differences of the buildings and the air variability between the buildings, the data obtained as a result of the analyzes were examined in detail, it was observed that the C01-C05-ML buildings were the building group with the highest pressure difference and showing similar characteristics in all wind directions. The positive wind pressure is the pressure acting toward the wall, whereas the negative pressure/suction is the pressure acting away from the wall of models. From the pressure contours, it can be observed that on the windward face a positive pressure distribution is observed. The maximum positive pressure is 0.75 kPa at the C01 building on the NNE–ENE

Figure 23.
Maximum & minimum pressure on roofs.

wind direction. Maximum negative pressures (suction pressures) occurred mostly at the ridges and edges of buildings as shown from pressure gradient results.

The wind load also varies between points on the building envelope, with ridges, corners, and edges most susceptible to high wind pressures. These locations are likely to require careful detailing.

When the ACH around the buildings is evaluated according to the ΔC_p values in **Table 1**, it is seen that it is an enough and good level in the regions where there are other building groups other than the building groups where the lowest and highest pressure differences are seen.

When the results of the analyzes on all prevailing wind directions and flows are examined in detail, building layouts can be revised and optimized to allow sufficient pressure on the facades of buildings with the lowest pressure values around each group of buildings. Otherwise, buildings with insufficient wind flow and therefore buildings with low-pressure values will be exposed the insufficient natural ventilation performance.

9. Conclusion

The chapter focused on a numerical methodology to assess the effect of building orientation and forms, and street orientations in terms of pedestrian level microclimatic comfort and natural ventilation of pedestrian level comfort conditions in historical urban texture within the dense structure of the city of the case study area, which is located in the historical texture of Montenegro region. The microclimatic conditions around the buildings in the urban texture depend on the layout design decisions of the buildings forming the texture and accordingly the actual wind condition conditions between the buildings. The actual wind condition is the result of the interaction of all kinds of ground obstacles around the buildings with the wind as well as the coming together of the buildings. It depends on the wind speed and direction at different levels from the ground and the shape of the obstacles (architectural form, physical plan), building airtightness (or permeability), and the position of adjacent buildings relative to each other (urban plan).

Making the design suitable for the microclimate in the urban texture; can be achieved by analyzing the wind speed and pressure differences between the buildings, choosing the appropriate place according to the natural morphology of the land, consciously designing the form of the building, placing the adjacent buildings, and arranging the distances between them correctly. The results obtained in the case study in question showed that; it has been observed that the desired air flows are obtained

even at very high wind speed in the areas between buildings, with the effect of the correct settlement in the urban texture and the correct spaces left between the buildings.

Consequently, architects and urban planners need to use wind and comfort analysis software effectively in the design process in-line with microclimatic comfort and sustainable urban planning sensitivity, both when making settlement decisions in historical texture and when making urban design and building architectural project design decisions in open land.

Author details

Enes Yasa^{1*} and Kadir Özdemir²

1 Faculty of Architecture, Department of Architecture, Istanbul University, Istanbul, Turkey

2 Faculty of Engineering, Department of Mechanical Engineering, Uludag University, Bursa, Turkey

*Address all correspondence to: enesyasa@istanbul.edu.tr

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