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Research paper

WIND FLOW MODELING IN EARLY URBAN DESIGN

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Abstract

Buildings affect the wind flow pattern over an urban area. The wind has a significant effect on the comfort and safety of pedestrians, urban microclimate, and pollutant dispersion. It is important to include wind flow modeling in the early urban design to minimize wind safety issues and ensure pedestrian comfort. In this paper, numerical simulations based on Computational Fluid Dynamics (CFD) are performed to study the effect of four case study building layouts on the distribution of wind pressure, wind speed, and turbulence kinetic energy. The ANSYS software was used to simulate wind flow. Three-dimensional numerical simulation was employed, with the standard k-ε turbulence model. Simulation results show that urban space design with narrow passages between buildings leads to a significant increase in local wind speed and causes wind nuisance for pedestrians. When the wind is perpendicular to the buildings, the reverse flow zone behind buildings is much narrower compared to other cases. The corners of the buildings are the regions with high-speed flow due to the side vortices. Placing restaurant terraces, gardens, etc. close to these regions should be avoided due to safety issues and discomfort. Findings from this research can equip architects and urban planners with informed decision-making tools to create more comfortable urban environments.

Key words: *urban planning; urban design, wind flow, CFD, turbulence*

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1. INTRODUCTION

Airflow depends on air pressure and temperature. Warm air rises, creating a low-pressure area while cool air sinks, creating a high-pressure zone. Airflow from zones of high pressure to low pressure creates winds. When it comes to buildings, the pressure distribution on the building envelope occurs due to the difference in the air density in the indoor and outdoor space caused by the temperature differences, the effect of the wind, and the ventilation system. Wind speed depends on many factors, such as relief, vegetation, and buildings. The roughness of the ground surface affects the airflow just above it due to the frictional drag. This surface friction slows the wind and changes the wind direction. This bottom layer, where friction changes the wind's speed and direction, is called the planetary boundary layer. Within the atmospheric boundary layer, with increasing height above the ground, the wind speed increases starting from zero (where frictional forces are maximum) to some constant value far from the ground. The thickness of the boundary layer depends on the shape and roughness of the ground surface. Over flat areas such as oceans and deserts, the height of the boundary layer can be less than 150 m, while over large cities with tall buildings, it can be 500 m. The impact of strong winds on structures can be very destructive. Therefore, it is necessary to determine the wind load on buildings to avoid safety issues on construction sites. The wind speed increases with the distance from the ground, so high-rise buildings are exposed to stronger wind. High-rise buildings change not only the wind direction but also change wind speed due to friction [1]. In urban areas, the wind speed is reduced by 25-30% compared to rural open areas. Although the mean wind speed is reduced, the gust wind speed in urban areas is significantly increased due to enhanced friction velocity and less atmospheric stability induced by urbanization [2].

Wind patterns becoming more erratic and turbulent due to extreme weather events related to climate change. The risks associated with strong winds are increased in urban areas, due to the abundance of objects. The change in wind speed influences pedestrian comfort near the building. Pedestrian comfort needs to be considered during buildings and urban design. To evaluate the wind conditions information is required on what acceptable or unacceptable conditions are. Table 1 shows the classification of wind speed and human body feeling based on [3]. A wind speed of 10 m/s at pedestrian level is considered to be uncomfortable with movements affected, while a wind speed from 1 m/s to 5 m/s is considered to be the most comfortable for humans [4]. The change in wind speed and direction in urban areas affects also the energy efficiency of buildings. The wind flow angle affects the natural ventilation and the building energy consumption [5].

Table 1. Wind speed and human body feeling

Wind Speed	Human Body Feeling
< 1	breezeless
1–5	comfortable
5–10	uncomfortable with movements
10–15	very uncomfortable with movement
15–20	intolerable
> 20	dangerous

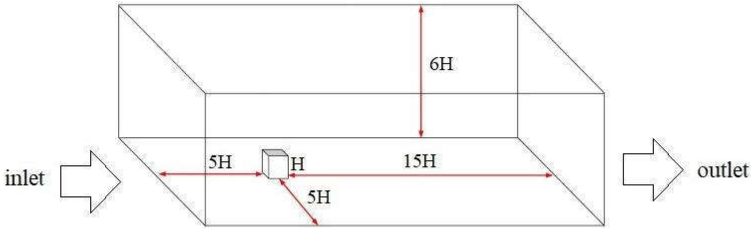
Wind disruption can be reduced by designing buildings with shapes that decrease downdraught. In cases of existing buildings, the best approach is planting trees to slow down wind [6]. A physical modeling investigation for wind engineering is carried out in wind tunnels on a scale model under strictly controlled conditions. Wind tunnel testing is used to evaluate the wind effects on buildings and structures. Field measurements give realistic parameters, however, they require a lot of resources, time, and labor. In the model tests, the hydrodynamic similarity between the model and real scale object needs to be ensured [7]. Wind tunnel tests are complex, expensive, and time-consuming, instead numerical simulations are used based on Computational Fluid Dynamics (CFD). The process of wind flow modeling consists of several steps. First, the size of the computational domain, which provides a volume where the flow takes place, should be determined. Second, the domain should be discretized with a mesh of finite volumes, and then appropriate numerical approximations should be adopted. A set of non-linear partial differential equations defines the wind flow. The final step is the definition of criteria that will enable the completion of the iterative procedure to solve the set of equations.

In cities, the wind flow becomes complex when it interacts with buildings, creating various effects that are often a source of discomfort for users such as acceleration, vortices, downdrafts, etc. Wind flow around buildings depends on building density [8], roof shape and angle [9], while heights and layouts of buildings affect urban ventilation [10], [11]. Wind flow around building layouts is crucial to consider in early urban design to ensure good living conditions in urban environment. Understanding wind flow patterns around buildings is important for urban microclimate, diluting pollutants, and improving living conditions in urban areas. This paper explores the wind flow around four different layouts of buildings using CFD simulations. This research is based on the questions: What is the change in the pattern of pressure, velocity, and turbulence kinetic energy with the change in building's layout? Simulations of wind flow around buildings were performed in ANSYS software [12].

2. METHODS

The CFD simulations of wind flow over four different layouts of buildings were performed in ANSYS software (Student Version 18.1) which is based on the finite volume method [12]. A 3D rectangular computational domain, shown on example of one building (Figure 1a), was used for wind flow modeling. The 5H (H is the building height) distance from the inlet to buildings and 15H from the outlet to buildings was used based on the study [13]. These distances ensure the full development of turbulent flow. The downstream length of the domain is larger compared to the upstream length due to reestablishing a uniform flow of wind flow on the building leeward side. From the top of the building to the upper boundary of the domain, a distance of 5H was adopted to prevent the induced acceleration in this zone. A tetrahedral grid shown in Figure 1b) was used for the computational domain and model of building. To capture more details of the wind flow patterns the finer mesh was used around the buildings. Larger grid elements were applied to the domain far from the building to decrease computing time. It was considered that the convergence is ensured when the residual fell below the 10^{-4}.

(a)



(b)

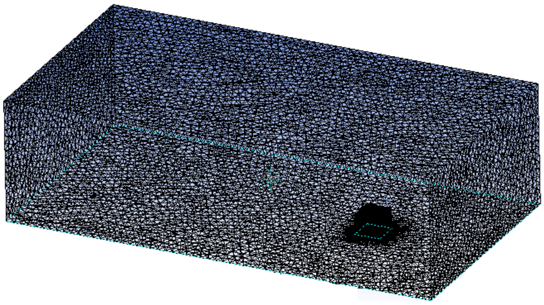


Figure 1. (a) Computational domain, (b) Grid used for the domain and buildings

Wind flow was represented by conservation of mass and momentum equations-RANS (Reynolds averaged Navier-Stokes).

$$\frac{\partial \bar{v}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j}\right) = \rho\bar{F}_i - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\eta\frac{\partial \bar{v}_i}{\partial x_j} - \rho\overline{v_i{}'v_j{}'}\right) \tag{2}$$

It is challenging to model wind flow because there is no mathematical way to determine turbulence. Turbulence is estimated by different models to account for turbulence kinetic energy and dissipation of turbulent kinetic energy. The standard k-ε turbulence model was used to simulate the mean wind flow characteristics for turbulent flow. Two supplementary equations are used for the turbulent kinetic energy and rate of dissipation of turbulent kinetic energy. The SIMPLE algorithm was used as a relationship between velocity and pressure corrections.

$$\left(\frac{\partial k}{\partial t} + \bar{v}_j\frac{\partial k}{\partial x_j}\right) = P - \rho\varepsilon + \frac{\partial}{\partial x_j}\left(\left(\eta + \frac{\eta_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) \tag{3}$$

$$\rho\left(\frac{\partial \varepsilon}{\partial t} + \bar{v}_j\frac{\partial \varepsilon}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\left(\eta + \frac{\eta_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

The production term represents an energy transfer between the mean kinetic energy and the turbulent kinetic energy (Reynolds stress).

$$P = -\rho\overline{v_i{}'v_j{}'}\frac{\partial \bar{v}_i}{\partial x_j} \tag{5}$$

Five empirical constants appear in the equations have the following values in case of simulation of wind flow.

$$C_\eta = 0.09 \quad C_{\varepsilon 1} = 1.44 \quad C_{\varepsilon 2} = 1.92 \quad \sigma_k = 1 \quad \sigma_\varepsilon = 1.3 \tag{6}$$

For the simulation of the wind flow following boundary conditions was used:

- wind speed at the inlet of the domain,
- atmospheric pressure at the outlet of the domain.

At the inlet to the domain, a constant wind speed was set along the height, while atmospheric pressure was set at the outlet of domain. The no-slip condition is used walls of the buildings. The air temperature at the inlet and outlet of the domain was 26°C, while the intensity of turbulence was 5%.

3. RESULTS

Wind flow around the four different layouts of buildings was simulated:

- Case 1: Two rectangular buildings with dimensions of 70x25x40 m. The distance between the narrowest and widest part is 25 m and 95 m, respectively and the angle between buildings is 60°. The wind flow speed is 7 m/s.
- Case 2: Cube parallel buildings with dimensions 10x10x10 m. The distance between the buildings is 10 m. The wind flow speed is 8 m/s and it is perpendicular to the buildings.
- Case 3: Cube buildings with dimensions 10x10x10 m rotated 45° towards the wind flow. The distance between the buildings is 15 m. The wind flow speed is 7 m/s.
- Case 4: Rectangular buildings, with dimensions 10x20x10 m. The distance between the buildings is 20 m in the longitudinal direction and 50 m in the transverse direction. The wind flow speed is 10 m/s. The buildings are rotated 45° towards the wind flow.

The pressure contours around buildings in a horizontal plane are shown in Figure 2. The horizontal plane is positioned at half of the building's height. In all cases, the positive pressure is on the windward side of the building, while the negative pressure is on the leeward side of the buildings. Besides the leeward side, the negative pressure can be noticed on the top face and lateral sides of the buildings, due to flow separation. The rectangular buildings have a larger zone of negative pressure on the leeward side compared to cube buildings. In Case 1 (two rectangular buildings, diverging flow) there is a Venturi effect because the buildings are close together. The Venturi effect is especially expresses when wind passes between two high-rise buildings [14]. The flow in diverging passages is a superposition of the corner flow near the upstream outer corners of buildings. In the shortest distance between buildings, there is a pressure decrease due to an increase in velocity. Many researchers have found that the urban space design with long and narrow passages between buildings can lead to a significant increase in local wind speed and cause wind nuisance for pedestrians [15-16]. The low-pressure zone draws in the wind from the high-pressure zone, where the wind with high wind speed creates a natural flow. In Cases 2, 3, and 4, the pressure is highest on the winward sides of the first row of buildings, while the lowest pressure is on the leeward sides of the first row of buildings. In the case of nonsymmetric buildings and non-perpendicular wind flow (Case 1, 3, and 4) the underpressure zone on the leeward sides of buildings is wider compared to Case 2.

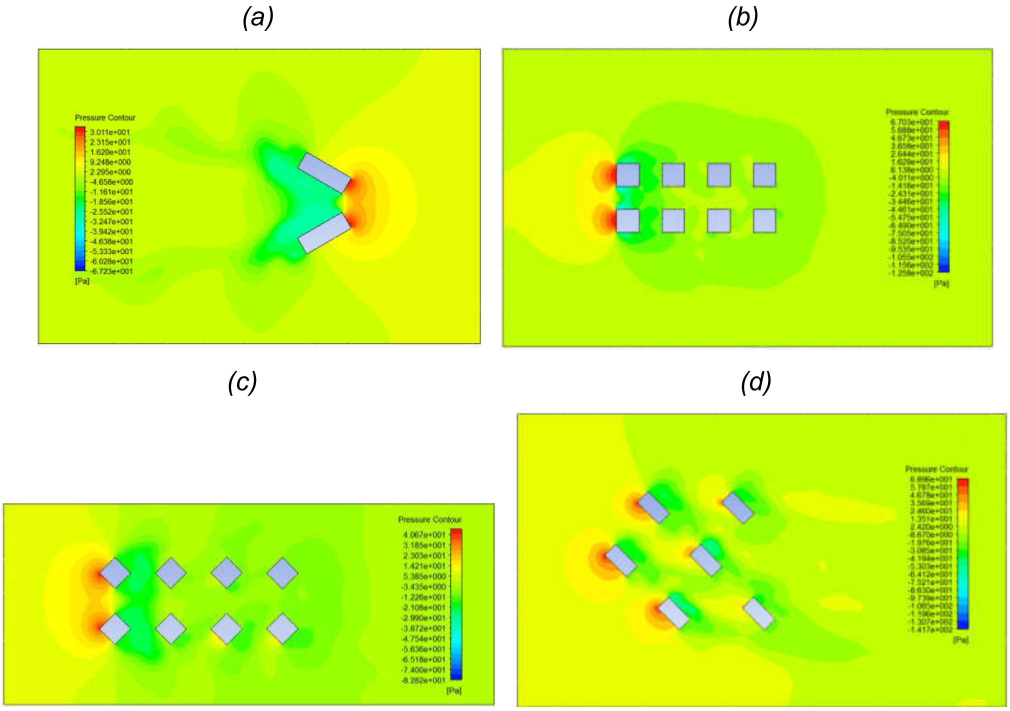


Figure 2. Pressure contours around buildings in horizontal plane:
a) Case 1, b) Case 2, c) Case 3, d) Case 4

The velocity contours around buildings in a horizontal plane are shown in Figure 3. In all observed cases, the flow separation occurs at the lateral sides of the buildings where zones of increased wind speed can be observed (red area in Figure 3). The wind speed in this region can be reduced by: rounding corners of buildings, designing buildings with decreasing heights (pyramid buildings), or adding rows of trees to provide shelter at the pedestrian level. There is a large velocity gradient in these positions and underpressure zones. The corners of buildings are the zones with the most discomfort, due to the side vortices created from the difference in pressure between the windward and the leeward side. It is recommended to avoid placing gardens and restaurant terraces close to these areas. The wind flow patterns show more substantial disturbance on the leeward side than on the windward side. The velocity contours clearly show the existence of a turbulent zone on the leeward side. The wind reaches the undisturbed field far away from the building. The wider buildings disturb a longer and wider region on the windward and leeward sides of the buildings. In Case 1, at the ends of the lateral sides of the buildings, there is a separation of the wind flow and an increase in its speed (red area in Figure 3a). In Case 2 and Case 3, the wind flow separates at the lateral sides of the first row of buildings (red area in Figure 3a and b). The Venturi effect can be noticed in the Cases 2, 3, and 4. This effect is very unfavorable, due to the increase in the load on the buildings and the impact on pedestrians. Between the buildings in the so-called passage or urban canyon, there is a decrease in pressure and an increase in wind speed. In Case 1, wind speed is the highest at the beginning of the passage, where the distance between the buildings is the smallest. Further, as the passage widens, the flow velocity drops.

In Cases 2, 3 and 4, the wind speed is higher in the first row of buildings compared to the other rows. As the wind flows towards the lateral sides of buildings, the direction of the wind flow is no longer orthogonal to the wall of the building. Instead, it becomes parallel to the wall, so the pressure gradient increases towards the corners of the building. On the leeward side of buildings the wind currents cannot immediately "approach" due to the inertia of the air, and the current wave remains where it is separated from the walls. This is in agreement with the study [17], in which it was shown that the return flow is formed only at the first building in a series of buildings of equal height. A zone of turbulent flow is formed behind each building. When the wind is non perpendicular to the buildings (Case 3 and 4) the zone of reverse flow behind buildings is much wider compared to Case 2. This turbulence flow contributes to the feeling of discomfort on the leeward side of the buildings. In Case 4, a zone of reverse flow is also formed on the leeward side of the buildings, but in this case, it quickly calms down before the wind current reaches the next building in the row. The distance between the buildings is greater, so after passing the first buildings, the wind renews its profile.

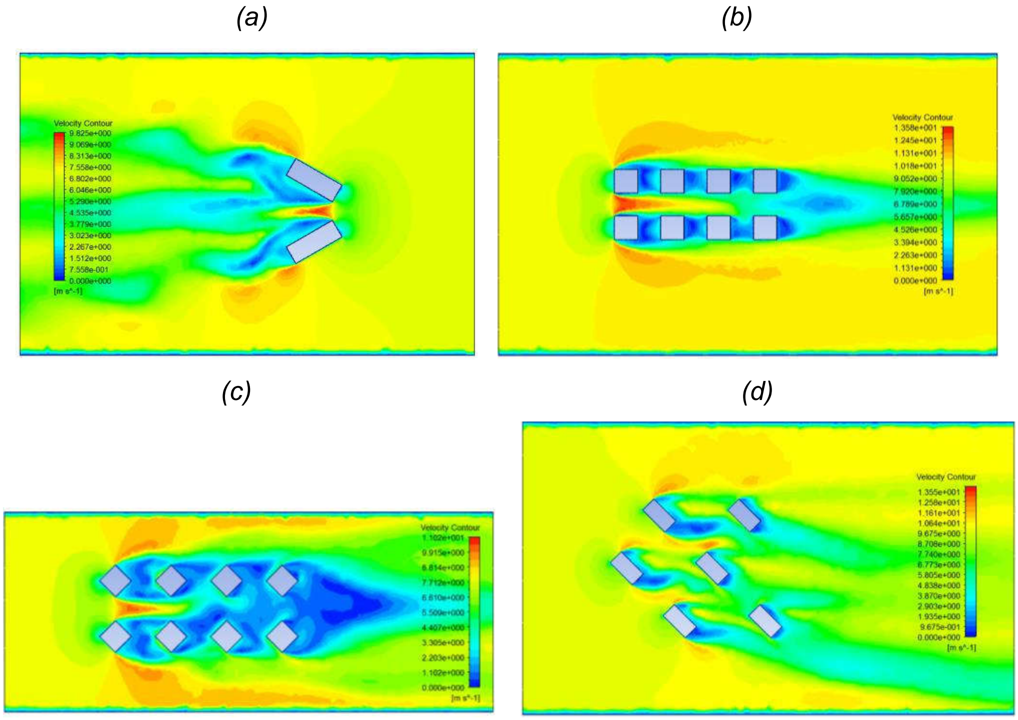


Figure 3. Velocity contours around buildings in horizontal plane:
a) Case 1, b) Case 2, c) Case 3, d) Case 4

The velocity contours around buildings in the vertical plane are shown in Figure 4, while the velocity streamline around buildings is given in Figure 5. The vertical plane is positioned at half of the domain width. In Case 2, the flow separation zone and return flow is formed only on the top side of the first row of buildings. This is in agreement with the study [18], which showed that in the case of row of buildings with same or similar height the return flow are formed only above the first row of buildings. The air currents above the top of the second row of buildings descend slightly. Also, in this case, pedestrian areas are generally protected from high wind speeds. When it comes to rectangular buildings (Case 4), the air current is attached to the roof. When the wind is not perpendicular to the buildings, the zone of reverse flow above the top of the first row of buildings is much smaller compared to other cases. In this case (Case 3), the zone of reverse flow on the leeward side of the last row of buildings is much longer compared to Case 2. The wind velocity around the winward edges and the lateral sides of the building increases with increasing building height. Figure 4 and Figure 5 show that at the top of the buildings and their lateral sides wind flow is detached from the surface and flow separation takes place. The separation bubbles are formed and characterized by reverse flows, low-velocity distributions, and high turbulence intensities. The lateral wind flows together with the flow over the top of the building causing the formation of 3D vortices on the leeward side of the buildings. In the Case 2 and 3, there are large pockets of turbulence between the two rows of buildings. These vortices negatively influence air quality because they trap vehicle emissions in street canyons.

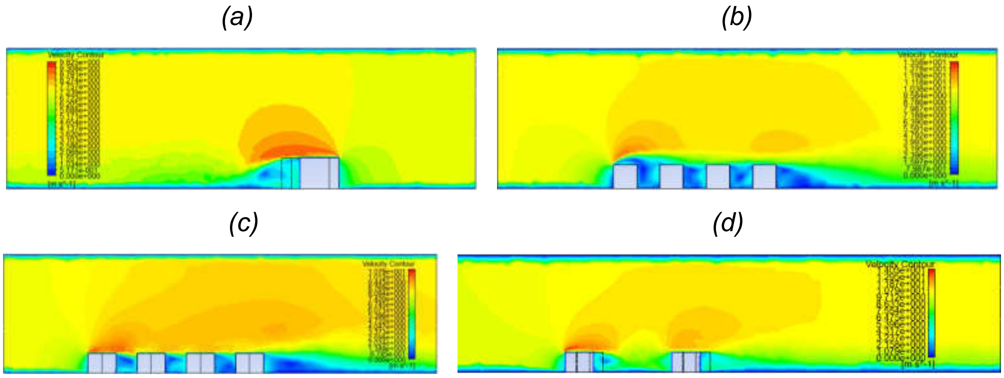


Figure 4. Velocity contours around buildings in vertical plane:
a) Case 1, b) Case 2, c) Case 3, d) Case 4

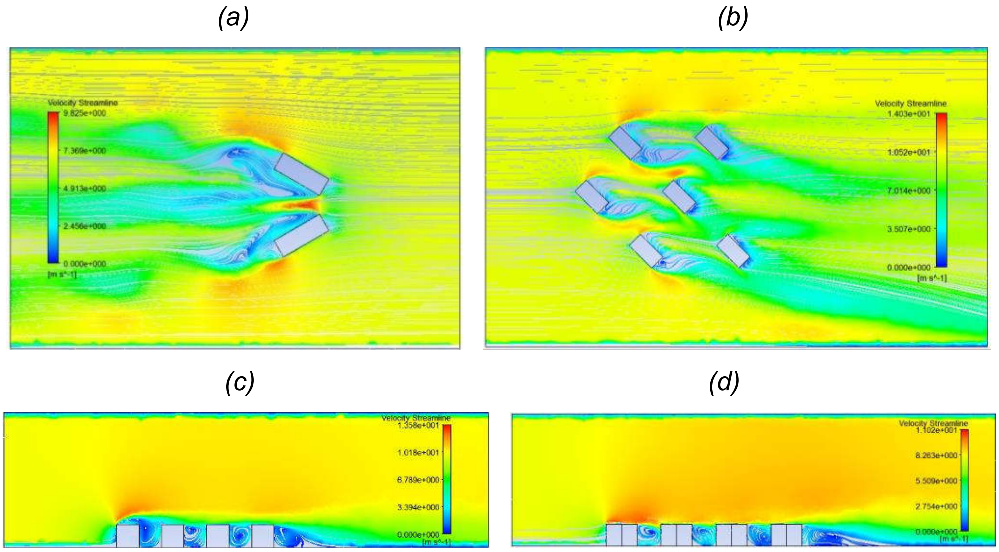


Figure 5. Velocity streamline around buildings:
a) Case 1, b) Case 4, c) Case 2, d) Case 3

The distribution of turbulence kinetic energy around buildings in the horizontal plane is shown in Figure 6. It can be seen that in the row of buildings, the turbulence kinetic energy is highest on the sides of the first buildings in a row. Between buildings, the highest values of kinetic energy of turbulence are on the windward side of the urban canyon. The turbulent kinetic energy is lowest in the inflow state. The turbulent kinetic energy increases when wind reaches the leeward side of the building because of the strong perturbations and a greater velocity gradient. The kinetic energy is transferred from large to smaller eddies. On the leeward side, with increased distance from the building, the turbulence kinetic energy decreases, due to dissipation. The turbulence dissipation rate is the velocity at which the mechanical energy of an isotropic small-scale vortex transforms into thermal energy, which greatly influences the diffusion process [19].

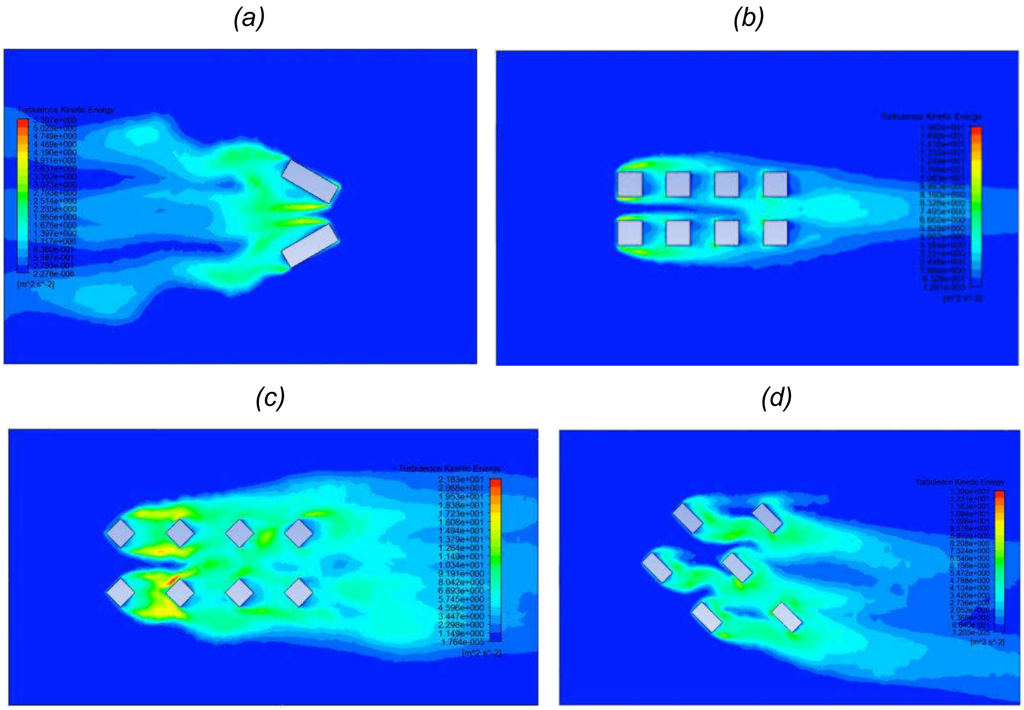


Figure 6. Distribution of turbulence kinetic energy around buildings: a) Case 1, b) Case 2, c) Case 3, d) Case 4

4. CONCLUSION

Wind conditions and wind flow patterns are strongly influenced by high-rise buildings and the urban environment around buildings because of the many flow situations arising from the interaction of wind with structures. It is essential to consider wind flow phenomena and integrate them early in the development of urban projects to achieve proper urban planning. Within such context, this paper investigates the influence of four different layouts of buildings on wind flow using Computational Fluid Dynamics (CFD) simulations. The ANSYS software was used to simulate wind flow around buildings. The distribution of wind pressure, velocity, and turbulence kinetic energy around buildings was analyzed. The simulation results show building layouts have a significant influence on the wind flow pattern. This paper can equip architects and urban planners with informed decision-making tools to create more comfortable urban environments. The main findings are as follows:

- pressure is positive on the windward side of the building, while negative on the leeward and lateral sides of the building,

- wind flow separation occurs at the corners of the buildings,
- zones of maximum wind speed are located on the lateral sides of buildings,
- narrow passages between buildings lead to a significant increase in local wind speed,
- when the wind is non-perpendicular to the buildings the zone of reverse flow behind buildings is much wider.

Understanding wind flow patterns allows urban and architectural designers to introduce a variety of wind mitigation measures early in the design process to improve the safety and comfort of pedestrians. This paper highlights the importance of wind flow modeling in early urban planning and architectural design. In future, the result of simulations needs to be validated with experimental data from wind tunnel tests. Future research also needs to explore the effect of inlet wind velocity which changes with the height of the domain.

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NOMENCLATURE

$\bar{v_i}, \bar{v_j}$ – Time-averaged velocity components, [m/s].

$\bar{F_i}$ – External forces, [kgm/s^2].

$\bar{p}$ – Time-averaged air presure, in [bar].

$v_i{}', v_j{}'$ – Fluctuating part of velocity components, [m/s].

k – Turbulence kinetic energy, [m$^{2/}$s^2].

t – Time, [s].

$C_{\varepsilon 1}$ – Empirical constants.

$C_{\varepsilon 2}$ – Empirical constants.

ρ – Air density, in [kg/m^3].

η – Dynamic viscosity, [kg/ms].

ε – Turbulent dissipation rate, [m^{2}s^3].

η_t – Turbulent viscosity, [m^{2}s].

σ_k – Empirical constants.

σ_ε – Empirical constants.

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