CFD Simulation of Wind Environment around an Isolated High - Rise Building for Wind Energy Harvesting

Ali Abdulkadir Aden[1], **Su Bo**[2]

[1]Department of Civil Engineering, Jiangsu University, Zhenjiang, 212000, China
Email: *aliduh10[at]gmail.com*

[2]Department of Electrical and Information Engineering, Jiangsu University, Zhenjiang, 212000, China

Abstract: ***The integration of wind energy utilization and high - rise building design is the combination of advanced building technology, energy utilization, and wind energy generation. This integration transforms the structure into a wind energy carrier. This topic focuses on how to increase wind power generation by using building design techniques to turn high - rise building into wind concentrators in order to increase wind power generation. The primary research works on the influence of fundamental high - rise buildings architectural forms on wind energy use are as follows. Firstly, the evaluation indexes of wind resources and wind resources in the built environment were presented, as well as the general laws of the distribution of wind resources in the built environment and evaluation indicators of building wind energy utilization efficiency. Secondly, based on case collection and literature reading, a basic form that facilitates the use of wind energy in a high - rise building is systematically summarized. A brief introduction to a high - rise building with an opening through architectural form suitable for placing wind energy harvesters of wind generators. Thirdly, the choice of CFD software is introduced. Then, using Fluent to numerically simulate the wind resources of two kinds of super high - rises, analyze their influencing factors on wind energy utilization. Finally, an experimental study on a newly developed wind - induced galloping energy harvester has been conducted. In the CFD results we can see the location with higher wind speed and lower turbulence intensity is suitable for the installation of wind - induced energy harvester. (1) The wind speed enhancement effect of the wind passage is related to the design height of the air passage and the shape of the inlet as well as the appeal factor. (2) The wind speed strengthens the effect is obvious, when the installed height of the wind - induced energy harvester is 3⁄4 of the total height and the shape of the inlet is an arc.***

Keywords: High - rise building wind environment; Building design; CFD; Wind energy utilization; wind - induced energy harvester

1. Introduction

It is estimated that there are 1.7 million terawatt - hours (TWh) of kinetic energy in the wind resources in Earth's atmosphere [1]. Power plants can benefit greatly from this renewable energy source because of its global availability, low carbon emissions, and few negative effects on the environment and human health. Wind power can be competitively priced with other traditional power sources under certain situations [2 - 4]. Wind power is becoming increasingly popular as a result of its attractive characteristics, which are backed up by a number of reputable sources [2, 5 - 9].

Opportunities to lower infrastructure costs and lessen energy loss due to long - distance transmission can be found in wind energy harvesting in metropolitan settings. Wind energy can be captured in urban areas through several different approaches, such as (i) retrofitting roof - mounted wind turbines onto existing buildings, (ii) installing stand - alone wind turbines in urban areas, and (iii) seamlessly integrating wind turbines directly into building structures [10 - 13]. Wind energy harvesting utilizing building - integrated ducted wind turbines in tall structures has been shown to be feasible in the existing literature [12, 13]. A few important factors, including duct geometry, urban planning, fluctuations in wind speed and direction, and local wind turbulence characteristics [14], affect the feasibility of this possibility.

Urban areas can benefit greatly from localized micro - grid wind energy generation since it enables the use of renewable energy sources close to the point of use, reducing power transmission losses and fostering resource diversity. Identification of suitable locations for such attempts and the development of methods to maximize flow characteristics in regions that generally experience low wind speeds and strong turbulence are essential if wind energy harvesting in urban contexts is to be fully realized. This process can be facilitated by incorporating wind turbines within buildings at appropriate locations, such as rooftops, spaces between buildings, through - building apertures, and within the building's structure [15]. These integrated solutions, referred to as Building Augmented Wind Turbines (BAWTs), combine architectural and aerodynamic design considerations with the goal of improving flow dynamics.

Through - building openings provide an opportunity to effectively utilize building architecture in urban settings while integrating aerodynamic components, such as diffuser - augmented wind turbines (DAWTs), to maximize airflow. DAWTs generate more power by enclosing the wind turbine in a specially designed shroud with aerofoil profiles, venturi, flanges, or other complex wind delivery devices [16 - 18].

This thorough inquiry uses two different parallel layout configurations to explore the complex dynamics of airflow within through - building openings. We hope to acquire profound insights into the flow characteristics and structural complexity of these openings using cutting - edge two - dimensional Ansys Fluent algorithms.

These through - building apertures act as open passageways for the wind to pass through and are located at either end of the building's width. They could also be used to power wind energy harvesting equipment. However, creating appropriate wind conditions within these corridors is necessary for effectively capturing wind energy. This entails increasing wind speed and reducing turbulence, both of which can be accomplished by careful design modifications.

We started our inquiry by carefully scrutinizing sample flaws related to the captured photos in order to ensure the integrity of our findings. In order to find outliers and regions with increased uncertainty, we then performed a two - dimensional Ansys Fluent uncertainty analysis. We validated the results of our two - dimensional Ansys Fluent experiment against a number of three - dimensional measures as part of our commitment to accuracy.

The key to our research was the three - dimensional pressure, which could resolve the three components of velocity and local static pressure. Using both measurement methods, we also delved into the world of probability distributions, specifically assessing the stream wise velocity fluctuations at the midway of each corridor layout design. These results gave us important information about the potential distinctions and similarities between the two layouts.

We carefully examined mean velocities along the streamwise and vertical axes, as well as their corresponding velocity fluctuations, across various layout designs in our effort to fully comprehend the flow characteristics. Through careful analysis, we were able to identify patterns and variations that are essential for maximizing these corridors' ability to capture wind energy.

Additionally, we started investigating the coherent flow patterns found within each corridor architecture in an effort to identify ideal areas for the erection of wind turbines. By paying attention to the subtleties of the flow patterns, this project has the ability to rethink the layout designs.

Finally, we used a simple but insightful flow visualization tool to identify where increased turbulence first appeared within one of the layouts. This priceless knowledge can help us improve our designs to reduce turbulence and increase energy - harvesting effectiveness.

In essence, our work is an extensive effort to decipher the complex dance of wind within through - building apertures, with the ultimate objective of efficiently and sustainably utilizing wind energy.

2. Methodology

Building model

A simplified building model that had the layout of a square and had the measurements (180 x 45 x 30) meters were carefully examined. The dashed lines that represent the windward openings in the enlarged building sketch served as a primary point of concentration for the investigation. In order to make the most efficient use of the available space, two through - building entrances were placed in key locations at a height of 3/4H (135 meters) above the standard corridor level. The letter "H" refers to the total height of the building. Figure 1a depicts the precise placement of these apertures in their respective locations. It had a tapered and expanding structure at both the inflow and the outflow sections of its piping system. The initial five - meter sections on either side of the apertures were meant to act as diffusers and contractions so that the flow of air could be controlled as it passed through the openings. This aspect of the design contributes to the regulation of the flow dynamics. According to Table 22 - 4, the portion of the air channel that has been designated as the test area has a higher total area of $b \times h \times l$ (2x2x20) m, than the other parts of the air channel combined. In this particular investigation, the experimental efforts will be concentrated on just one particular part.

Table 1: The through - opening in the building

	Height (m)	Width (m)	Length (m)
Inlet	2	4	5
Middle	2	2	20
Outlet	2	4	5

In order to give a thorough reference, the dimensions of both the building model and the through - building apertures have been included in Table 1 and Figure 1. This ensures that the ensuing studies will be accurate and makes them easier to do. These comprehensive specifications and graphic representations provide a solid basis for more in - depth research into the energy dynamics and performance of the building model that is being investigated.

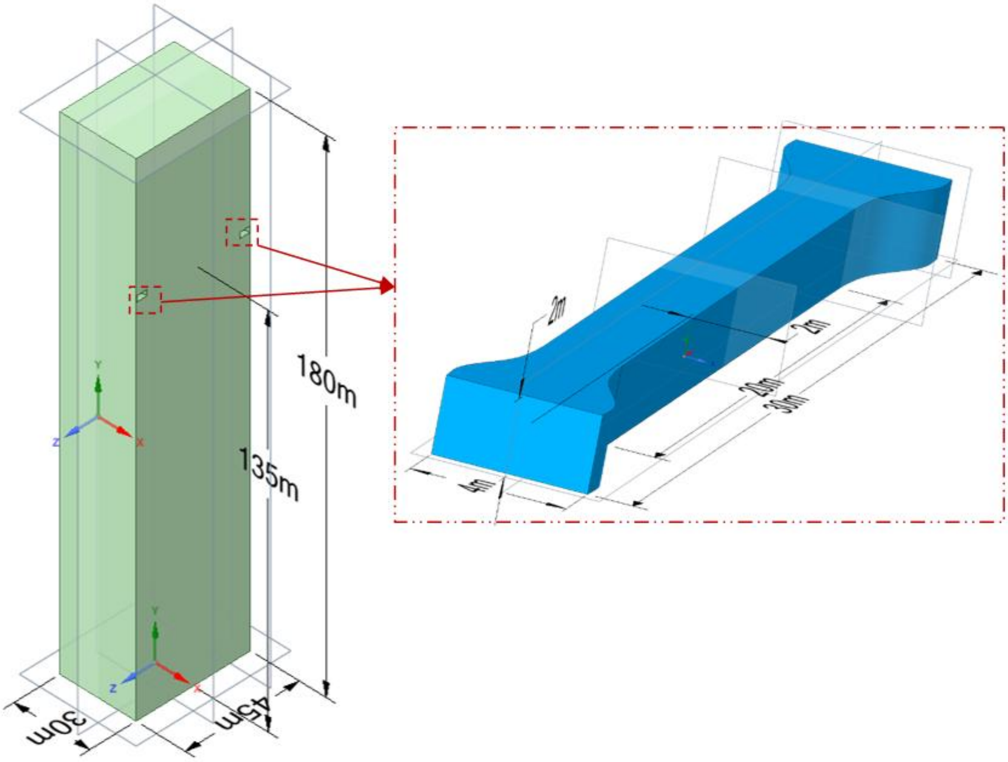


Figure 1: High - rise building with an opening through at 3/4H.

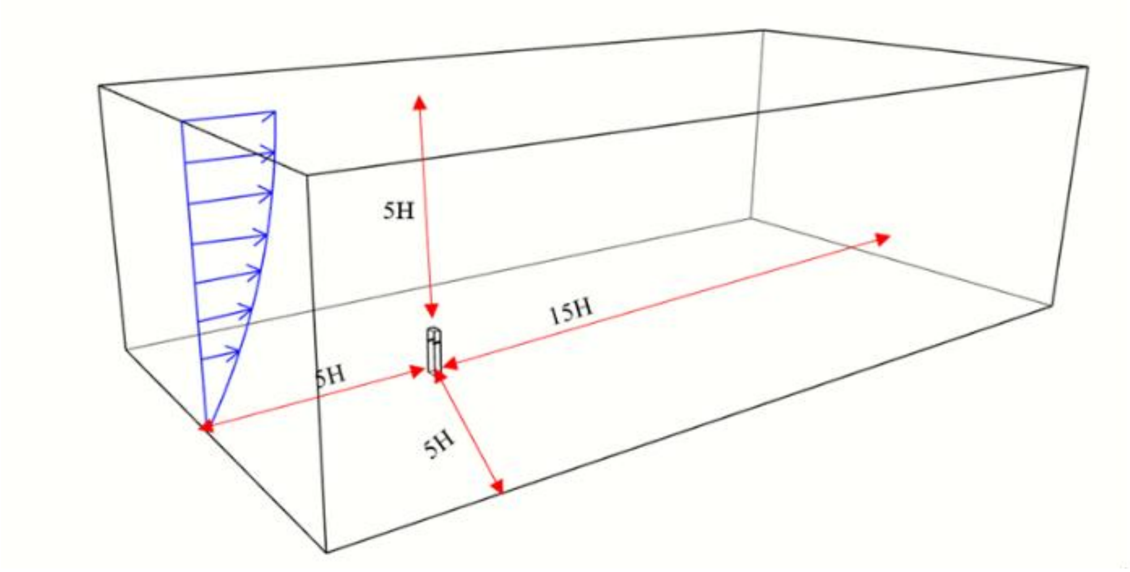
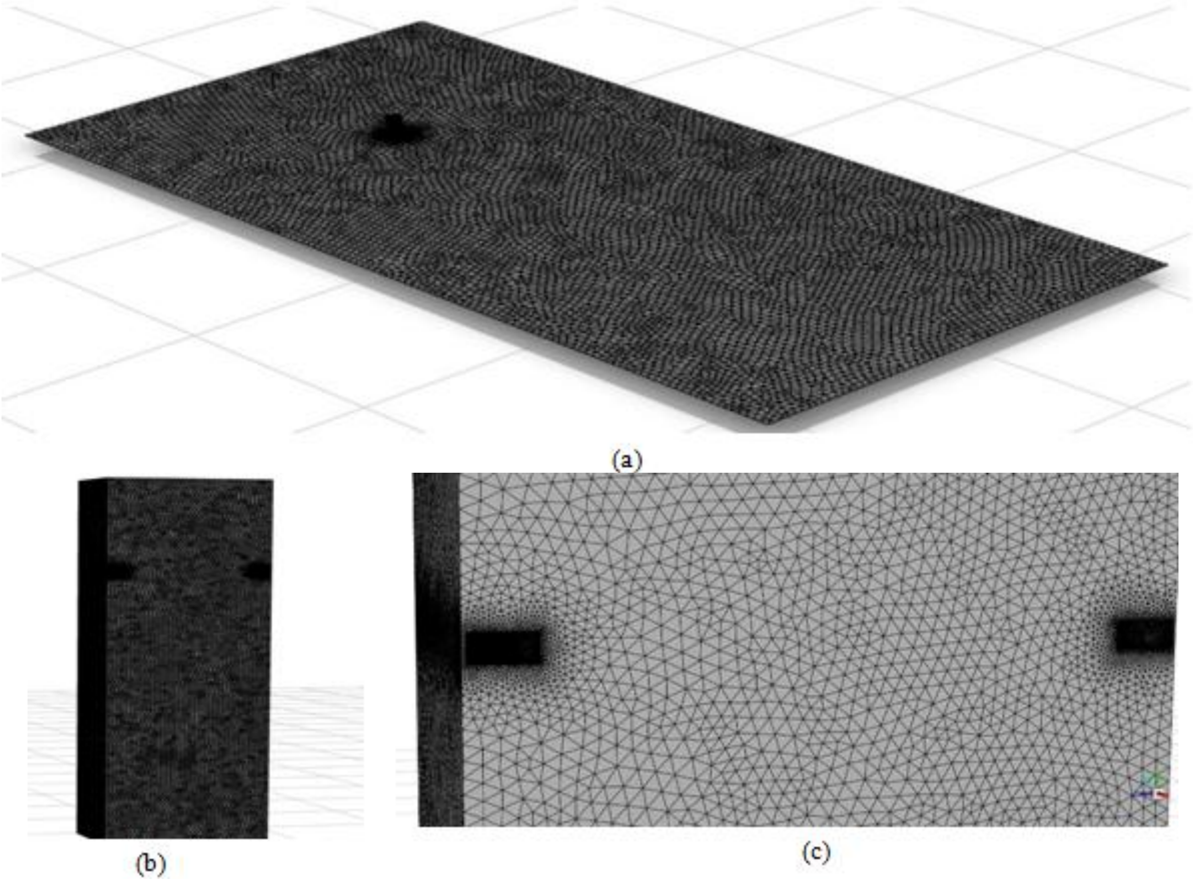


Figure 2: Computational domain geometry

This investigation focuses heavily on the exterior calculation domain to achieve an accurate simulation of the entire atmospheric environment surrounding the target structure. To ensure an accurate representation of wind distribution across a building's surface, the computation domain size must be carefully considered. If the calculation domain is too small, the simulation may not achieve the intended level of accuracy. In contrast, an excessive number of grids can result in excessively lengthy simulation periods and impede the achievement of convergent results.

As shown in Figure 2 to define permissible boundaries for computational fluid dynamics (CFD) flow simulations in urban areas, established standards recommended by the Wind Engineering Research Group of the Architectural Institute of Japan (AIJ) are adhered to. This simulation is executed by the AIJ. It is recommended that the side and upper limits of a single building be placed at a distance greater than 5H from the building's perimeter, where H is the height of the target building. It is essential to note that this recommendation only applies to single - family homes. In addition, the discharge boundary must be at least 15H from the building's rear. Figure 3 is a visual representation of the suggested boundary placement.

This research guarantees a comprehensive and realistic simulation of the atmospheric conditions surrounding the building of interest by adhering to these principles and precisely defining the calculation domain's boundaries. These factors contribute to the reliability and validity of the numerical simulations conducted in the United States, allowing for a more rigorous examination of the effects of wind on the building's surface.

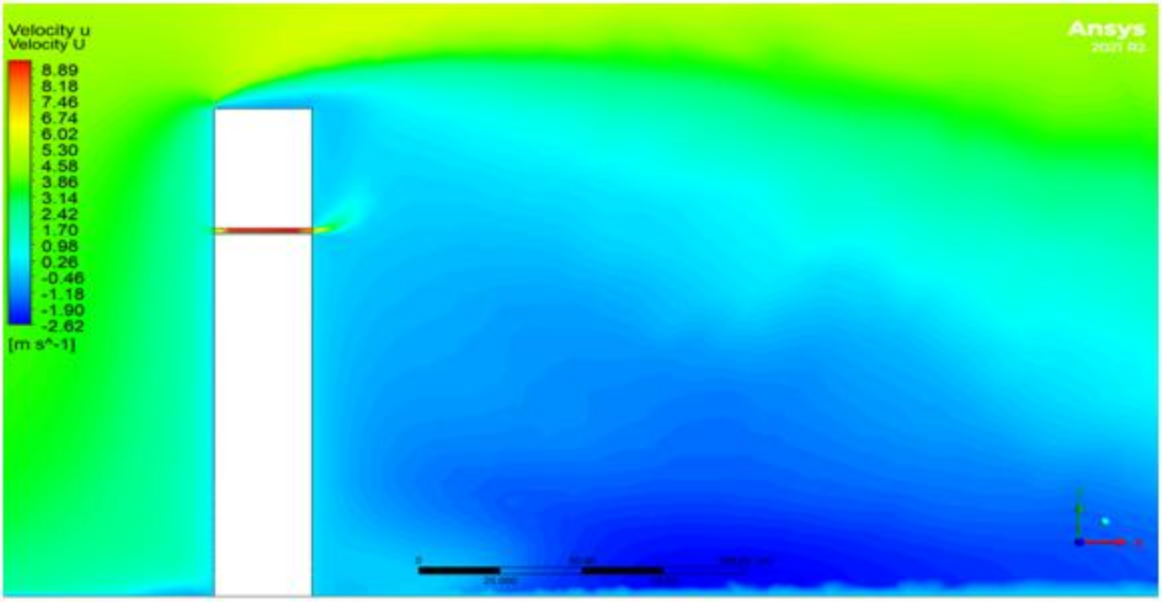

(a)

(b)

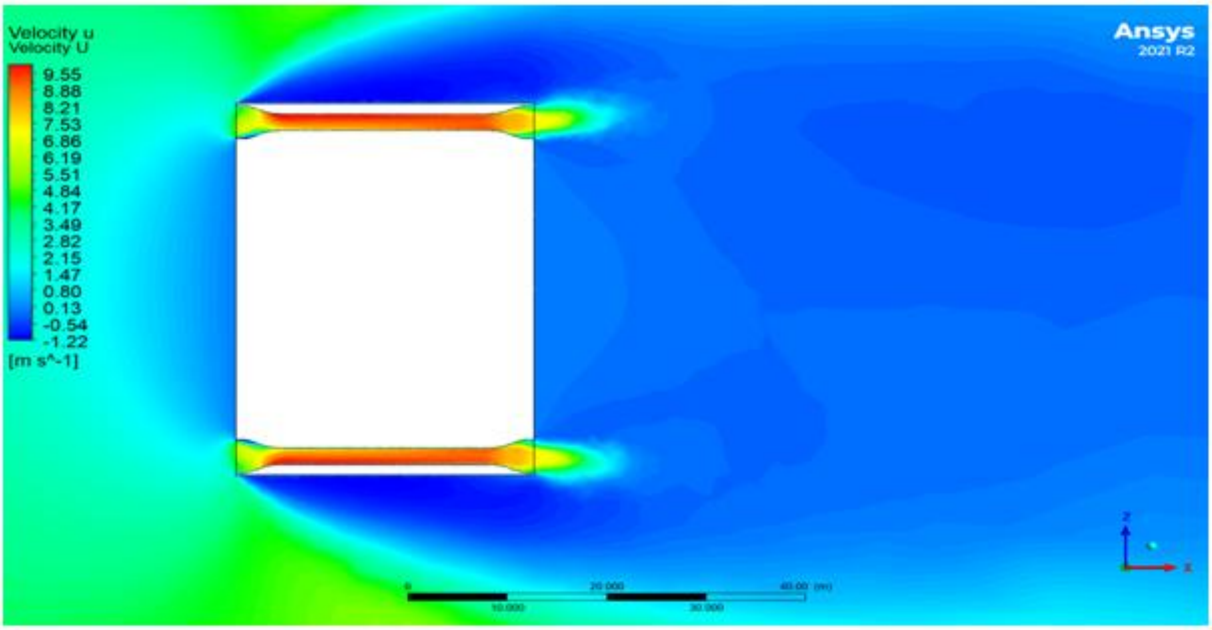
(c)

Figure 3 Schematic diagram of grid division. (a) watershed for the domain, (b) building scale, (c) opening through scale

3. Results and Discussion



(a)

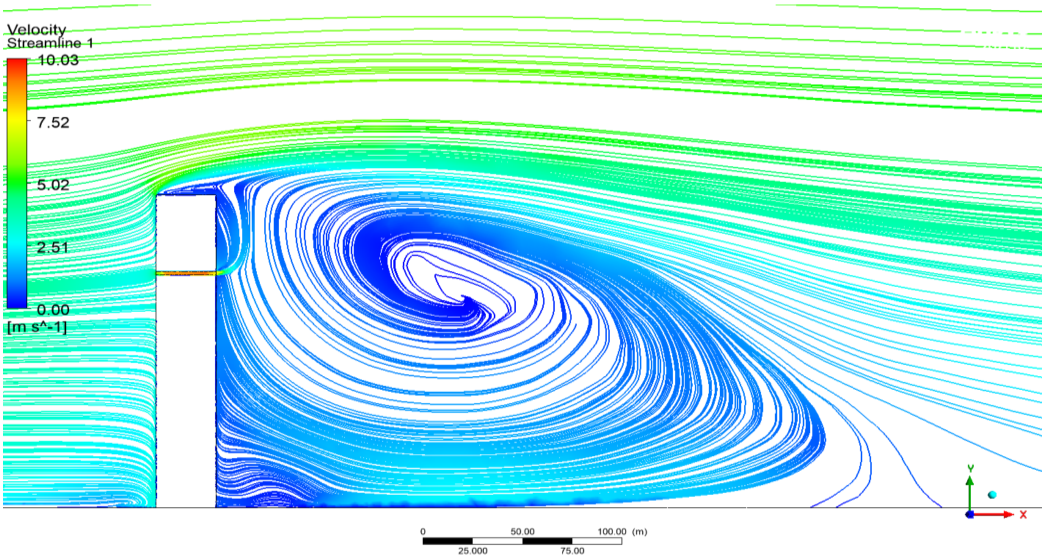


(b)

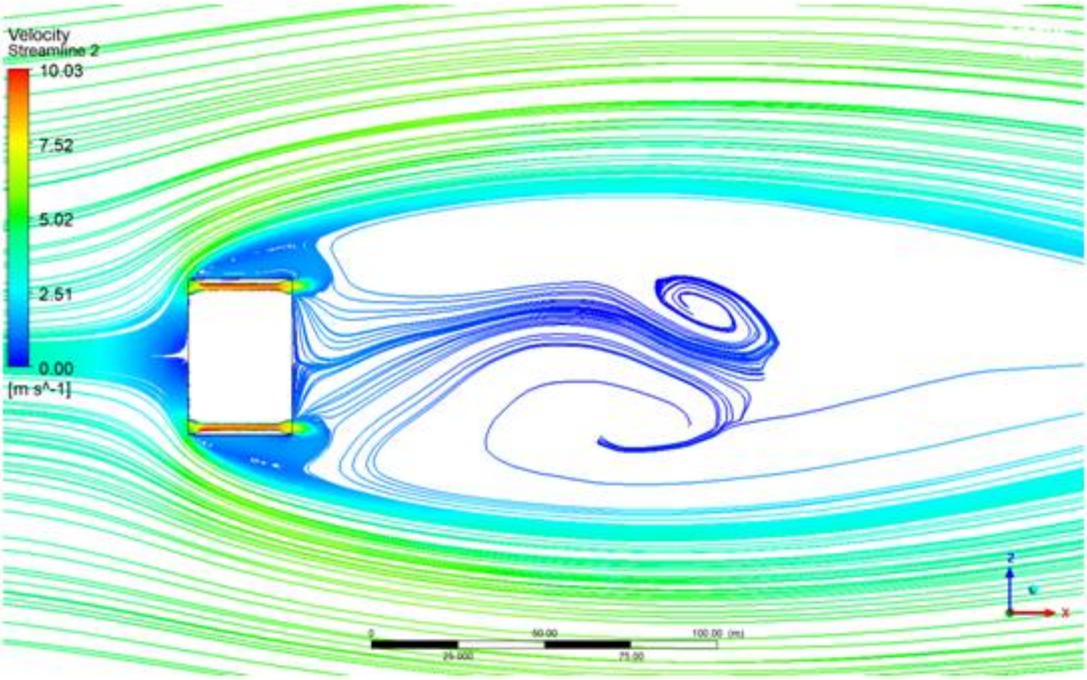
Figure 4: Velocity magnitude contours (a) Around the building and along the through - building openings and (b) Along the openings at 135m elevation.

The contour plot of velocity magnitude obtained from a cross - sectional analysis of the high - rise building, specifically focusing on the through - building openings at predetermined elevations above the ground level, is presented in Figure 4 (a). The velocity magnitude contours provide a visual representation of the wind flow behavior as it interacts with the building and enters the openings. The contours reveal a notable deceleration of the approaching wind upon entry into the openings, while still maintaining a suitable velocity of 5 m/s within the interior of these openings. It is crucial to note the remarkable similarity and consistency in both velocity magnitudes and flow regularity within the openings. This observation suggests a relatively uniform and consistent wind environment within these apertures, which has significant implications for wind energy harvesting strategies and the design of efficient wind turbine installations.

Illustrated in Figure 4 (b), the plan view of the velocity magnitude contour is presented at an elevation of 135 meters above the ground, specifically focusing on the through - building openings. Observing the contour plot, it becomes evident that the flow entering the openings exhibits non - uniform characteristics near the inlet regions. However, as the flow progresses toward the central portion, a noticeable improvement in flow uniformity is observed. This non - uniformity can be attributed to the occurrence of flow detachment or separation at the entrance of the openings, which acts as the primary factor contributing to the lack of uniformity throughout the system. These findings highlight the importance of carefully considering the entrance design and aerodynamic features of the openings to mitigate flow detachment and promote a more uniform airflow distribution, ultimately enhancing the efficiency and performance of wind energy harvesting systems within the studied high - rise building.



(a)



(b)

Figure 5: Streamlines Velocity U (a) Side view (b) Top view

Figure 5 shows the flow patterns that were observed around the lone building exhibited parallels to well - documented flow patterns that are typically encountered near bluff buildings, as stated in reference. These patterns include a number of different zones, such as the impingement area, flow separation, shear layer, and recirculation zone. It should be noted that an impingement flow was seen in front of the building models, which is evidence that the approaching wind physically impacted the buildings. On the other hand, flow separation was observed above the building, which indicates that the flow was detached from the building's surface. It was discovered that there was no evidence of a downward flow or a vortex formation; rather, the flow preferred to travel upward as it skirted the building.

The visualization of the flow revealed several interesting aspects, one of which was the presence of a shear layer directly above the building. This layer was distinguished by a positive velocity gradient and was one of the most conspicuous aspects. An additional notable discovery was made when researchers discovered a large vortex behind the structure. This vortex had a radius that was about equivalent to half the height of the building. This vortex exhibited a particular circulation pattern, which influenced the behavior of the flow in its immediate surroundings. In addition, a recirculation zone was seen on the floor area just beneath the building model. This finding suggests that there is either air that is regularly being recirculated or air that is standing still.

These in - depth studies of the flow patterns around a single structure that contains a duct opening make a significant contribution to our comprehension of the intricate aerodynamic interactions that take place between structures and the wind. These kinds of insights are essential for strengthening building designs and putting effective methods into place in order to increase energy efficiency and lessen the effects of wind - induced events.

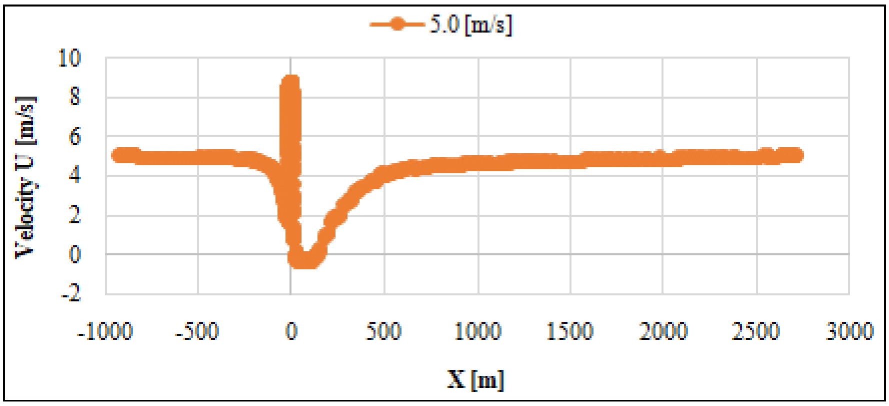


Figure 6: Velocity U through the whole domain at the height of the opening through (135m)

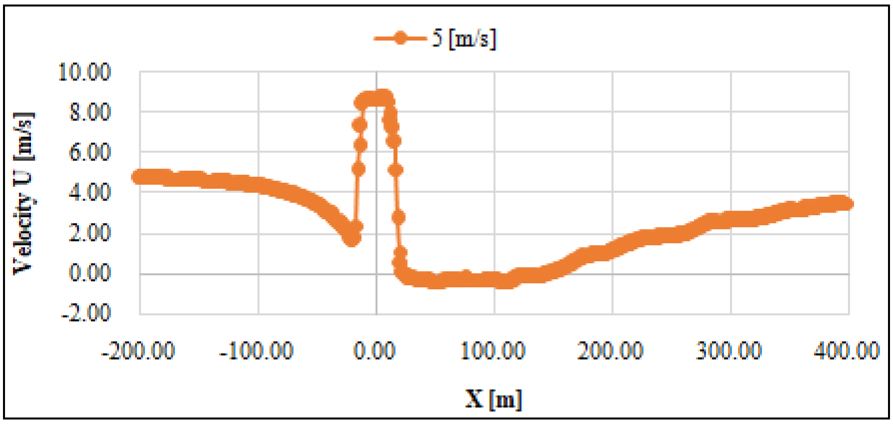


Figure 7: Velocity U from - 200m to 500m of the domain

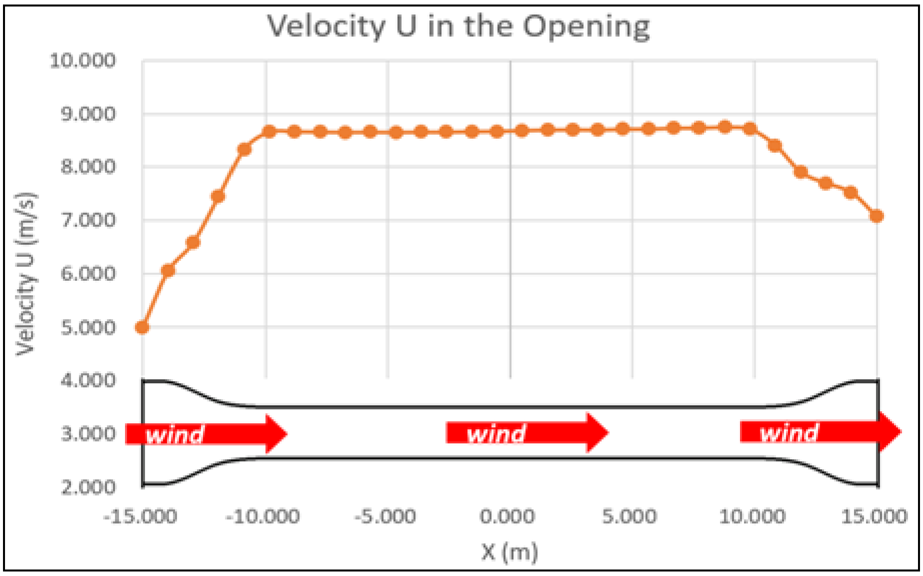
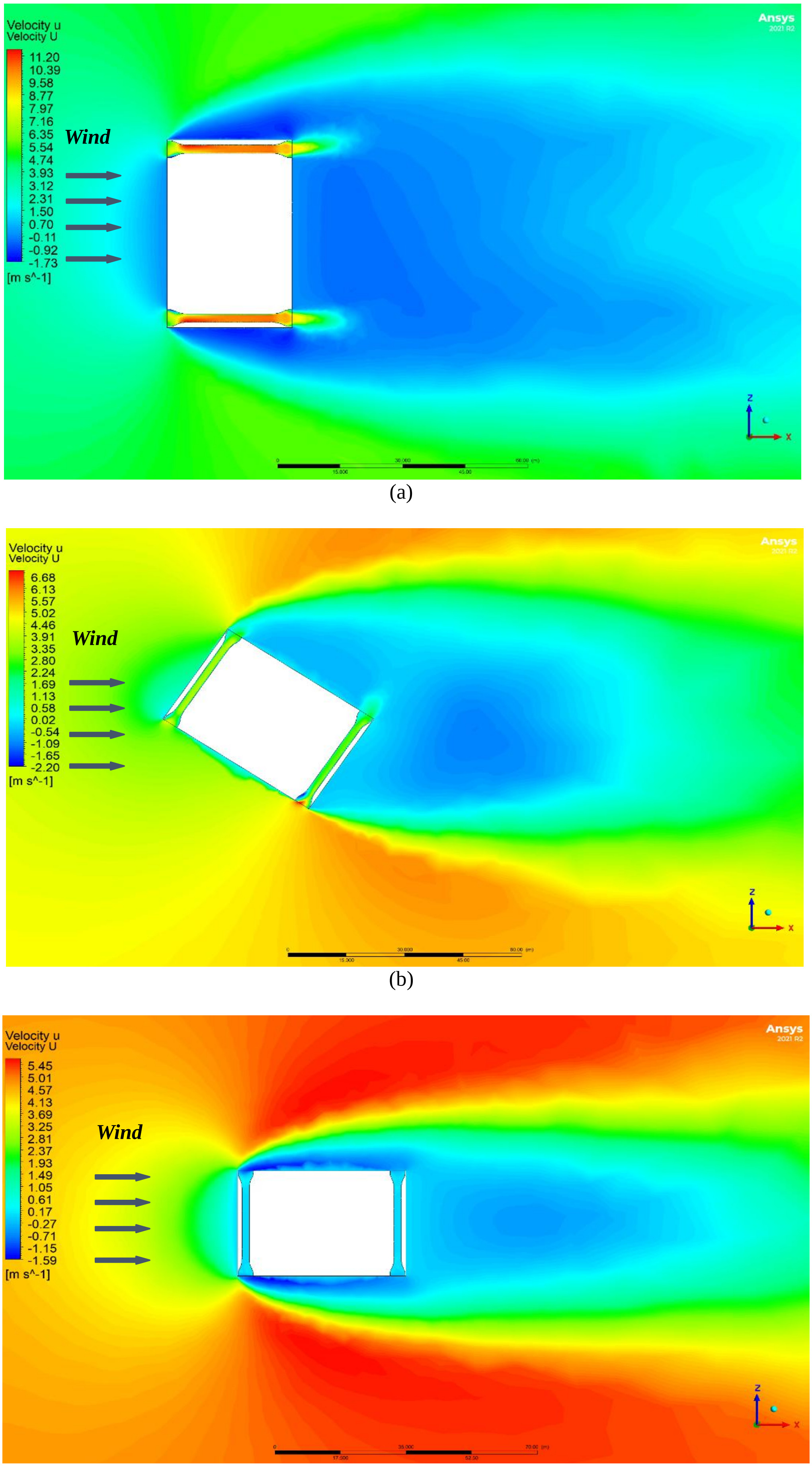


Figure 8: Velocity U in the Opening through

The velocity amplification factor, which is the ratio between the mean velocity inside a limited corridor and the mean velocity at the same height in a free stream, has been evaluated across a variety of reference velocities. This factor represents the ratio between the mean velocity within a confined corridor and the mean velocity at the same height in a free stream. The empirical values of this component are illustrated in Figures6, 7 and 8. The intrinsic aerodynamic features of through - building apertures, which comprise recessed sections and curving walls, may be responsible for the observed amplification. Surprisingly, the factor varies from 1.8 to 2.0, which corresponds to a variety of free stream velocities ranging from 1 m/s to 5 m/s. This significant range exemplifies the significant efficacy of aerodynamic devices in efficiently increasing flow velocity by up to about thirty percent. In addition, the fact that the slope of the amplification factor curve decreases as the reference velocity rises hints at the likelihood of the curve reaching a plateau at greater speeds when the reference velocity is increased. These findings provide light on the possibilities of aerodynamic design solutions to maximize flow dynamics within constrained areas and provide new insight into the field.



(a)

(b)

(c)

Figure 9: Velocity contour of the ducted flow at wind incident angles: (a) 0°, (b) 45°, and (c) 90° when the free stream velocity is 5m/s at the same elevation

In the experimental investigation, the building was rotated at several angles, including 15°, 30°, 45°, 60°, 75°, and 90°, in order to explore the effects of these rotations on the flow's velocity, pressure, and turbulence intensity as it passed through the ducts. Each rotation angle had its own set of measurements obtained, which were then recorded. Figure 9 (a - c) depicts the resulting velocity profile that was observed at three different incidence wind angles (0 degrees, 45 degrees, and 90 degrees) when the free stream velocity was set at 5m/s at a particular place on the building (3/4H), H stands for the height of the building. An examination of the velocity contours reveals that, in the apertures at an incident wind angle of 0°, the ducted flow demonstrates a higher velocity in comparison to the free stream flow at the same height. This is especially true when the building is removed from the openings. When the building is rotated by 45° or 90°, there is a significant reduction in the velocity of the ducted flow, as seen by the comparison between Figures 1 (b) and (c).

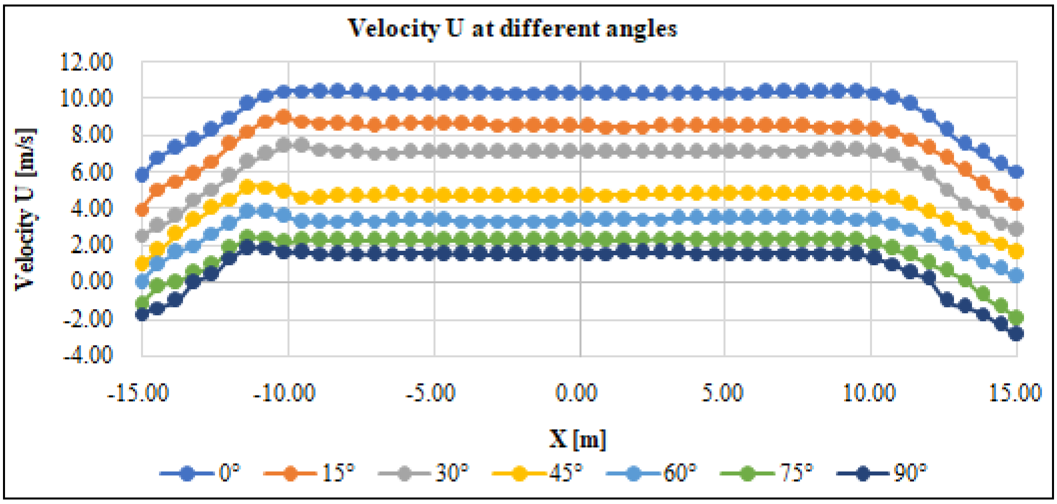


Figure 10: Velocity U in the Opening through at different angle of wind attack

4. Conclusion

Using super high - rise buildings to increase the utilization efficiency of wind power generators to reduce the energy consumption of buildings is a topic worthy of further research. It is necessary to make full use of the means of architectural design to make the super high - rise building itself a wind energy concentrator to increase the power generation of the wind generator. At the same time, consider how to organically combine the design of super high - rise buildings with the design of wind energy utilization, realize the zero - distance transportation of energy, and achieve the practical significance of reducing building energy consumption. Through the study of wind resources, this paper verifies that in the high - rise building environment, the wind speed and power generation can be increased by means of building shape design to improve the power generation efficiency of wind turbines. and the applicability of numerical simulation of wind conditions. Using the Fluent numerical simulation method to analyze the analysis of the foundation model of the super high - rise building which is beneficial to the utilization of wind energy, and put forward the optimal design strategy of the basic shape of the building suitable for wind power generation. The main conclusions of this study are as follows: (1) There are two ways to judge the location suitable for installing wind energy harvester devices. One is to have a higher wind speed, and the other is to have a lower turbulence intensity; the evaluation must combine the two values for comprehensive judgment. Because a larger wind turbine requires a higher start - up wind speed, and a higher wind speed level can increase the power generation and power generation efficiency of the wind turbine. The lower turbulence intensity and the more stable airflow pattern can make the service life of the wind turbine longer and increase the power generation life of the wind turbine. (2) Wind - induced oscillation energy harvesters are a novel and developing alternative to conventional turbines. Due to their potential integration with self - powered microdevices and wireless sensor networks, particularly in urban settings, low - energy power generation devices are gaining increased attention nowadays. (3) The simulation results of the high - rise building with two opening through in the face of the dominant wind direction. The opening through of the air channel the building has the effect of increasing the wind speed obviously, and also the turbulence intensity 47 drops, due to the shape, size of the inflow port, and the wind speed at the inlet port of the air channel is enhanced.

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