Finite Element Model for Wind Comfort Around a Tall Building: A Case Study of Tower of Qazaqstan

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Abstract. Pedestrian wind comfort plays an essential role in the urban environment. In our work, we consider a model obtained using Computational Fluid Dynamics (CFD) around a tall building. Our focus is the Tower of Qazaqstan or Abu Dhabi Plaza in Nur-Sultan city (Kazakhstan), which will be the tallest building in Central Asia with a height of 310.8 m. We investigated the effect of the wind velocity on pedestrians by solving the incompressible time-dependent Navier-Stokes equations in the deal.II library by the Finite Element Method (FEM) using the projection method. We present numerical simulation results for various scenarios. It has been found that the velocity profile can vary in the domain that creates different pedestrian comfort conditions including the exceeded category at places dedicated to pedestrian walking.

Keywords: Tall building · Wind comfort · Wind simulation · Navier-Stokes equations · Finite element model

1 Introduction

Understanding of wind profile around a tall building is important in modern cities for engineers because this can be useful to ensure the comfort of pedestrians. Architectural designs of buildings are becoming more complex in modern cities due to the expansion of urbanization. The wind behavior around modern buildings has an impact on humans' lives. The modeling of the wind effects allows decision-makers to take into account human activities at an early stage of the city plan.

In the literature, several studies have used Computational Fluid Dynamics (CFD) to assess wind conditions in urban areas. Most of results were obtained by various (commercial) software tools in the study of the impacts of climate conditions including wind on buildings [6–8,18]. Many places were taken into account with local weather conditions including Amsterdam [19], Hong Kong [10], Dublin [15], Dubai [16], Jeddah [11], Bursa [9] and others.

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To investigate the impact of the local weather conditions, such as wind, on people, we consider a model of the Tower of Qazaqstan or Abu Dhabi Plaza in Nur-Sultan city, Kazakhstan, as shown in Fig. 1(a). According to [20] the tower is expected to be the tallest building in Central Asia with a height of 310.8 m. The tower is surrounded by four small buildings. There is a Linear Park for pedestrians behind the buildings as shown in Fig. 1(b). The location of the Nur-Sultan city is in the steppe and it is common to have windy weather near the tower. The green forest was planted around the city from 1997 to 2016, a so-called green belt zone that can help to mitigate the negative effects of winds on the city infrastructure.

In [12], the wind effect was studied for "Transport Tower" or building of the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan with 34 floors from Nur-Sultan city. As a result, the experimental measurements of the sensors at the different floors (27th and 31st floors) showed a high acceleration, $9.23\,\mathrm{cm/s^2}$ on a relatively calm day. However, the comfort of building under wind-induced load was the focus of their study.

Another application of CFD for some buildings from the Dostar micro district (Nur-Sultan city) was discussed in [17]. The specific configuration and orientations of buildings with the pressure profile at the height of 20 m were explored using the commercial software in the wind model.

In this paper, we study the behavior of the wind velocity around a tall building using the time-dependent Navier-Stokes flow model. To the authors' knowledge, such a model using computational fluid dynamics (CFD) has been scarcely investigated for the Tower of Qazaqstan in Nur-Sultan, Kazakhstan. To examine our model, we used the Finite Element Method (FEM) in the open-source deal.II library [3]. The deal.II library allows us to control nearly all parameters crucial to the simulation. By utilizing the library, our model solves the incompressible time-dependent Navier-Stokes equations by the finite element projection method. The numerical model is verified by the experimental data of the velocity profile near the building.

It is principal to analyze our model from the point of the pedestrians since they are the main clients of the urban environment. Hence, in this paper, we associated every obtained result with the wind comfort categories, which give information about the comfort of the pedestrians for wind conditions. These wind comfort categories can be found in Fig. 2.

2 Methodology

2.1 Computational and Mathematical Tools

To identify wind comfort categories, we compute wind velocity values in the problem domain. For that, we utilize the deal.II [5] – an open-source library specialized in solving partial differential equations numerically by FEM. The library uses the C++ programming language. Along with the classes and methods, the library maintainers created a set of programs that solve particular problems. Step-35 is one of such programs that allowed us to solve the incompressible time-dependent Navier-Stokes equations using the projection method [13].

(a) The Tower of Qazaqstan.

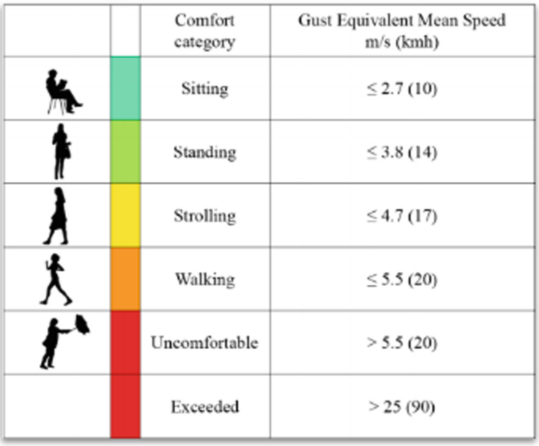
(b) The Linear Park and the Tower of Qazaqstan. Adapted from [1].

Fig. 1. Different views of the Tower of Qazaqstan.

The incompressible time-dependent Navier-Stokes equations themselves are as follows:

$$\begin{aligned} \mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u} - \nu \Delta \mathbf{u} + \nabla p &= f, \\ \nabla \cdot \mathbf{u} &= 0, \end{aligned}$$

where $\mathbf{u}$ is the velocity of the wind, ν is the diffusion, f is the force and p is the pressure. We assume the laminar flow behavior.



		Comfort category	Gust Equivalent Mean Speed m/s (kmh)
		Sitting	≤ 2.7 (10)
		Standing	≤ 3.8 (14)
		Strolling	≤ 4.7 (17)
		Walking	≤ 5.5 (20)
		Uncomfortable	> 5.5 (20)
		Exceeded	> 25 (90)

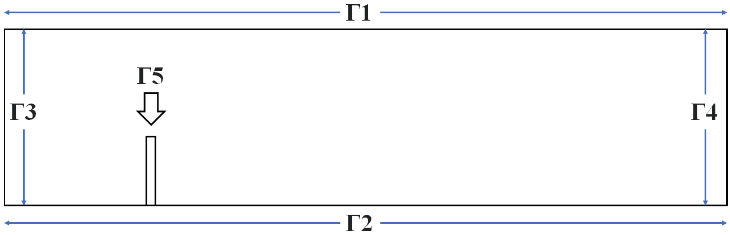
Fig. 2. Wind Comfort Criteria. Adapted from [2].

To solve the equations, we need specific initial and boundary conditions. First of all, we imposed no-slip boundary conditions on the top $\Gamma 1$ wall, the bottom $\Gamma 2$ wall, and the building $\Gamma 5$. Next, on the left vertical part $\Gamma 3$ of the domain we set the initial velocity values of the incoming flow. Its x-component has a parabolic structure, meaning that this component at height y has the form of $y(y_{max}-y)$, where y_{max} is the height of the considered domain. The y-component of the incoming flow velocity equals 0. So this means the incoming flow velocity achieves its highest value towards the middle of $\Gamma 3$. Finally, we set boundary conditions on the right vertical boundary $\Gamma 4$, where the values of the pressure and the y-component of the velocity equal 0 (Fig. 3).

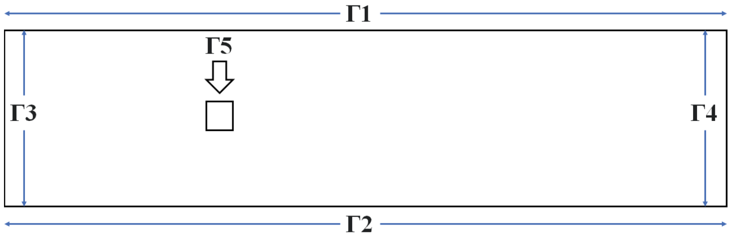
2.2 Domain and Mesh Generation

We describe the computational flow model with its settings. The domain of our problem is the Tower of Qazaqstan and its surrounding. Since we conducted numerical simulations for various scenarios in 2D, we needed to conduct simulations in different views to solve the 3D problem. At a high level, there are 2 main scenarios. The first scenario is the view from the side of the building, and the second is from its top. The domain differs depending on the scenario.

For the side view, the domain consists of the building, a smaller area in front of it, and a larger area behind, which contains the Linear Park dedicated to pedestrians. The domain is bounded by the ground from the bottom and a smaller area for the sky from above. Since the building was under construction at the time of simulations, we assumed that it would be rectangular.



(a) Boundary Values for Side View.



(b) Boundary Values for Top View.

Fig. 3. Boundary values.

For the top view, the domain is similar except for the bottom and top boundaries. These boundaries correspond to the borders of buildings on the other side of parallel streets – Akmeshit and Turkestan, respectively. In addition, we considered two different corner structures for the building – sharp and round.

It is noteworthy that the simulations are done under the assumption that there is no other building nearby except those on the borders. In reality, the Tower of Qazaqstan is surrounded by shorter buildings. Despite that, the simulations are viable in approximating the results at greater heights. Consequently, at rooftop levels, the top view scenario does not suffer because of this assumption. However, for the side view, the results are approximated well for greater height values only.

We generated the mesh for the provided setting, and the code refined it 3 times and then discretized it for the Navier-Stokes problem. During mesh generation, we constructed finer mesh around computationally-heavy parts of the domain, that is, around the building and, especially, around its corners. This will allow us to acquire more detailed information about the wind flow around the building. The results are shown in Fig. 4 by the ParaView, which is open-source software. The exact values used for the domain and subsequent mesh generations are presented in Table 1.

Table 1. The Domain's Parameters.

The Domain'sparameters	Numerical value	Corresponding value for side view (ratio equal 3/382)	Corresponding value for top view (ratio equal 7/317)
Building's length	41 m	0.32198953	0.90536278
Building's width	41 m	0.32198953	0.90536278
Building's height	311.24 m	2.44427	6.87280757
Domain's length	1132.14286 m	25	25
Domain's height/width	317 m	6.1	7
Wind's velocity (1)	4.63 m/s	0.03636126	0.10223975
Wind's velocity (2)	23 m/s	0.18062827	0.50788643
Wind's velocity (3)	28 m/s	0.21989529	0.61829653
The mesh generation parameters		Value for side view	Value for top view
Number of active cells		8320	8448
$dim(X_h)$		67520	68608
$dim(M_h)$		8560	8704

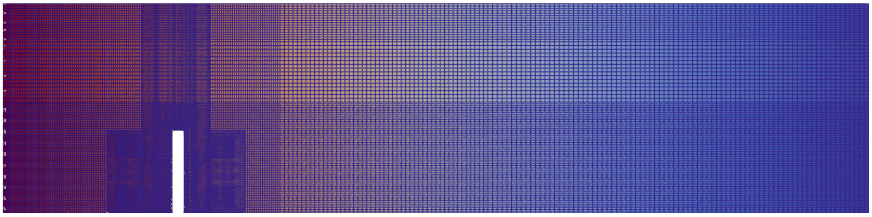
3 Numerical Results

Different simulations were conducted in different views to investigate the wind velocity profile in the domain. Although the total number of the simulations is far more, here, we present an only important portion of it. The main emphasis was put on the parametrization of the different views on the domain, Reynolds numbers, and the highest magnitude of the incoming flow velocity (x-component). This is done to investigate the effect of different parameters on simulation results.

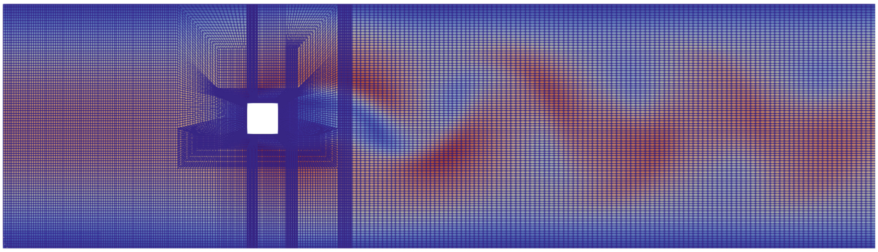
The most plausible values for the Reynolds number are 50, 100, and 200. For the incoming flow velocity, the chosen values are as follows. 4.63 m/s is the average velocity of the wind in Nur-Sultan. 23 m/s is slightly below the threshold value of 25 m/s, which indicates exceeded (the worst) category for pedestrian comfort [2]. Finally, 28 m/s is a higher value that represents wind velocity that occurs in Nur-Sultan regularly. Finally, we compared the velocity profile in the domain for different corner structures (round corners and sharp corners) in the top view case. Tables 2 and 3 show particular parameters for the simulation results.

3.1 Verification

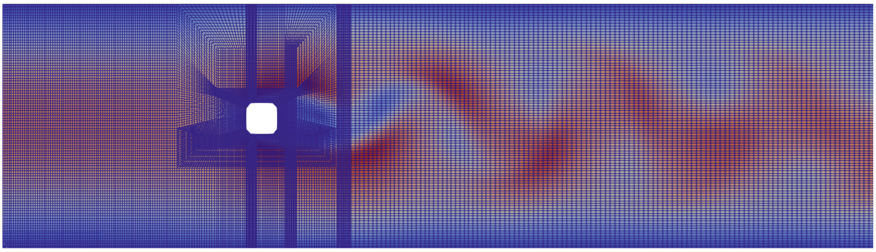
Before conducting the numerical experiments, we need to verify our computational model with the similar models of other researchers. The verification of the simulation results across different meshes and different input values is necessary to understand the scope of acceptable input values for our research simulations. We compared qualitatively our top view result with results from other work, see



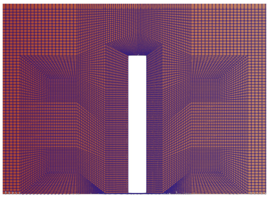
(a) The final mesh of the side view setting.



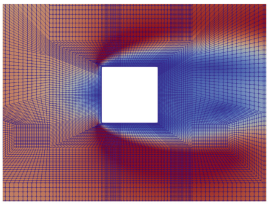
(b) The final mesh of the top view setting with sharp corners.



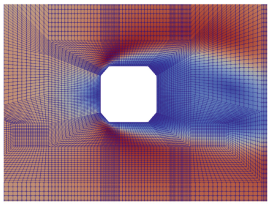
(c) The final mesh of the top view setting with round corners.



(d) The zoomed part of the final mesh of the side view setting.



(e) The zoomed part of the final mesh of the top view setting with sharp corners.



(f) The zoomed part of the final mesh of the top view setting with round corners.

Fig. 4. Generated Mesh Structures.

for more details Fig. 5. The result of one of the conducted simulations, which has a Reynolds number of 200, and a velocity value of 28 m/s, is shown below with the comparison with the result of the SimScale CFD simulation. One can see similarities in terms of the behavior of wind trails and areas of appearance of the vortexes.

Table 2. The chosen constant parameters' values for simulations in the results.

Parameter	Value
Duration	100
Time Step	5e−3
Iterations (Max)	1000
Stopping Criterion	1e−8

Table 3. The chosen variable parameters' values for simulations in the results.

Parameter	Value 1	Value 2	Value 3
View	Side	Top (Sharp)	Top (Round)
Reynolds number	50	100	200
Incoming velocity	4.63 m/s	23 m/s	28 m/s

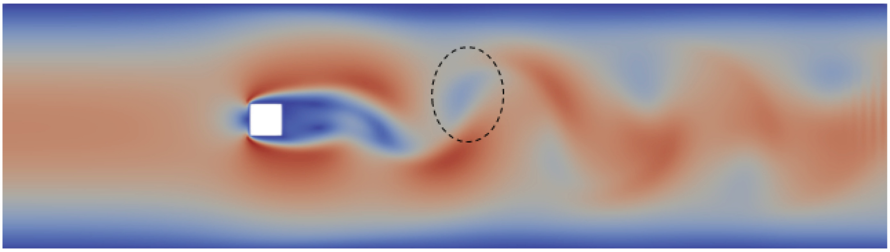
Another approach to verify our model is to compare it with the laboratory experimental result. Now, we consider simulations for the side view case similar to the experimental setting. We used the experiment results described in [14] as a reference model. Figure 6(a) shows the experiment's setting.

In this model, the incoming velocity profile has a parabolic structure as shown in Fig. 6(b). The velocity value raises quadratically as the point of interest raises in height. Moreover, the incoming velocity profile has only x-component as non-zero, which makes it identical to that of our simulations. It is also noteworthy that the height of the building is exactly 2 times longer than its width. This allows comparing the results of different simulations with that simulation if the proportions are concerned.

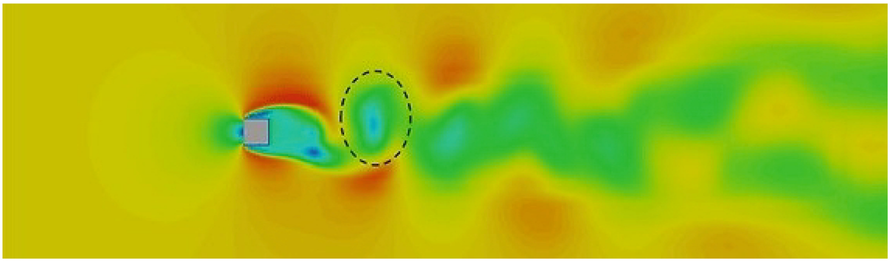
Following the experiment was not an easy task since some of the computation-related parameters can only be induced. However, knowing the inflow velocity profile, adjusting mesh for different boundary conditions (here, we set a slip boundary condition with zero pressure on the top $\Gamma 1$ wall, while other boundary conditions remained the same), and optimizing the comparison across time steps we obtained the results shown in Fig. 6(c). Note that a comparison was made for the final wind velocity values along a particular vertical line connecting 61–66 points in the mesh.

3.2 Simulation of Side View

In our first run, we tried a structure that depicts the side view of The Tower of Qazaqstan. For the side view, we did only a sharp corners case. In Fig. 7 we present some of our results. Figure 7(a) illustrates the resulted magnitude and direction of the velocity of wind across thousands of points on the model. We can see that the placement of such a tall building resulted in a vortex just behind it.



(a) The top view run with sharp corners with the maximal value of initial velocity being equal to 28 m/s. Reynolds number is equal to 200.



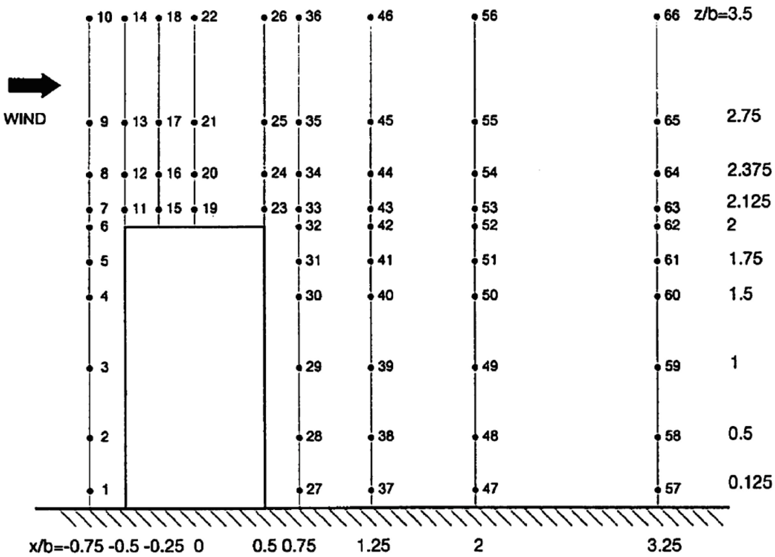
(b) The top view setting of SimScale simulation with sharp corners. Adapted from [4].

Fig. 5. Qualitative verification for top view.

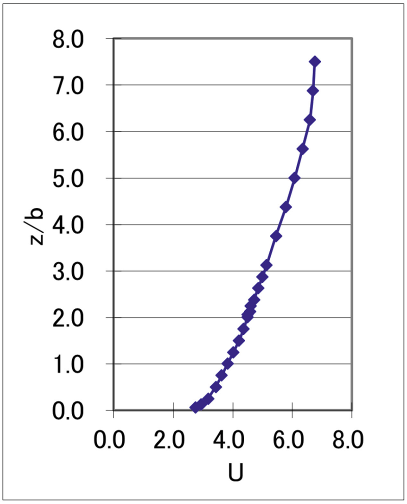
Figure 7(b) shows the highest velocity areas that can be uncomfortable for pedestrians. Note that dark red depicts such places. For example, one of such places is near the bottom boundary. Here, approaching the building in reverse x-direction against the wind becomes hard. The velocity value is around 25 m/s, which is the upper threshold level for uncomfortable wind velocity for pedestrians [2]. Note that this value occurred due to comparably similar initial wind velocity at top points in the domain. It implies that the shape of the building made high levels of wind get to lower levels, meaning the building's structure resulted in an artificial increase of wind velocity near the bottom of the domain, which is the pedestrians' walking place.

3.3 Comparison of Different Corners for Top View

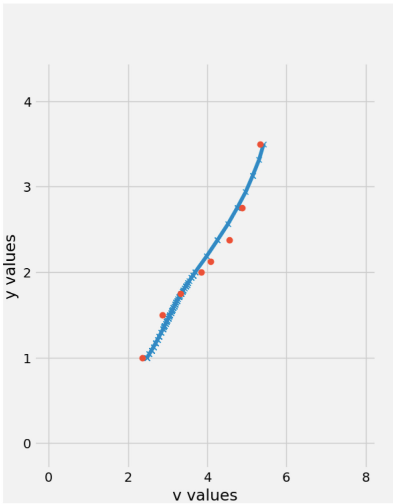
In the top view case, we tried a structure that depicts the rooftop view of the Tower of Qazaqstan. We studied a lot of simulations, one of which has a Reynolds number of 100 and a velocity value of 28 m/s.



(a) The experiment's setup. Adapted from [14].

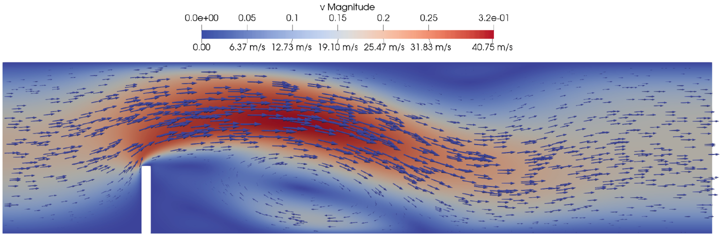


(b) The input velocity profile of the experiment. Adapted from [14].

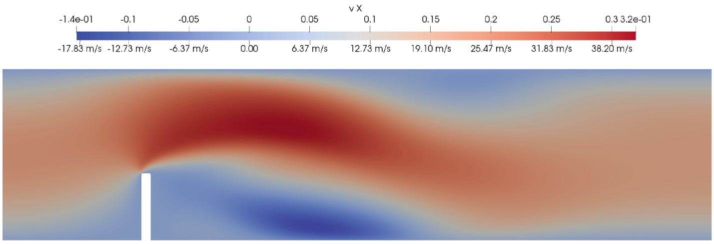


(c) The comparison between our last experimental model results (with a final time of 1) and the experiment results.

Fig. 6. Numerical verification for side view.



(a) The side view setting with final wind velocity values and directions.



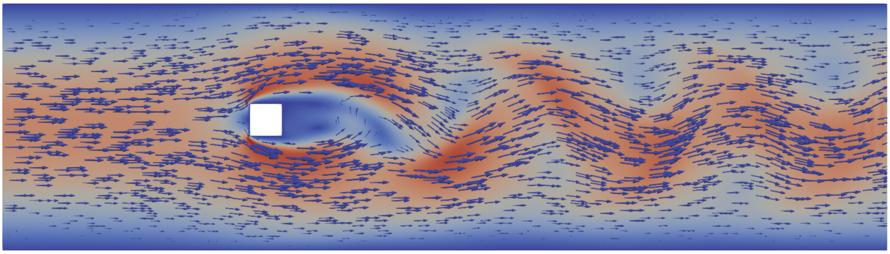
(b) The side view setting with x-components of final wind velocity values.

Fig. 7. Simulation results for the side view with the maximal initial wind velocity of 23 m/s and the Reynolds number of 200.

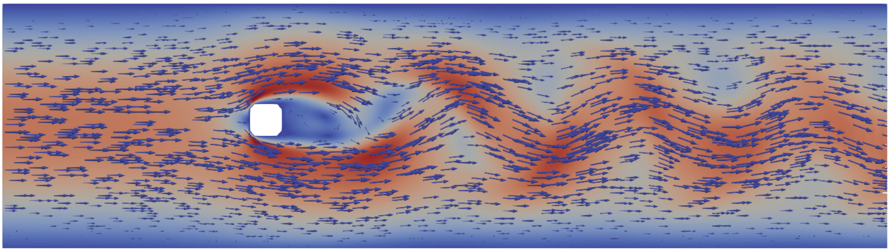
Figure 8(a) illustrates the results for a case with sharp corners. Here, the maximal wind velocity has a value of around 32.61 m/s, which is a wind velocity that belongs to the exceeded category of pedestrian comfort [2]. Note that this value occurred due to very high initial wind velocity at central points of the domain. So this suggests that the building's shape is affecting pedestrian comfort.

Now, we investigate the case with round corners. Other parameters remain the same. The results of one of these simulations, which has a Reynolds number of 200, and a velocity value of 28 m/s, is shown in Fig. 8(b).

Now, let us compare two different corner structures for the top view with the same parameters chosen above. Visually the difference can be seen in Figs. 8(a)–8(b). Numerically, it turns out that the maximal velocity of wind in the case with sharp corners is higher than that of the case with round corners by approximately 1.36 m/s. So this value for sharp corners is around 32.61 m/s and for round corners is nearly 31.25 m/s. This implies that round corners best serve for purpose of holding the velocity of the wind from increasing its value.



(a) The top view (sharp corners) with final wind velocity values and directions shown as magnitudes and directions of arrays, respectively.



(b) The top view (round corners) with final wind velocity values and directions shown as magnitudes and directions of arrays, respectively.

Fig. 8. Simulation results for the top view with the maximal initial wind velocity of 28 m/s and the Reynolds number of 200.

4 Discussion

During the investigation of this problem, several assumptions were made due to the complexity of the research topic. Results of simulations were converted under the assumption that the conversion rate is constant as can be seen in Table 3.

The numerical results suggest that the building's structure is the reason for the wind velocity of the exceeded category in some areas. For the side view case, the height of the building is the main factor of the increase in the wind velocity. For the top view case, the corner structures affected the results more. The round corners are better than the sharp corners for pedestrian comfort.

Some of the areas with the wind velocity of the exceeded category are located in the park behind the building. It is evident to plant trees and add more obstacles in such places, where we can minimize the wind velocity so that pedestrians can walk even if outside of this structure the wind velocity is very high. Finding such places, adding more parameters such that temperature, and decreasing the error in verification for the side view case are our focus for future studies.

5 Conclusion

Using CFD with FEM, and open-source software, we investigated the problem of wind effects on a tall building. Specifically, we conducted simulations around the modeled Tower of Qazaqstan. The Navier-Stokes model was solved by the projection finite element method in the deal.II library. The verification of the model was conducted by comparing the velocity profile of the experiment with the FEM model. The different velocity profiles are presented in a domain that is one of the important parameters of the wind flow model.

We found that the shape of this tall building might cause an increase in the wind velocity around areas dedicated to pedestrians. The numerical result of the side view shows that the increase resulted in a wind velocity of 25 m/s which implies the exceeded category of wind comfort. In other words, it makes it hard for pedestrians to commute. Planting trees and adding more obstacles in such areas might reduce the wind velocity.

In addition, we found that round corners best serve for purpose of holding the velocity of the wind from increasing its value. This might give interested people new ideas on the construction of buildings.

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