Investigate the Performance of a Proposed Micro-Turbine Design in Small Scale Openings in High Rise Buildings

INVESTIGATE THE PERFORMANCE OF A PROPOSED MICRO-TURBINE DESIGN IN SMALL SCALE OPENINGS IN HIGH RISE BUILDINGS

by

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DEDICATION

This thesis is dedicated to my beloved wife, Maryam, who has always fully supported me in my studying during this master program.

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Abstract

Increase in urbanization and industrialization around the world in recent years has led to a consequent rise in energy demand. In recent years it has been reported that approximately 75% of generated power is consumed in cities. It also worth to mention that about 50% energy consumption in U.S is in building sector which 41.7% is for operating buildings.

With the global energy demand in 2040 being expected to be about 30% higher than that of 2010. For this reasons, an urgent need for the incorporation of alternative energy as well as energy efficiency measures has to be incorporated in urban planning and construction.

Until now, two main approaches that have been integrated into large scale wind energy in urban settings are either locating wind energy farm in the periphery of the urban areas or integration of wind energy systems into the building design.

It was observed that the installation of wind turbines in order to meet 10–15% of global energy demand might cause surface warming by increasing the temperature by 1 °C on land. Moreover, there some issues that can be considered as a disadvantage for large wind turbines. For Instance: noise production, the social aesthetic acceptability, negative impact on birds, the cost of maintenance, transportation, sufficient infrastructure and etc.

In contrast to large-scale wind turbines, small wind turbines are much simpler and exploitation of building. In high-rise buildings, the heights and onsite energy generation imply an absence of big towers required to capture high wind speeds and minimum transmission losses, as well as a contribution to the configuration of zero-energy buildings.

On the other hand, to improve safety and serviceability of super-tall buildings in strong winds, aerodynamic optimization of building shapes is considered to be the most efficient approach. Aerodynamic optimization is aimed at increasing the structural resistance against winds.

The idea of generating wind power in high rise buildings is experienced in some constructions that the further study reveals the cons and pros about them. The Pearl River Tower, which is one of the latest and successful building in this type, considered as the case study for this research.

The research proposing the distributed opening as an effective modification to improve the aerodynamic behavior of the high rise buildings and devising the micro-turbine within the penetration for wind energy generating.

The CFD simulation shows the improvement in coefficient drag factor in the proposal design option and the wind tunnel test reveals better aerodynamic performance as well.

The conclusion shows better performance for wind harvesting and wind energy generating besides reducing the structural weight that would be needed in comparison to the original building. On the other hand, the proposal design shows more lift forces on the building and the other challenging issue would be maintenance the higher number of the small turbine.

The further study will be needed to controlling the vibration and noise level inside the wind ducts and optimizing the wind penetration pattern on the building façade.

Introduction

This research is based on general idea about pay attention to some underestimated potential in the high-rise building and The development and growth of tall buildings around the world within the past decades is due to many factors including the availability of more rental areas with less environmental damage, land use, and constructional cost efficiency, particularly in populated cities.

Attention should be paid to this trend of tall building construction, i.e., Manhattanization, and increased construction of ingenious tall buildings acting as landmarks or city symbols should also be highlighted.

A lot of efforts have been made in the last few decades in exploring wind energy and improving wind energy application technologies to optimize performance and increase generation in turbulent urban wind profile.

The high demand of energy consumption and rising the global population need careful consideration. Also, there is a great increasing trend in terms of high rise building construction due to increasing demand of urbanization. Meanwhile, to harvesting more wind power, there is an endless trend to reaching the higher elevation in wind turbine industry. Considering the growing high rise building construction and higher wind turbines at the same time, can brings the idea to use the integrated turbines in high rise building. This idea can have beneficial by onsite energy generation implies an absence of big towers required to capture high wind speeds and minimum transmission losses.

This research is investigating a practical way to use the wind energy in high ride building to first reduce the wind impact on building and then generating energy from wind force. The idea could be beneficial by not having the major influence on the shape of the building and utilizing the unused spaces in buildings instead of considering a specific space for devising the turbines. Another important issue in high rise building would be the pedestrian outdoor comfort which can be improved by reducing the turbulence effect around the building.

It’s worth to mention that the conventional wind turbines are the complex machine and need costly maintenance annually. By simplifying and localizing the wind turbine, it’s much easier to service the turbines and reduce the cost of manufacturing and maintenance.

1. Problem Statement

Increase in urbanization and industrialization around the world in recent years has led to a consequent rise in energy demand [1,2]. The expectation that more people will move to urban areas during the next few decades, especially in developing countries [3], has increased the need for more safe, secure, affordable and environmental friendly energy sources to satisfy the growing population [4–6]. In recent years it has been reported that approximately 75% of generated power is consumed in cities [7]. Generation of power within the city could be of great importance to help reduce both the generation load and transmission infrastructure. In addition, it may also minimize transmission losses due to reduced distance from users [8]. With the global energy demand in 2040 being expected to be about 30% higher than that of 2010 [9], it is predicted that more challenges such as increased environmental problems, depletion of fossil fuels and unstable oil prices will intensify.

A lot of efforts have been made in the last few decades in exploring wind energy and improving wind energy application technologies to optimize performance and increase generation in turbulent urban wind profile [11]. Until now, two main approaches that have been integrated in large scale wind energy in urban settings are either locating wind energy farm in the periphery of the urban areas or integration of wind energy systems into the building design. Although the former has been widely employed in the recent years to overcome the challenges of turbulence, noise, size, space and visual impact created in the city among others, wind turbines outside the city comes with additional cost to provide electricity network to transmit power to a distant electrical load [12]. On the other hand, the latter eliminates the need to expand the high voltage electricity network to provide electricity for these loads although it faces challenges such as low or poor wind turbine output, shadow flicker, strong visual impact and to some extent vibrations and noise issues in buildings [13]. In addition, it also requires detailed planning and design to be able to take maximum advantage of the wind in the urban environment.

During the past decades, some countries and regions across the world have experienced rapid industrialization and urbanization. A huge number of tall buildings have been constructed to cater for the demands of expanding population, and to sustain the steady social development. Nevertheless, it is worthwhile mentioning that as the construction industry grows vigorously, the consumption of fossil fuel resources associated with tall buildings has risen dramatically, which may be responsible for the deterioration of the natural environment.

Previous researches have indicated that approximately one-third of the global energy-related CO2 emission is associated with residential and commercial buildings [14–16]. Under such circumstances, the development of sustainable building (or green building) is highly required with a view to strategically mitigate CO_2 emission and alleviate greenhouse effects and other extended environmental problems.

The effect of large scale wind farms on the climatic conditions has been studied by various authors. Wang et al. [18] have per- formed simulations using a three dimensional climatic model in order to study the various potential climatic effects of future large scale wind farm installation over land and ocean. The simulations were run on a global scale for a period of 60 years as the temperature changes need a longer duration to show the gradual impact. It was observed that the installation of wind turbines in order to meet 10–15% of global energy demand might cause surface warming by increasing the temperature by 1 °C on land. Similar simulations for the 1 °C increase in temperature over the oceans have also been computed by increasing the ocean surface drag but a further study has to be done on its validation.

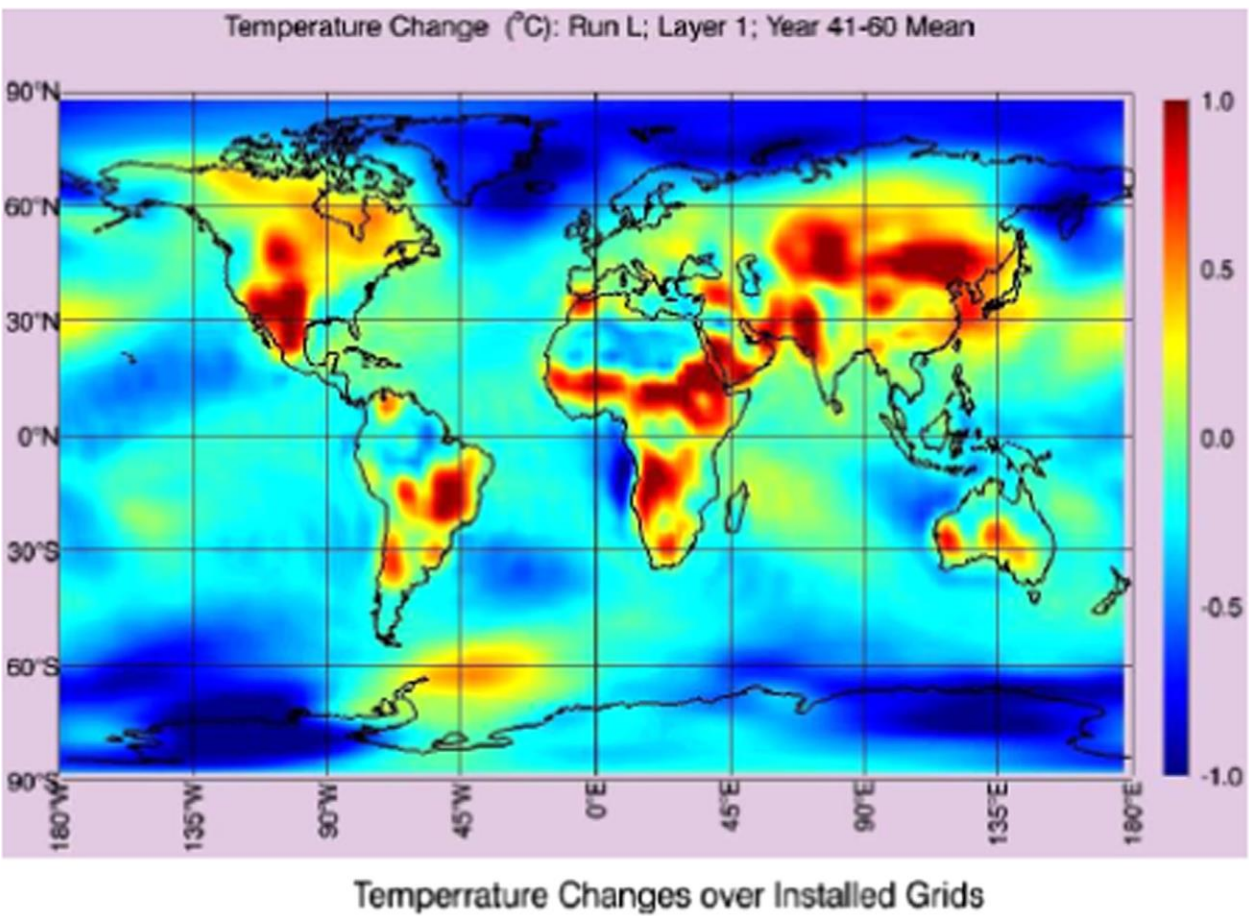


Figure 1 Temperature changes due to the deployment of large scale wind turbines [4].

Fig. 1 shows the temperature changes in one of the models due to the deployment of large scale wind turbines over the land in order to generate 158 EJ/year. All the above conclusions can only be made after considering the special or new parameters that affect the wind turbines. Due to nonlinear variation of climatic changes with surface roughness, defining the optimal arrangement of wind turbines is challenging. Climatic effects increase with the power generated and decrease with conversion efficiency, leaving out the potential environmental effects on birds, weather radar, ambient noise levels etc.

Fiedler et al. [18] have performed simulations for 62 warm seasons on a regional climatic model, and observed that there was 1% increase the precipitation rate. It was also seen that a larger rate of precipitation has occurred for a larger wind farm [19,20]. From the above results a conclusion can be drawn that installing large scale wind farms might lead to significant weather changes, so there arises a need to effectively use this wind energy without causing any adverse effects to the atmosphere.

The large scale wind farms are not a sustainable viable option for renewable power production. The best option available is by installing the decentralized grid system i.e., by using small scale wind turbines. Small scale wind turbines produce power around 10 kW which is sufficient for our domestic needs. This energy can be effectively utilized so that the energy extracted from the conventional resources could be saved for a larger period of time. Hence there arises the need to understand the characteristics of small scale wind turbines. The majority of work on small scale wind turbines was done over the past few years. The disadvantages of small wind turbines are high initial cost, effective placement, wind fluctuation, change in wind direction and also aero-acoustic noise. [20]

The role of the built environment is crucial to these objectives. Buildings account for about 50% the UK energy consumption, and housing produces 27% of CO2 emissions [21]. European legislation now requires energy performance certificates and the 2008 budget announced a target for all new housing to be carbon neutral by 2016, with all new buildings carbon neutral by 2019.

Much of this legislation is directed at new buildings, however, these represent only 1.5% of the UK building stock year. The Carbon Trust has identified that 60% of the buildings due to be standing in 2050 already exist and, even more importantly, nearly half of these buildings will have been built before 1985 when Part L was first introduced [22]. Consequently, both new and perhaps more importantly, existing buildings, will need to reflect these standards.

1.1. Size Evolution of Wind Turbines

Wind turbine technology has since 1980 encountered a constant size evolution that transformed the sector of small-scale turbines of tens of Watts to the sector of MW machines. During this time of evolution, the need for upscaling along with the urgency to exploit economies of scale managed to overcome every technological barrier appearing, resulting in the construction of rotors that nowadays even exceed 120 m.

The main drivers behind this unceasing trend of size increase concerned the need to exploit higher winds at higher altitudes, maximize area exploitation, and minimize system operational costs per unit power. Size evolution is summarized in Figures 2–4, where the time evolution of the rotor diameter along with the evolution of hub height and nacelle mass in relation to the former provides an overview of swept area, height, and mass increase of wind turbines over time [24].

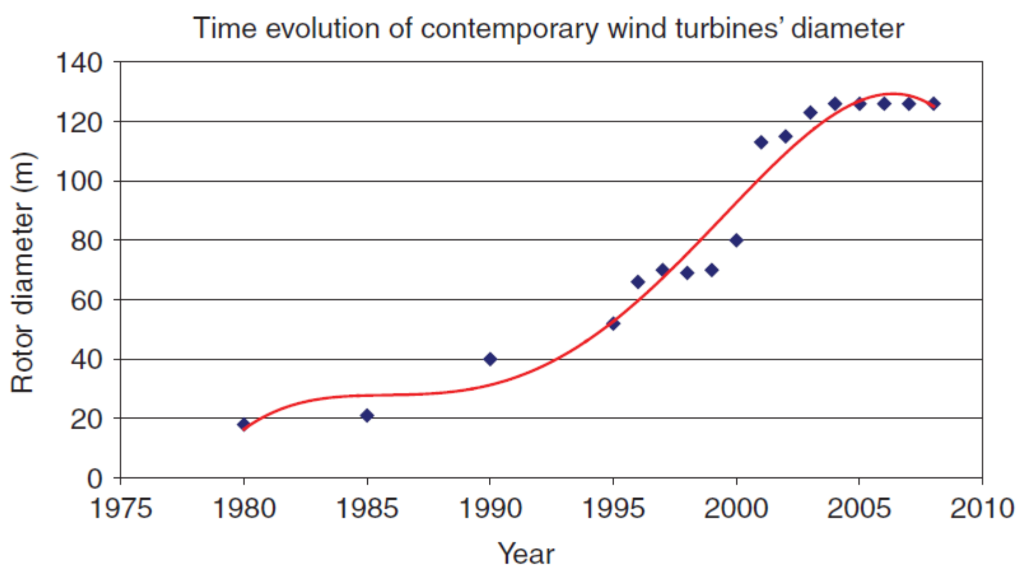


Figure 2 Time evolution of rotor diameter.[23]

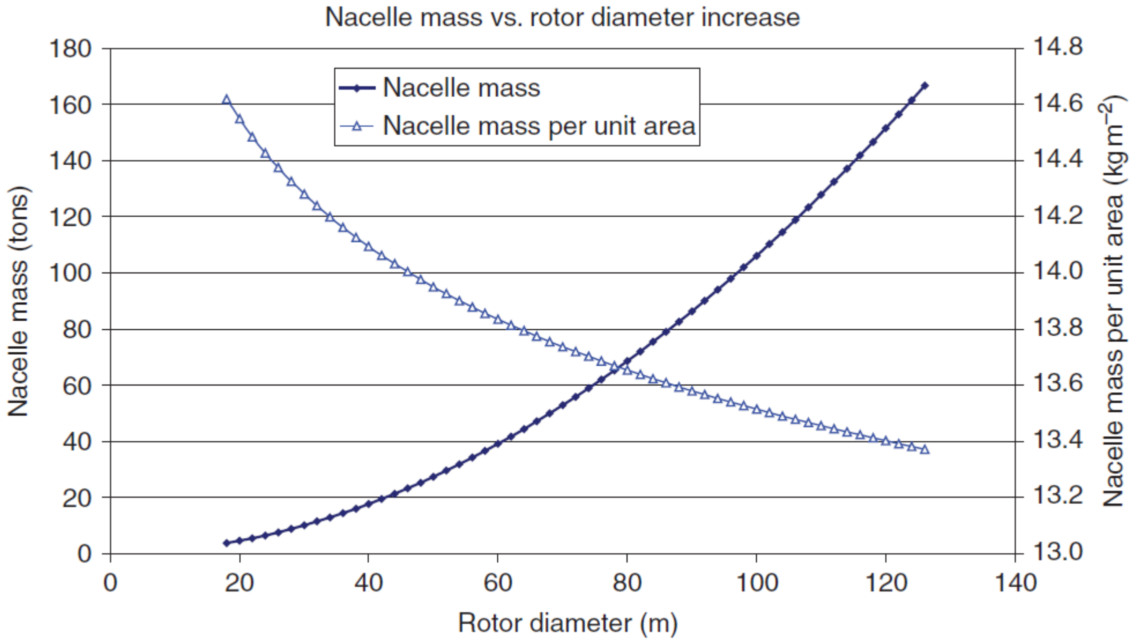


Figure 3 Relation between nacelle mass and rotor diameter.[23]

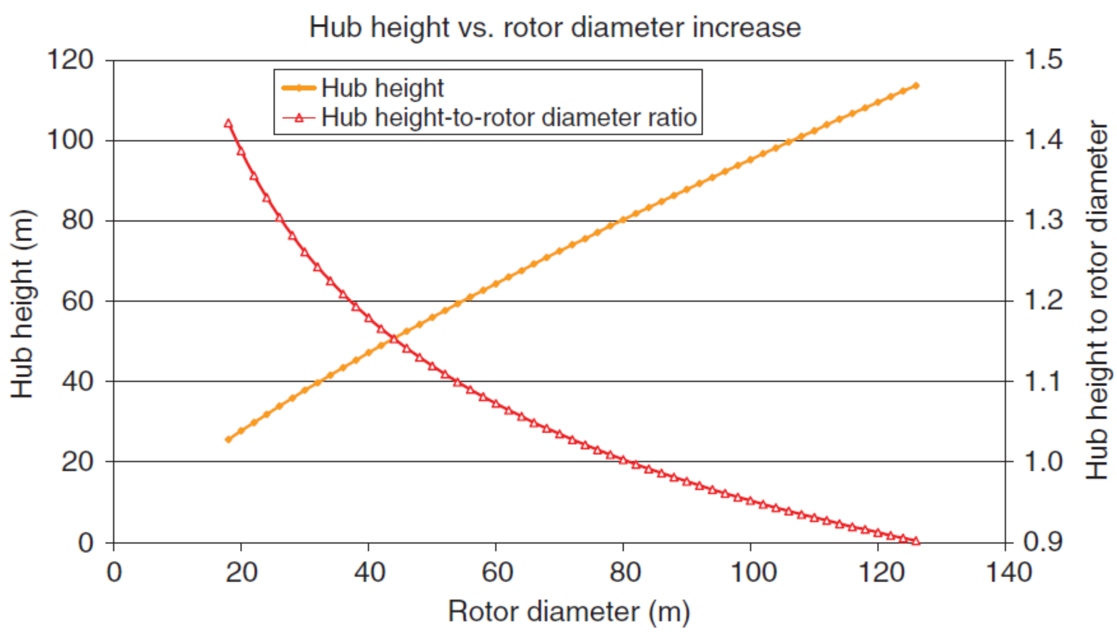


Figure 4 Relation between hub height and rotor diameter.[23]

In addition, according to the characteristics (thickness) of the atmospheric boundary layer, wind speed increase at heights greater than 120m is not as appreciable and, thus, there is no actual energy gain with further increase of the tower height. [23]

1.2. Environmental Impact Reduction

The considerable increase of both installed wind power capacity and contemporary wind turbine size, and the need to operate wind farms in areas that are close to available electricity grids and are determined by sufficient infrastructure, have raised issues of social acceptance, as a result of impacts caused to the environment and local societies by the operation of wind farms.

In this regard, although it is a common true that any type of impact caused by the operation of a wind farm is by far less important and more restricted (normally within a relatively limited area of some square kilometers in the vicinity of the wind farm location) than that caused by the majority of power stations (nuclear, thermal power, large hydropower, etc.), much attention has been given during the recent years to limit (if not to eliminate) the environmental impacts of wind energy [57]. What must be noted, however, is that with the current levels of social acceptability [58, 59] and appreciation of social benefits deriving from the operation of wind farms, installation of wind farms may well keep up with the up-to-now progress, allowing for integration of wind energy in all areas of the globe.

Among the most important environmental impacts caused by the operation of a single or more wind turbines is noise production (especially aerodynamic noise since mechanical noise has already been much limited on the basis of past efforts) [28]. As a result, emphasis is currently given on both the advanced design of blades in order to reduce noise produced and the optimum siting of the machines in an area of given characteristics. Special attention has also been given during recent years to the operational mode of the machines (e.g., reduction of the rotor rotational speed and variation of the angle of attack) in order to avoid annoyance. Finally, a significant part of the current research efforts has been concentrated on the noise propagation through and upon water [29], as a result of the growth met in offshore applications.

Moreover, one of the most important issues determining levels of social acceptability of wind turbines is also their aesthetic adaptation. Taking into account the extreme size of contemporary wind turbines (with the blade tip height above the ground even approaching 200 m), it becomes apparent that adaptation concerns have become critical. For this purpose, there are various calculation and photorealistic models currently developed [30], aiming at the minimization of the visual impact. In addition to the above, one of the issues that has long since been considered as a negative attribute of wind energy is the impact of wind turbines on birds.

For this purpose, there are serious attempts carried out nowadays so as to interpret behavior of birds in a given area and also record the paths of migratory populations [31], using suitable systems that are able to monitor and record the courses followed by birds and thus eliminate the already reduced fatalities [32].

As far as the rest of the wind energy environmental impacts are concerned, it must be noted that land occupation has considerably improved over the course of time, with the use of higher and larger-scale machines both offering greater power output per square area and allowing for land activities to occur even next to the wind turbine foundations. Besides, the gradual shift toward offshore applications has also much contributed to the amelioration of the land use impact. Local issues such as shadow flicker and interference with telecommunication signals can be thought of as resolved, especially if practices and regulations already available are properly applied. Finally, special emphasis has been given during the past 20 years to the issue of communication with local societies as well as to the development of integrated strategies that may assess impacts and better comprehend the factors that configure the behavior of local inhabitants [33,34].

One should also consider the involvement of various types of scientists, originating from different subject areas such as communication, sociology, psychology, biology, and strategic planning. Interaction of all these different experts then focuses on comprehending the opinion of the local societies, as well as determines the benefits accruing from the operation of wind energy in relation to the avoided costs deriving from the operation of alternative, usually conventional power sources. In addition, considerable effort should also be spent in the development of strategies that will allow the approach of local inhabitants and help them to both overcome their worries and become active participants in the development of new wind energy applications [35]. What should always be taken into account is that during every stage of developing a new wind park, all parties involved should acknowledge and appreciate the fact that wind energy comprises a sustainable energy solution that has the ability to sufficiently support the energy needs of contemporary societies.

2. Aerodynamic mitigation techniques for high rise buildings

For typical tall buildings, aerodynamic forces are drag force (along-wind), lift force (across-wind) and torsional moment (Fig5).

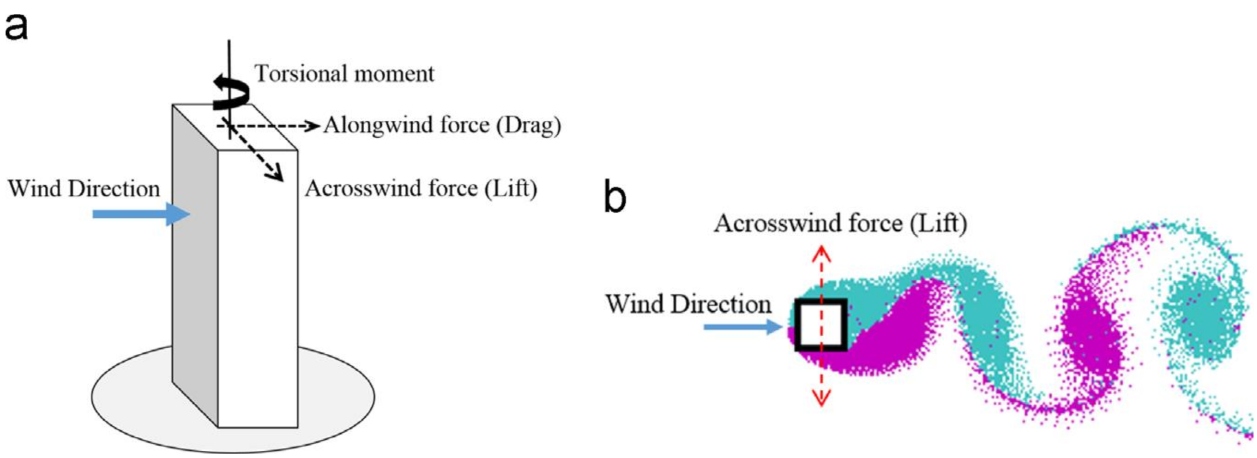


Figure 5 (a) Aerodynamic forces on a tall building; (b) Vortex shedding (plan view).[36]

The wind-induced response of tall buildings is usually dominated by dynamic across-wind loading resulting from wind vortex shedding [36] as shown in Fig.5. When wind blows over a bluff structure, flow separates and causes periodic shedding of vortices. This periodic vortex shedding exerts across-wind forces on the body by creating fluctuating pressures. Strouhal number is a non- dimensional parameter that defines the dominant frequency of the fluctuations in the across-wind forces and is expressed as:

$$S = fB/U \quad (1)$$

where, f is the frequency of vortex shedding, S is the Strouhal number, U is the wind speed and B is the building width. Strouhal number is a function of the shape of the building with values between 0.1 to 0.3, e.g. about 0.14 for a square cross section and 0.2 for a roughly circular cylinder [37]. Vortex-induced vibrations (VIV) occurs when the frequency of vortex shedding, f, approaches one of the natural frequencies of the building. This leads to amplified across-wind response. Vortex-induced vibrations are the prime problem in self-excited vibration of tall flexible buildings.

Aerodynamic mitigation techniques which utilize modifications to the external shape of a building (e.g. corner modifications, variation of the cross section shape and size along the height of the building, etc.) can significantly reduce building response under wind loads by altering the wind flow pattern around the building and can lead to a more economic and comfortable design [37-39]. Shape effects from a wind engineering perspective have been investigated by Davenport [40] through aerodynamic model tests. Many researches were performed to study the relationship be- tween the aerodynamic characteristics of a structure and the resulting wind-induced excitation level [41-48].

2.1. Modification of cross-sections

A well-known example of aerodynamic modification on building's cross-section is shown in Fig 6 . The cross-section (the floor plan) of Taipei 101 Tower shown in the figure was originally designed to be square. During the wind tunnel testing, a corner recession scheme was developed which effectively reduces the overall design wind loads by about 25% compared to its original design [49,50]

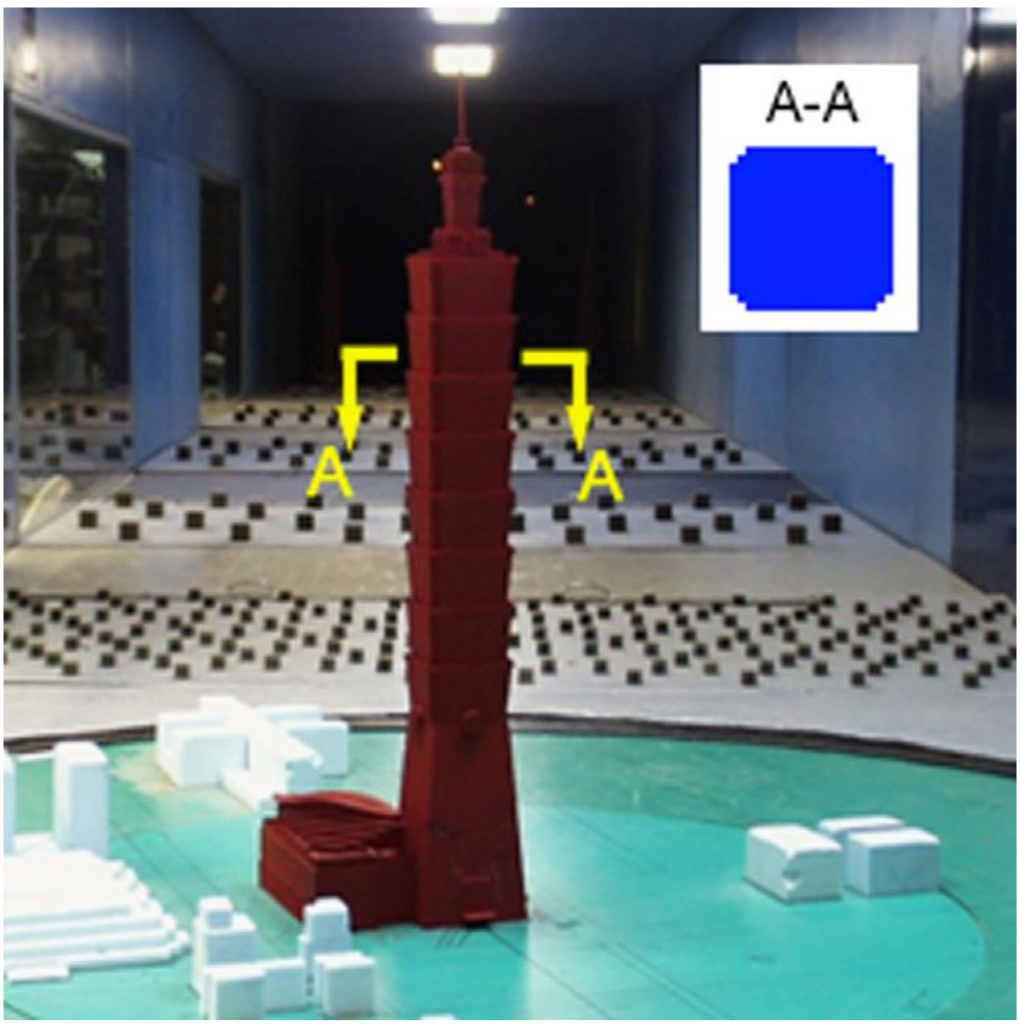


Figure 6 Corner recession [49]

Fig 7 shows a few commonly used schemes of corner modifications. To ensure the effectiveness of these modifications, a rule of thumb is that the dimension of the modifications should be about 0.1 B (10% of building width) or greater. The scheme of corner balconies can be viewed as an aesthetical alternative to traditional helical strikes which are commonly used to suppress vortex excitation on chimney stacks. Some studies verified that commonly designed corner balconies can reduce both vortex shedding and wind loading.

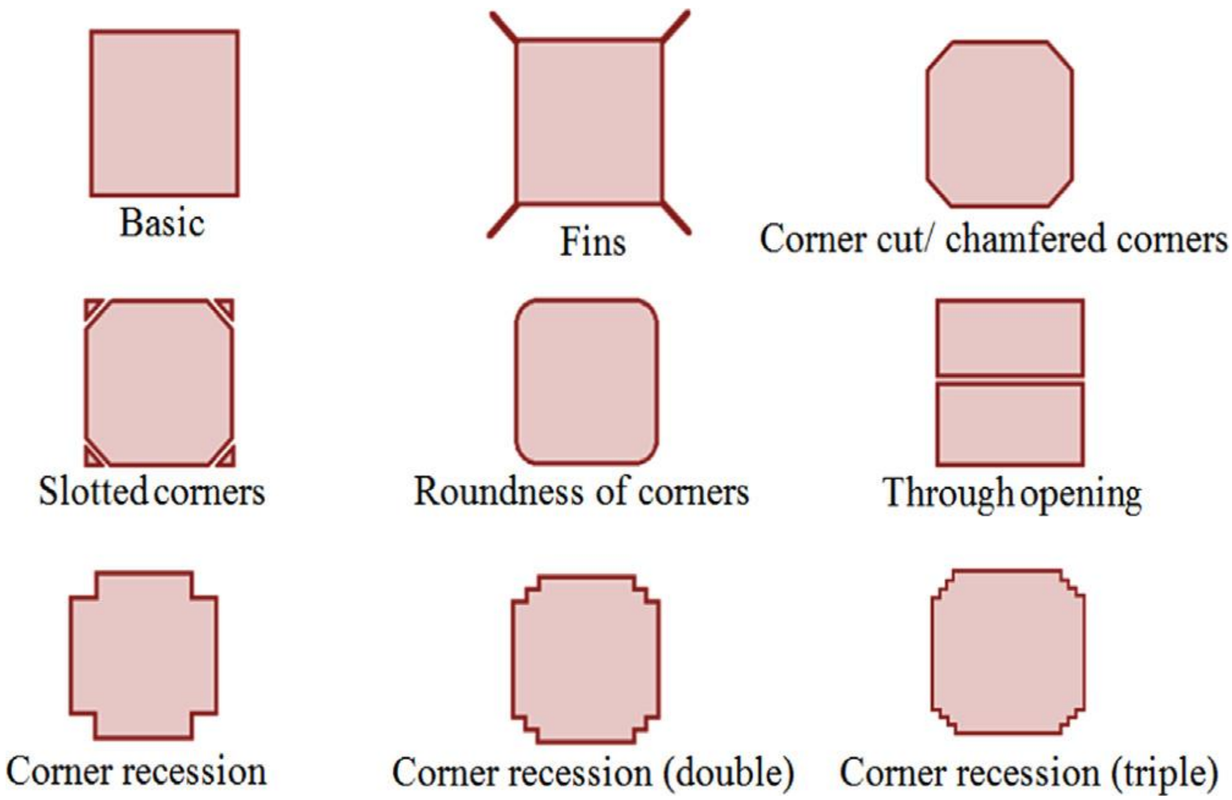


Figure 7 Illustration of corner modifications [51]

Opening or corner slot is not commonly used in design practice due to unfavorable consequence of indoor space loss. However, in a few special cases the corner slot cannot only reduce the across-wind excitation, but also improve the indoor space usage, shown in Fig8.

Figure 8 Opening and Corner slot [50]

2.2. Modification of building elevations

The basic concept of this approach is to increase the variation of building shapes with height, either by section geometry, by section dimension or by section orientation. There are four basic forms of elevation variations:

1. tapering
2. twisting
3. stepping
4. sculptured top

These forms share a common mechanism in reducing wind response. Due to variation of building geometries with height, the properties of vortex shedding varies with height as well, resulting in much less correlated excitations. The study conducted for twisting effects (Fig 9) indicates that effectiveness of twisting increases with the increase of twisting angles. However, by taking into consideration of both aerodynamic benefits and potential complications for the cladding system, the designers were convinced that the 1201 twist version with top openings for turbines should be the overall best one, which represents about 15% reduction of design wind loads compared with its original configuration of 1001 twist [52,53].

Figure 9 Shanghai Tower, twisting and tapering modification.[52]

The tapering effects of reducing across-wind response can be explained in a similar manner as for the twisting. Since the vortex shedding frequency is inversely proportional to building width, the tapering causes the outstanding frequency of wind excitation to vary with the building height so that the outstanding frequencies are spread out over a wide range with the magnitude of overall excitation being significantly reduced.

As mentioned before, modifications to building elevations can cause dramatic visual impacts and can lead to a totally different design. Therefore, modifications to building elevation are acceptable only during an early stage of architectural design.

While aerodynamic modifications bring in benefits of reduced design wind loads and building motions, these modifications often create conflicts with other design aspects. A good design has to compromise many design aspects. For this reason, it is important to have an approach to estimate the level of effectiveness for various aerodynamic options, so that the pros and cons of these options can be assessed and compared with each other.

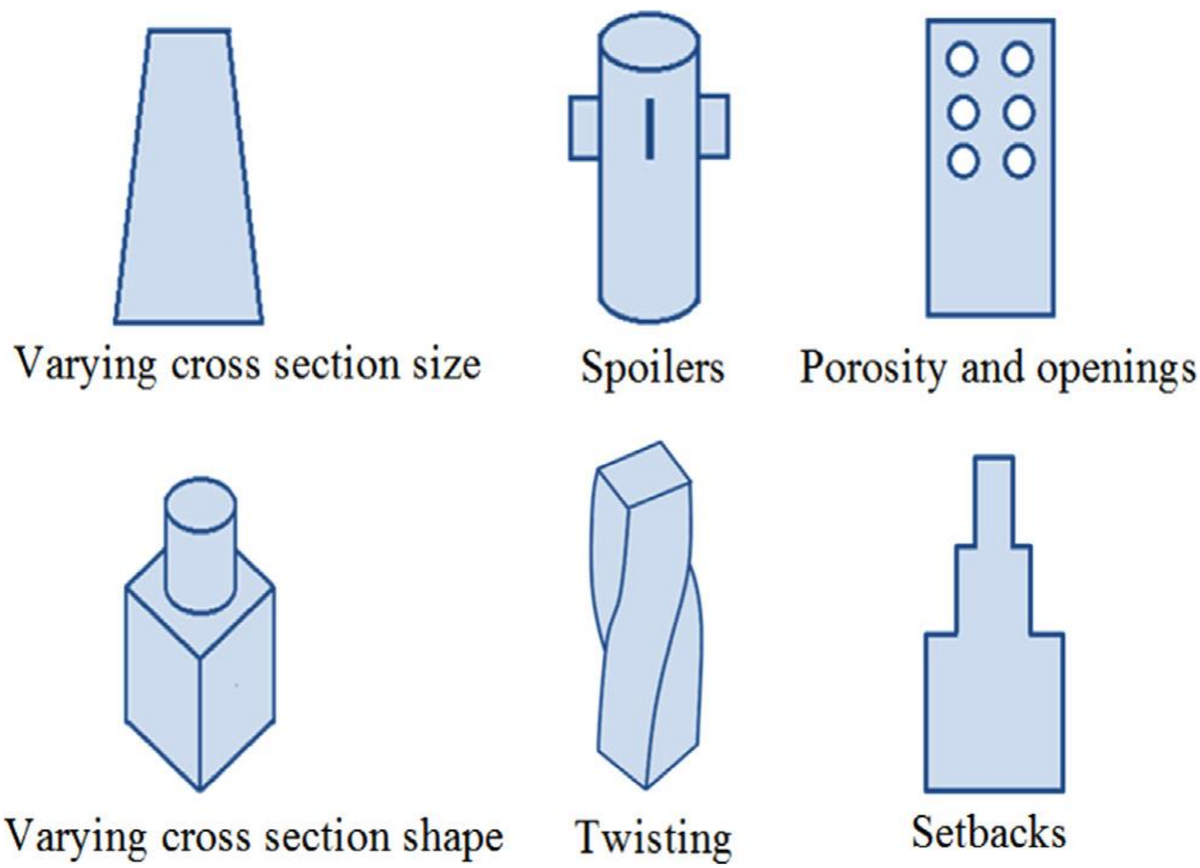


Figure 10 Modification of building elevations[53]

3. Common types of wind turbines currently being used in urban environment

The kinetic energy in the wind is harnessed by wind turbines and transforms it into electrical power or mechanical work [54]. Since wind profiles in urban areas tend to be more turbulent due to the presence of buildings, trees along the streets, and other obstacles [55], urban environment has unique challenges in development of wind energy systems. Much of the on-going developments on these systems are noise reduction, esthetics, integration into architectural systems, and efficient use of the available wind resource [56]. Over the past few years the major advancements in development trend has been to increase the size, efficiency and reliability of wind turbines, making their deployment more cost-effective. Although there are many different configurations of wind turbines [57], two classified types of wind turbines used in urban areas are horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [58].

3.1. Horizontal axis wind turbines (HAWTs)

Until now, the common types of wind turbines used in urban environment are horizontal axis wind turbine types. Modern utility-scale of HAWTs is near the theoretical maximum for efficiency, a reason why the industry focuses on that type of turbine [59]. These types of wind turbines have their axis of rotation of the blades in a horizontal position [60]. During operation, the wind blows through blades, converting wind's energy into rotational shaft energy. The propeller-type rotor mounted on a horizontal axis needs to be positioned into the wind direction by means of a tail or active yawing by a yaw motor [61,62]. Due to the sensitivity of HAWTs, changes in wind direction and turbulence especially in urban environment negatively affects the performance because of the required repositioning of the turbine into the wind flow [63,64]. The real and perceived problems with large HAWTs in urban environment are the dangers to birds and aircraft, esthetics, manufacturing issues, maintenance, etc., HAWT's blade sizes are also part of their limitations in their use in urban environment [65]. After certain length of the blade, you cannot make them larger. However, stacking up large VAWTs, possibilities of building a larger structure within the urban exists, opening up more change for VAWTs penetration in urban market. Fig 11 shows different orientations of HAWTs that can be used in urban environment.

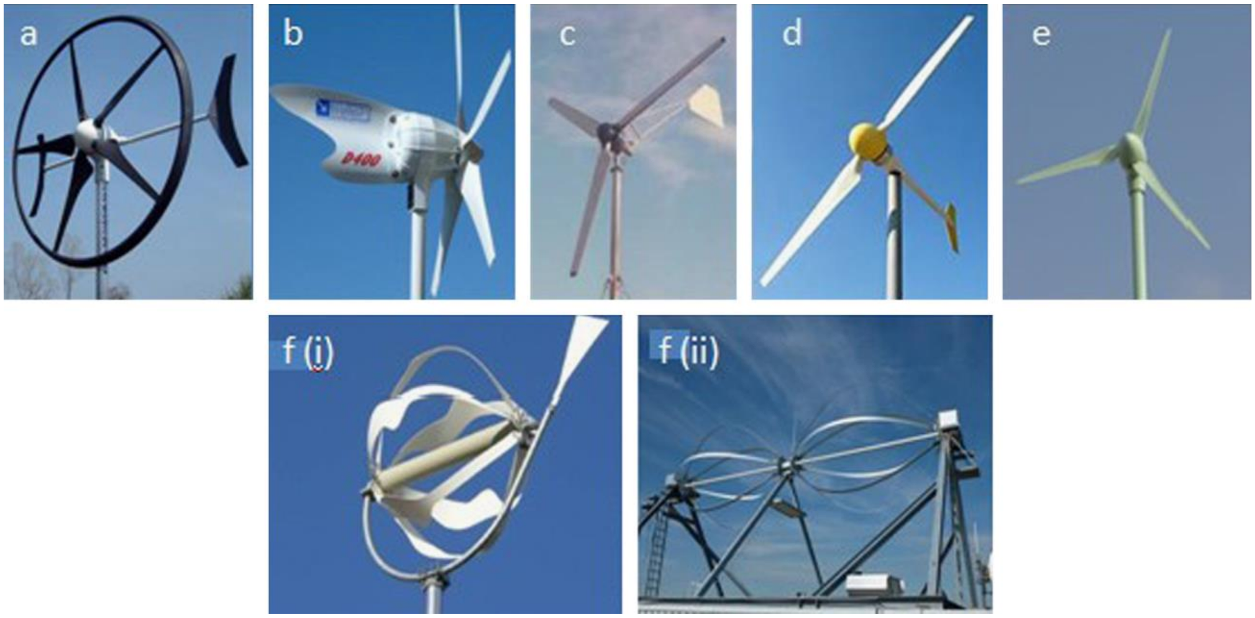


Figure 11 Examples of HAWTs. (a) Swift wind turbine [66], (b) Eclectic wind turbines [62], (c) Fortis Montana wind turbine [67], (d) Scirocco wind turbines [68], (e) Tulipo wind

3.2. Vertical axis wind turbines (VAWTs)

The vertical axis wind turbines have a vertical axis of rotation of blades about the vertically positioned shaft [74]. The advantage of these types of machines is that they do not have to face in any particular direction with respect to wind; this makes them perfectly suitable for urban environment [65,73]. Another benefit of these types of turbines is that the generator and gearbox can be installed at ground level making them easy to service and repair apart from being suitable in building mounting in urban environment. Due to the turbulence nature of the wind in the urban environment, the vertical wind turbines provide a much better option for small scale production as they can handle much higher turbulence and varied wind speeds as compared to HAWTs. Consequently, because of their lower elevation, they are ideal for cities and other densely populated areas where it has not been possible to set up wind turbines. In general, most of the electricity produced by VAWTs is utilized on-site. These types of wind turbines are preferred in small scale installations, and generally generate very little energy as compared to their horizontal axis counterparts [75].

The overall increase in the use of smaller VAWTs in the urban environment has been due to the ease and low manufacturing cost for smaller turbines. These turbines are more scalable and can be installed at a lower elevation above the ground. For these reasons, the market share of these types of turbines is improving due to their relatively low maintenance costs as well as decreased impact they cause on birds and aircrafts. Compared to farms of HAWTs, the VAWT farm has three times the power density at one tenth of the height [76]. There are four main types of vertical axis wind turbines used in urban environment today as shown in Fig 12.

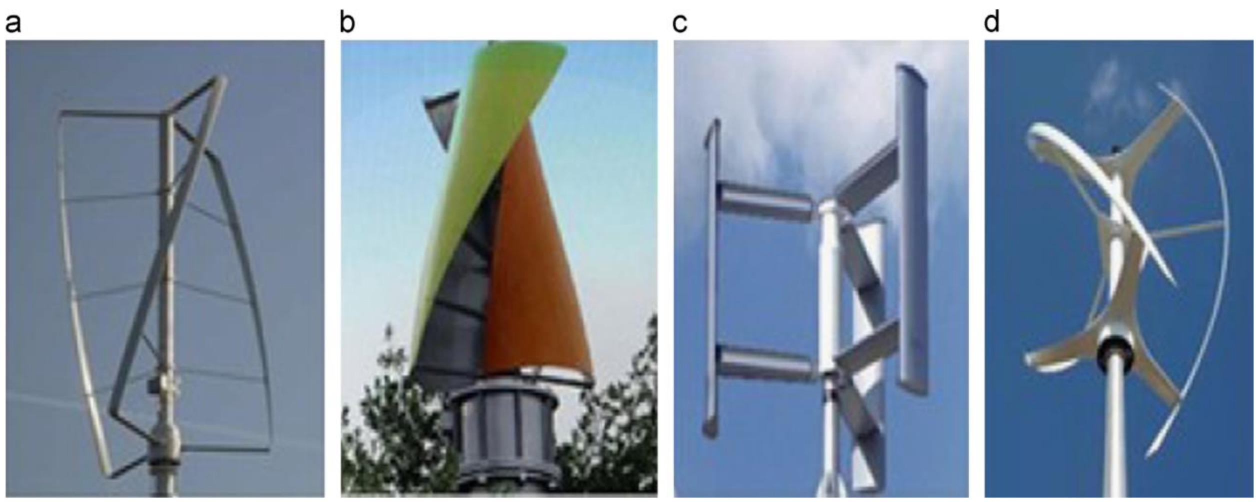


Figure 12 Different types of Darrieus wind turbines. (a) Turby turbine [111], (b) WindSide [112] Turbine, (c)

As mentioned before, unlike the large open windmill farms, extracting wind energy in an urban scenario is challenging because of the tight space constraints and the fact that wind profile is highly turbulent with rapid fluctuations, both in terms of magnitude as well as direction. Due to this, development of a revolutionary and extremely efficient small-scale variable pitch VAWT, with a simplified blade pitching mechanism, is among the recent main research topics. Kinematic coupling of the blade pitching mechanism with turbine rotation could reduce the additional power required to pitch the blade. In addition, it enables easy blade pitching with changes in wind direction [77]. This capability of the present VAWT pitch mechanism, to immediately respond to changes in wind direction, is the key to maximize the power extraction in urban environments where wind direction changes rapidly [78]. Recent research on the VAWT blades is also focusing on light-weight systems to minimize turbine structural loads and provide high strength-to- weight ratio [79]. This reduces the cases of large bending and torsional deformations due to the large transverse centrifugal loading, which would hamper the turbine efficiency during operation. The present blades use an innovative, high strength-to-weight ratio, composite blade structural design, which is similar to the blades used in case of the flying cyclocopter [80], where the blades operate under larger dynamic loads due to the higher rotational speed of the powered rotor.

With the idea of designing and building suitable small-scale wind turbines for urban environments in mind, various HAWTs and VAWTs have been researched on to determine their suitability. Simple construction and cost of materials has been a major driving factor in the decision making process. Large utility-scale HAWTs are very expensive to produce and also require enormous manufacturing facilities. Smaller VAWTs can be produced in more modest facilities using standard techniques leading to lower overall costs. Despite the fact that they have not been commercially successful, VAWTs have been preferred for small scale power production in urban environment as they possess the required design factors [85]. Until now, HAWTs are highly developed and currently available in the entire existing wind farms [19]. Studies estimate that within the next 2–3 decades, VAWTs can dominate the wind-energy technology, especially in urban environment, because they require less land space and using the same space; they are capable of producing more energy than that of its counterpart [86].

4. Venture effect and high rise building

The influence of buildings on the wind micro-environment has aroused increasing attention in the area of urban planning and design [87-89]. Many researchers have found that the urban open space design with long and narrow passages between slab-type buildings can lead to a significant increase in local wind speed and cause wind nuisance for pedestrians [90-97]. This phenomenon is traditionally explained as the result of the Venturi effect [90,96] since the flow speed in the building passage shows an increase along with a decrease in the section area, which is thought to be analog with the Venturi phenomenon described for duct flow well documented in fluid engineering [98]. This view has been widely recognized and propagated [97,100-103].

The passage flow between buildings is mainly influenced by the building orientation, building arrangements, building dimensions and passage width. [104] conducted wind tunnel experiments to consider a typical passage model with two identical buildings of 100 m x 10 m x 30 m (L x B x H, in full scale) placed perpendicular to each other, which is believed to be a suitable arrangement for the occurrence of Venturi flow. Two types of wind flow were considered, i.e., converging flow (a=45^0) and diverging flow (a=135^0) depending on the wind direction. [150]

The passage width is assumed to be constant as W=30 m (in full scale). In total, 12 cases were considered by varying a from 0^0 to 180^0 with a step-change of 15^0 (0^0 and 180^0 are the same cases). The top view of the building models is shown in Fig 13. [150]

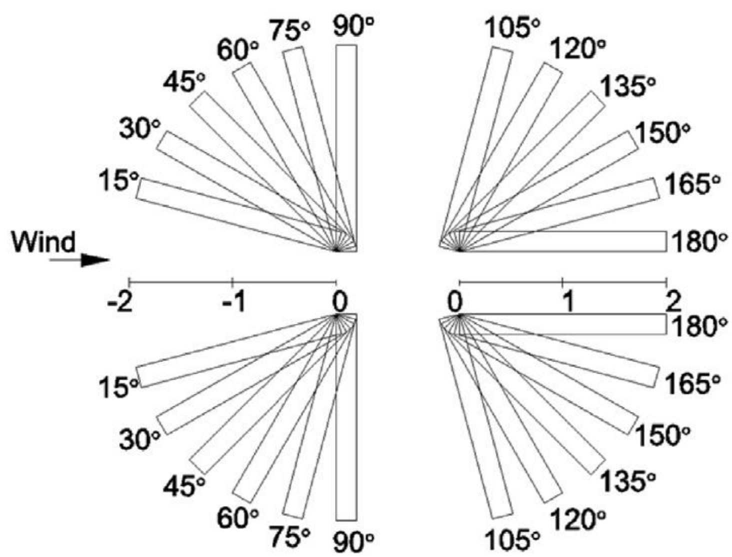


Figure 13 Top view of the passages between buildings with different orientations[150]

4.1. Converging flow vs. diverging flow

Results are discussed in terms of the amplification factor K at the height of 2 m (full scale). Fig 14 shows the contours of K in and around the building passage. Generally, the higher K-value areas appear around corner streams and within passages in all cases, and the calm-wind areas are evident near windward and leeward sides of the buildings. [150]

It is clear that the wind speed in most diverging passages is considerably larger than that in converging counterparts. In addition, Fig 14 shows that the K value is higher near the upstream outer corners than that within the passage for all a < 90^0 cases. [105]

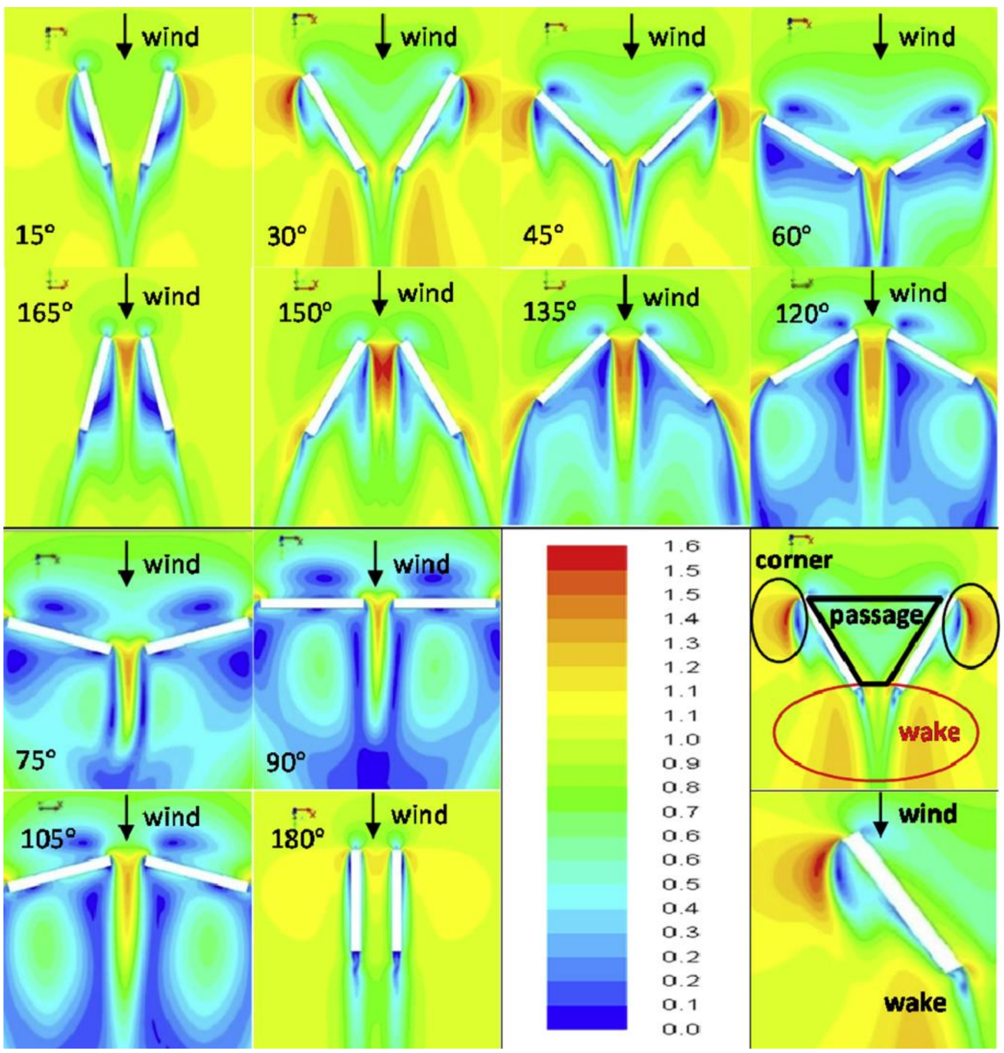


Figure 14 Amplification factor K in a horizontal plane at 2 m height above the ground; wind direction and building orientation a are shown in each figure; two schematic diagrams are illustrated based on the a=30^0 case.[205]

4.2. Drag coefficients

A principal effect of wind flow around passage buildings is the wind-blocking effect, which forces the air to flow over and around buildings rather than just going through the narrow passage opening. Drag force/drag coefficient is normally used to describe the resistance of buildings to the air. Considering the important force of buildings acting on air, the drag coefficient, defined by Eq. (4) is exhibited in Fig 15, including three drag coefficients along the x, y, z coordinates respectively. [105]

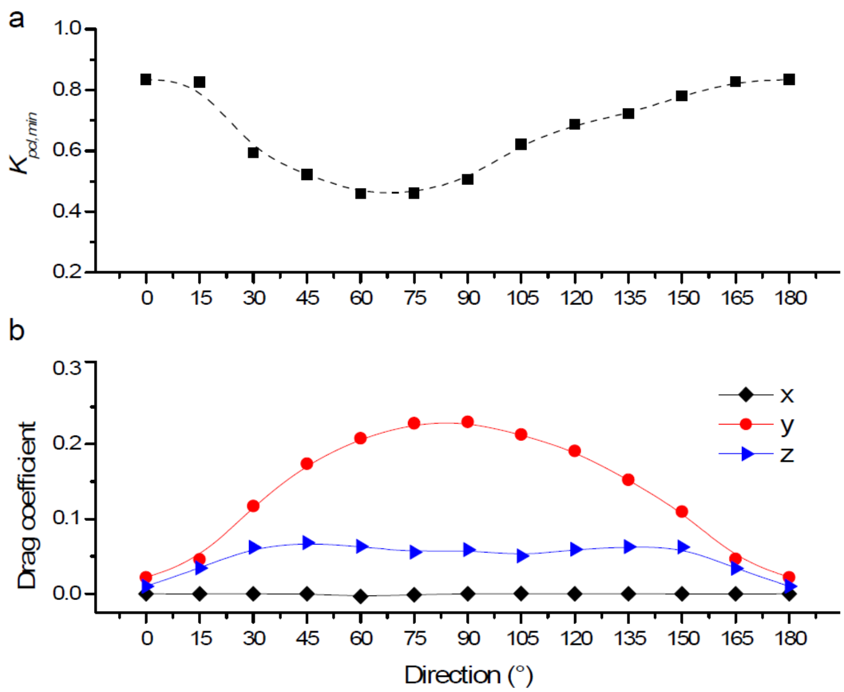


Figure 15 (a) Amplification factors as a function of the building orientations; (b) Drag coefficients for the x, y, z coordinates defined by the Ug and the total surfaces area of buildings.[105]

4.3. Wind-power generation

The power output of a wind generator can be expressed as :

$$P_W = C_P\left(\frac{1}{2}\rho A V^3\right)$$

where PW is the power of the wind, ρ is the air density (kg/m3), A is the swept area of rotor (m2), V is the wind speed (m/s), and CP is the power coefficient of wind rotor.
It is clear from Eq. (1) that the power of the wind increases with the cube of the wind speed, which is the explanation for why wind turbines should be located at relatively windy sites. Further- more, the power is also proportional to the swept area of rotor. In

other words, there are two ways to increase the power by enhancing the wind speed or/and by increasing the mean diameter of rotor. Obviously, the most effective way for increasing wind-power generation is to enhance the approaching wind speed, since even a small increase in wind speed will result in a large gain in power output. [106]

5. Hypothesis

According to the literature review, one of the effective modification to improving the aerodynamic behavior in high rise building is devising the opening. The scope of this research will be the evaluation of the following question.

"Is It possible to distributing the façade penetration by increasing the numbers and reducing the size of the holes to reduce the wind impact on building and increasing the wind energy harvesting capacity? "

This research, as fundamental research, evaluates the finding of wind energy generation in high-rise building without considering the specific context and function for the building and looking for the impact of wind pattern on distributed small opening in building façade.

6. Research Question

According to the initial idea and the literature review and to find the proper answer for the Hypothesis, the following research questions are considered:

1. Is it possible to improve aerodynamic behavior of opening modification by increasing the number and reducing the size of them?
2. How is possible to generate energy from wind power within small penetration
3. Is the overall energy generation of many small turbines surpass the giant turbines?
4. What are the advantage and disadvantage of using small turbines instead of big ones?

7. Research Methodology

For this research, two methods use to gain the best result by providing the comparison between digital and real world simulation. Also, the 4 case studies considering for studying to determining the advantage and disadvantages of each of them.

At first, 4 buildings as the existing construction that use the idea of wind energy generation with integrated turbine are chosen. After further studying the Pearl River Tower chosen to provide a base to testing the idea on it. The reason for choosing this specific building is the shape of it that design specifically to harvesting the wind power and also the scale of it enable the wind tunnel test to have a realistic size for penetrations versus Shanghai tower that is too big and by decreasing the scale of it, the size of the penetrations become too small that cannot modify the physical model.

The second step is using Computational Fluid Dynamics (CFD) as a digital wind tunnel simulation. For this purpose, Autodesk Flow Design use to generate numeric result.

The third step is testing all idea in real world situation. The laboratory testing the physical model is using visualization observation the glycol smoke to observing the smoke pattern and the performance of the physical model in the real world.

8. Case Study Research

The idea of integrated wind turbine in high-rise building become popular during recent years. The evidence of this matter can be found in the recent highest tower built in China. The Shanghai tower, designed by Gensler, which at this time is the second highest building through the world wide using the same idea to harvesting wind by devising small turbines on the top the building. [107]

Figure 16 Shanghai Tower Site, Lu Jia Zui[107]

The Gensler design team had anticipated that significant reduction in both tower structural wind loading and wind cladding pressures could be established if the building further improved its proposed geometry following the variables previously explained. To establish the best possible case for reducing these loads, several scenarios were proposed involving rotation at 90°, 120°, 150°, 180° and 210° and then scaling off 25%, 40% , 55%, 70% and 85%. All these scenarios were analyzed against each other and then compared to the base case scenario that was proposed, in the form of a tapered box. [107]

Results acquired through this process have shown that a scaling factor of about 55% and rotation at 120° can account for up to 24% savings in structural wind loading and cladding pressure reduction as compared to base-case tapered box. This equates to about $50 million (USD) in savings in the building structure alone. Additionally, it helped optimize and distribute maximum cladding loads on the building while maintaining desired aesthetics. Aesthetic concerns prevented the 180° rotation from being pursued, even though it would reduce loading by an additional 9% (Figure 19). [107]

Figure 17 Wind tunnel study scaling models.[107]

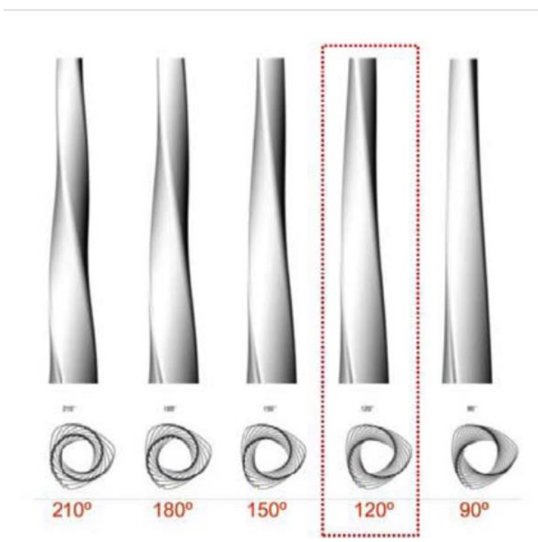
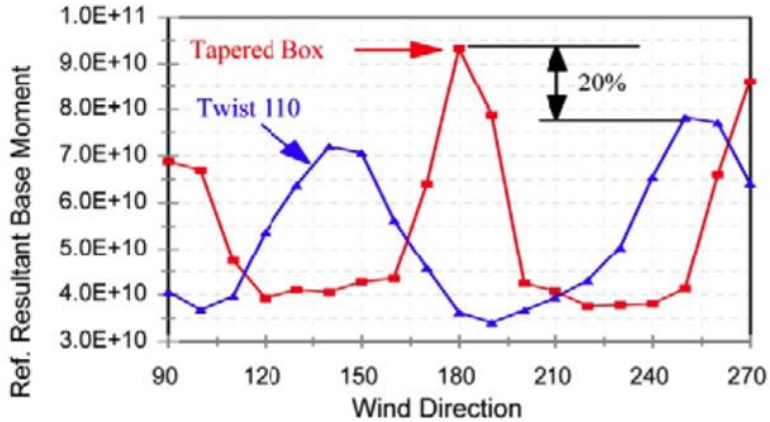


Figure 18 Wind tunnel study rotation models.[107]



Configuration	My (N-m)	Ratio	Mx (N-m)	Ratio	Ref.Resultant	Ratio
Base (Tapered Box)	5.45E+10	100%	4.98E+10	100%	6.22E+10	100%
100° (107°)	4.53E+10	83%	4.19E+10	84%	5.18E+10	83%
110° (118°)	3.97E+10	73%	4.31E+10	87%	4.92E+10	79%
120° (129°)	3.43E+10	63%	4.29E+10	86%	4.75E+10	**76%**
180° (193°)	3.39E+10	62%	3.65E+10	73%	4.18E+10	67%

Total Construction Cost 9.0 billion RMB
Structure 24% - 288m USD
5% load reduction = 70 m RMB = 10 million USD

Figure 19 Wind loading testing results comparison (RWDI).[107]

In keeping with the client's desire to demonstrate cutting-edge technologies, wind turbines at the top of the building will power the exterior lighting for the building and some of the park areas. The turbines will produce an estimated 54,00 kWh/year in renewable energy. [107]

Figure 20 Shanghai tower wind turbines [108]

Another building that can consider as a pioneer design to use the integrated wind turbine in building is Bahrain World Trade Center. The Building was completed in 2008 costing about $150 million.

The pioneering design of a twin-tower building with three integrated 35m diameter, 250kW horizontal axis wind turbines has now become an iconic form representing this field. Figure 2 present this design together with the first serious attempt which has since emerged to emulate these ideas – the World Trade Centre, Bahrain (constructed in 2007–2008). This building has three 29m horizontal axis turbines suspended between two 34-story towers of prime office space. Both of these towers have been designed to catch and accelerate the prevailing winds. In the case of Bahrain’s World Trade Centre, it should be noted that these are mild coastal winds and the building form is not fully aerodynamically optimized. [109]

Figure 21 First large-scale building-integrated turbine project World Trade Centre in Bahrain, 2008. [110]

At least, that was the architects' intuitive idea. But according to Bert Blocken, professor of Building Physics at TU/e, this assumption is incorrect. "Ideas about wind flows are often based on intuition, but that leads to suboptimal designs." Using precise wind tunnel measurements and computer simulations on a model of the Bahrain WTC, Blocken calculated that the towers would actually produce 14 percent more wind energy if they were positioned the other way round. Or better still, suspending the wind turbines further back would have given a 31% higher energy output per year, Blocken discovered. But that is no fair comparison, says the researcher. "Because of constructive and financial reasons this option isn't realistic."[111]

Figure 22 Results of computer simulations on the two configurations of the Bahrain WTC. The left picture shows the current configuration of the two towers, the right picture the situations in which the towers are built the other way round. The colors indicate the wind strength and the wind direction is up. The horizontal line between the towers indicates the position of the wind turbines. It is clear that on the right picture the area around the line is more red, indicating stronger wind flows. [111]

The third case is Strata Tower in London. In June 2010 the Strata tower was complete, a 150m high, 43 story complex residency to over 1000 people including top floor penthouses valued between £1.2M and £2M. Having three 5 blade, 9m diameter, 19kW custom turbines installed in its structure the strata has an estimated energy production of 50MWh per year, enough to produce 8% of the towers annual energy consumption.

Figure 23 Strata Tower with 3 HAWT [112]

The turbines hardly ever turn, and when they do it's almost impossible to work in the offices below because of all the noise." To build projects like this better in the future, Blocken is now leading a workgroup in a large European consortium. The aim is to carry out effective research to formulate guidelines for the generation of wind energy in the built environment. [111]

Among all the high rise structure with integrated turbine, the Pearl River Tower can be considered as a most remarkable and successful building.

There are up to 10 highly innovative technologies that work together to reduce the building's energy consumptions and improve indoor air quality [113]. The two most innovative aspects of these 10 technologies are: 1) the generation of renewable energy through wind power and solar photovoltaics and 2) the high efficiency and energy savings performance of the radiant cooling system, which features displacement ventilation and high-performance wall facades. Pearl River Tower is thus expected to constitute one of the world's best examples of a high-quality, low-energy and environmentally friendly tall building. [113]

It is noted that most wind-power generation has been achieved with wind turbines mounted on open sites or on the tops of buildings or integrated between two buildings, such as, Energy Tower in Dubai, Bahrain World Trade Centre in Bahrain, Transbay Transit Centre in San Francisco, etc. Hence, Pearl River Tower constitutes the first instance of wind- power generation through the incorporation of wind turbines into tunnels inside a tall building.

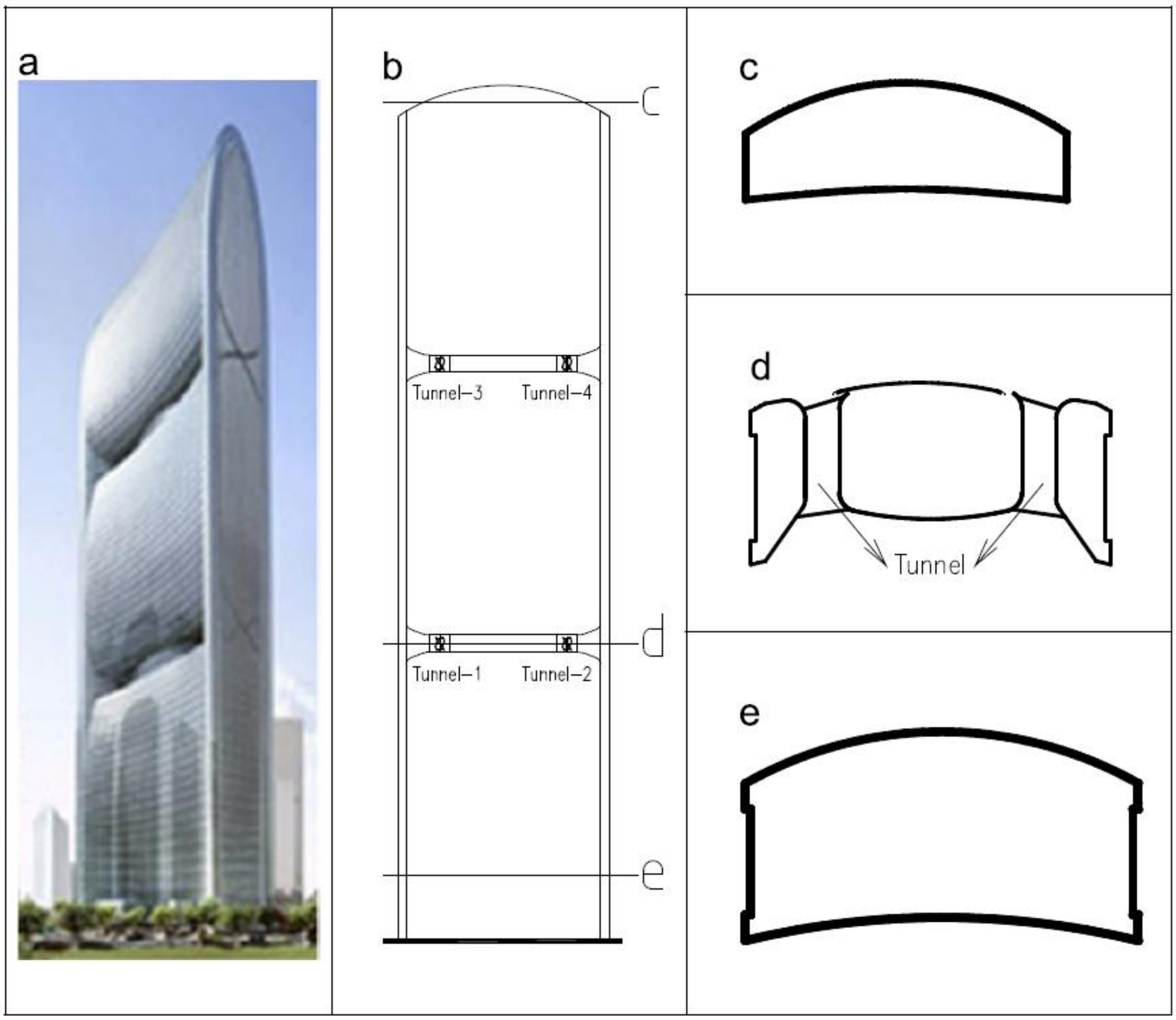


Figure 24 View of Pearl River Tower: (a) overview, (b) locations of four tunnels, (c) plan form at height of 295 m, (d) plan form at height of 108 m and 209.4 m for wind turbines.[114]

Pearl River Tower, located in Pearl River New Town, Guangzhou, has 71 stories and rises about 310 m from the ground. The tall building is of a steel and concrete composite structure and is of curved in shape with a concave wall in the south and a convex wall in the north. There are four open holes (called tunnels in this paper) located at mechanical floors on two height levels and each tunnel is with a bell-mouthed shape at both ends. As shown in 24(b), the height of two tunnels at the lower level (i.e., Tunnel-1 in the west and Tunnel-2 in the east) is about 104 m above the ground, and that of two tunnels at the upper level (i.e., Tunnel-3 in the west and Tunnel-4 in the east) is about 205.4 m. The longitudinal and transverse lengths of the ground floor are about 75 m and 41 m, respectively. The aspect ratio between the height and transverse width of the tall building, as can be seen in Fig. 24(c–e), is more than 7, which exceeds the criteria in China's current design codes and standards. [114] Guangzhou is located in the southeast coastal region of China, a region prone to typhoons and strong winds. Hence, there is a need to conduct wind tunnel tests to determine the wind effects on the high-rise structure at its design stage. [114]

The bell-mouthed shapes of the four tunnels with contracted inner sections are helpful to increase the wind speeds in the tunnels for the wind-power generation by the turbines.

9. Research idea

One of the strategies for building profile modification or building façade modification is the “open through”. Although the advantage of this modification is Clearfield in different studies, there is not a sufficient attention to using this method in a real project. The main problem that can be considered is the special consideration to devise the holes into the buildings which can have some confliction with the design aspect of the buildings.

The main idea for the present research is distributing the penetration over the building façade to reduce the building resistance against the wind and increasing the wind harvesting capacity for generating energy. Moreover, since proposing a specific modification that can be applied only on a unique building is not considering for this research, a fundamental approach is considered to generate penetration over the building façade. Inside the buildings, there are many spaces that are not in use, such as the spaces in the back of the dropped ceilings or raised floor. These spaces that usually are room for the mechanical systems, not using completely and always some major part of them leave empty. These unused spaces are shaped along the whole floor area can provide the corridor between two sides of the building.

The ultimate idea is connecting two sides of the high-rise building with the horizontal shafts that utilize the unused spaces in back of the dropped ceilings or raised floors.

For testing this idea, the case study research is considered to enable the author to modify the idea over a case and compare the final results. For this purpose, the Pearl River Tower is chosen and as it is explained in the previous section.

Although the Shanghai tower as a most recent tower can be considered as a case, the size of the tower didn’t enable the wind tunnel simulation. The tower is too big and by reducing the scale of the tower, the size of the penetration will be too small for fabricating and testing in the wind tunnel.

10. Computational Fluid Dynamics (CFD) Simulate

The first tool for using in this research is CFD simulation. The digital simulation can deliver the fast and quantities results. For all the computer simulation the air flow pattern is laminar.

The software for doing CFD simulation are "Autodesk Flow Design" for the initial phase that provides a virtual wind tunnel that can measure the drag force and "Autodesk CFD" for studying in more detail about the air flow.

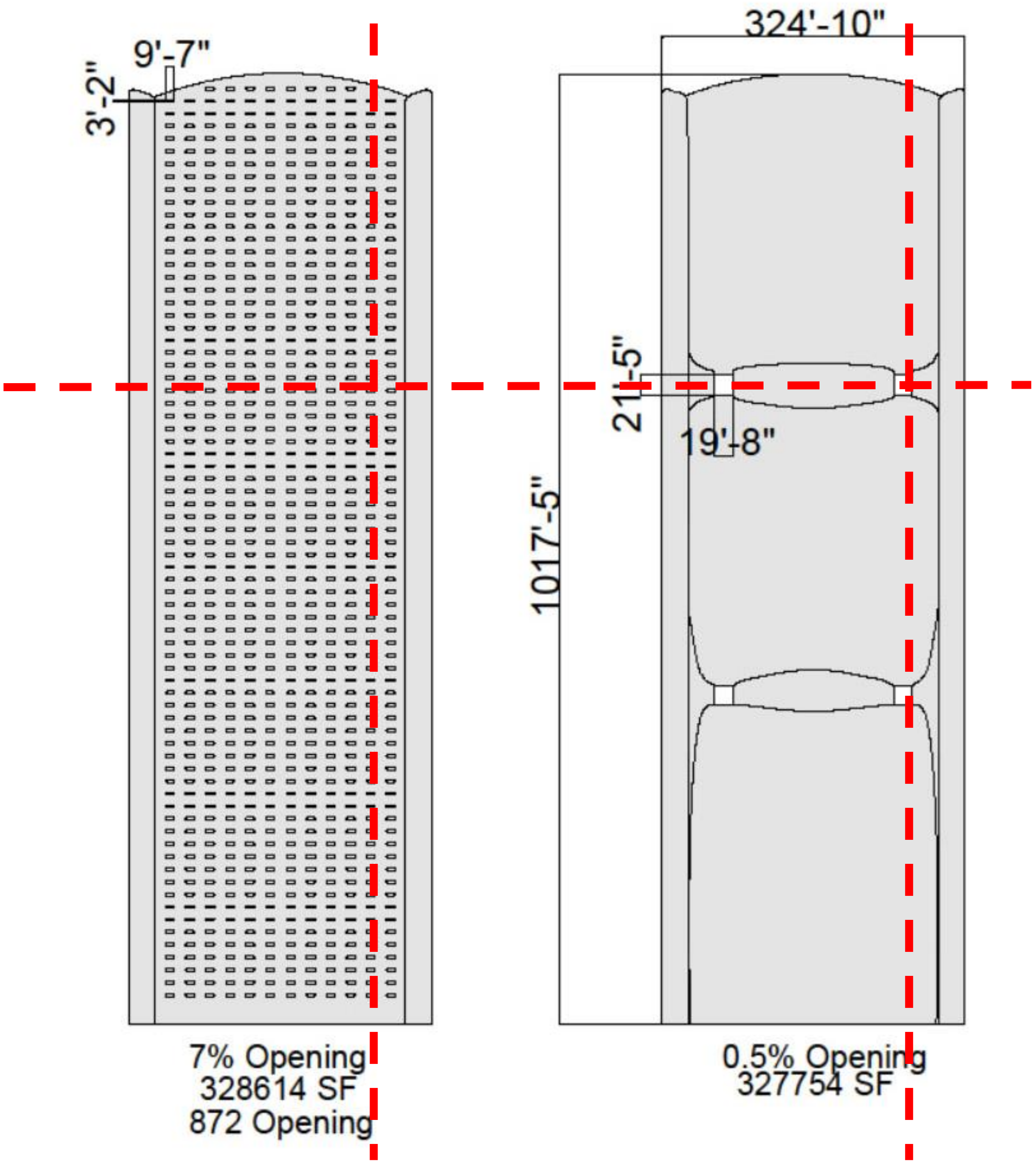


Figure 25 The original building on the right in comparison to the proposal design idea on the left. The cross sections areas considered for the further study. (Figure by author)

At first, the original 3d model and the proposal design was tested by the virtual wind tunnel. The initial finding shows the drag force for the proposal design is less than the original one. In the other words, the proposal idea needs less strength for resistance against the wind force that can reduce the cost of the structure.

The drag force is the amount of force imparted on the model by the wind as it flows into, over, and around the model. Like drag, higher values of force require more energy to propel through the wind at speed.

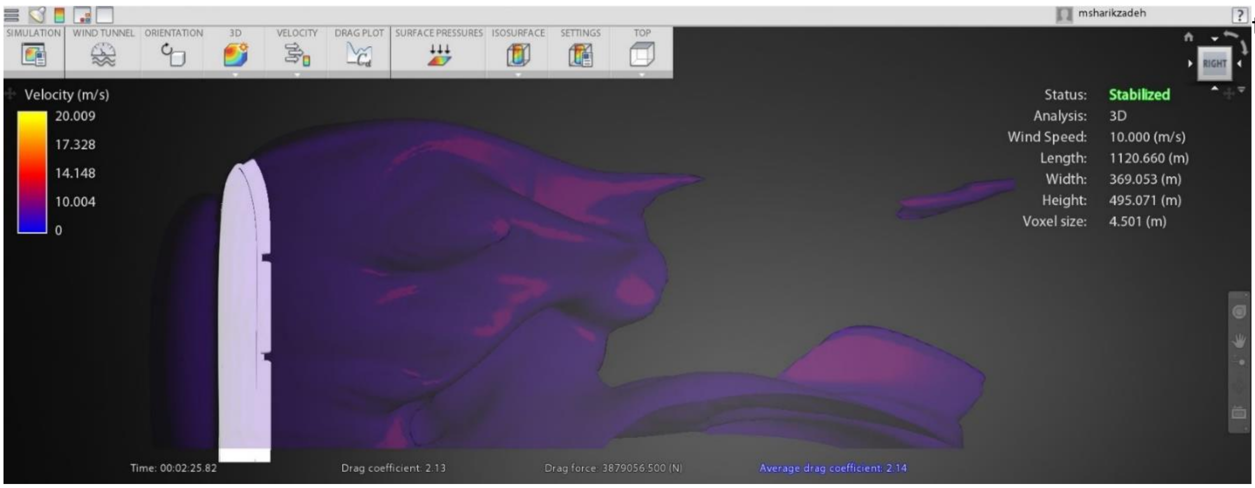


Figure 26 The original design drag force simulating by Autodesk Flow Design software. (Figure by author)

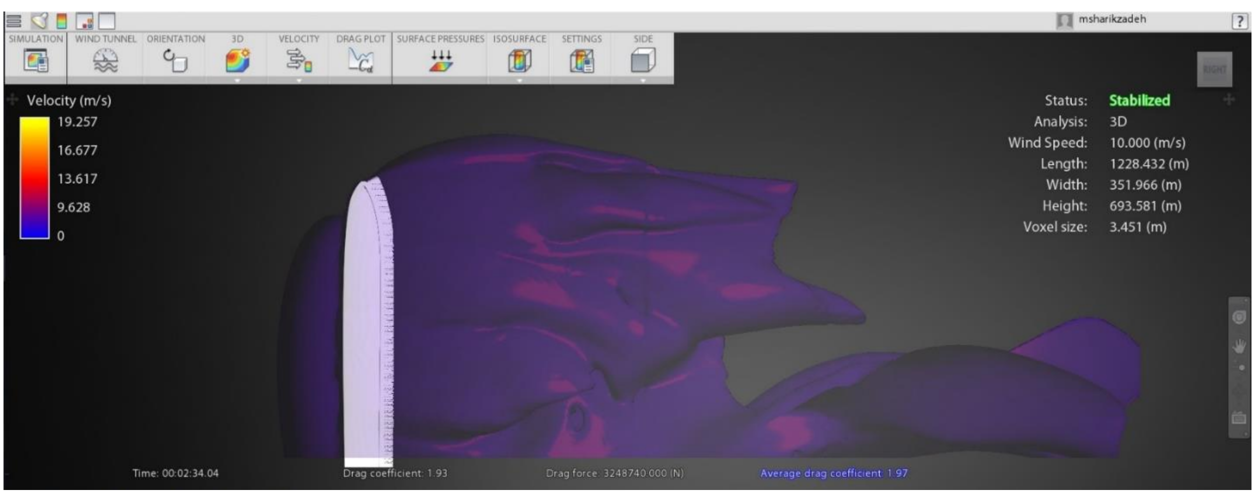


Figure 27 The proposal design drag force simulating by Autodesk Flow Design software. (Figure by author)

The factor to determine the drag force is the drag coefficient which is a dimensionless quantity that represents the amount of aerodynamic drag of the object. Higher values indicate a greater resistance to the flow, which in turn means that more energy is required to push the object at the required speed. Lower values indicate less wind resistance, which in turn means that less energy is required to propel the object at speed. [115]

For further study the CFD simulation run over the detail part of the models. Unfortunately, the Flow Design software is not able to calculate the air flow around the small objects. The figure 28 shows the lack of accuracy for the small opening.

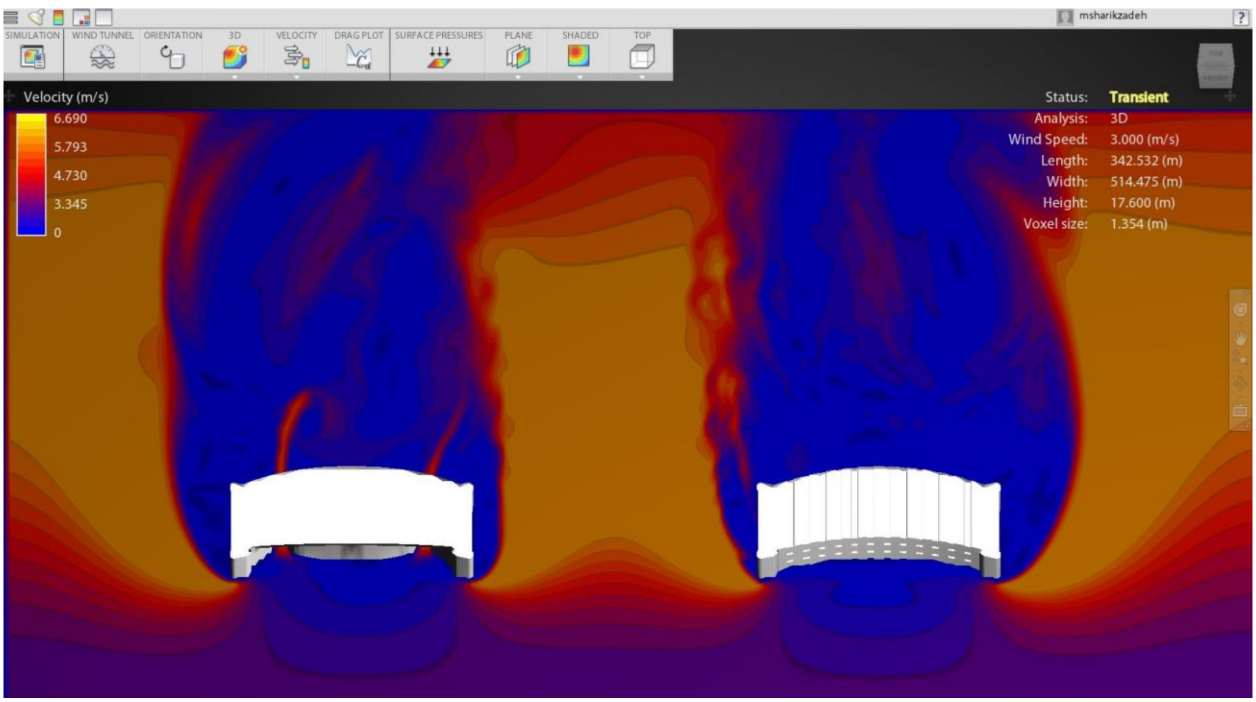


Figure 28 Testing the detail part of the design by Autodesk Flow Design Software. (Figure by author)

To getting more accurate and reliable result, another software was chosen for studying about the airflow pattern which is “Autodesk CFD”. This software is a powerful tool to calculate the flow pattern around many kinds of solid materials in the different fluid. The air velocity for this simulation is 3m/s and the fluid considers as the air.

The first run of the two 3d models that was tried to tested with Flow Design. The initial results show that the software is able to calculate the air flow even in small part of the building. Meanwhile, the calculation shows that the intake shape for the original building is able to amplify the airflow twice, exactly the same amount that is measured in reality and scientific researchers.

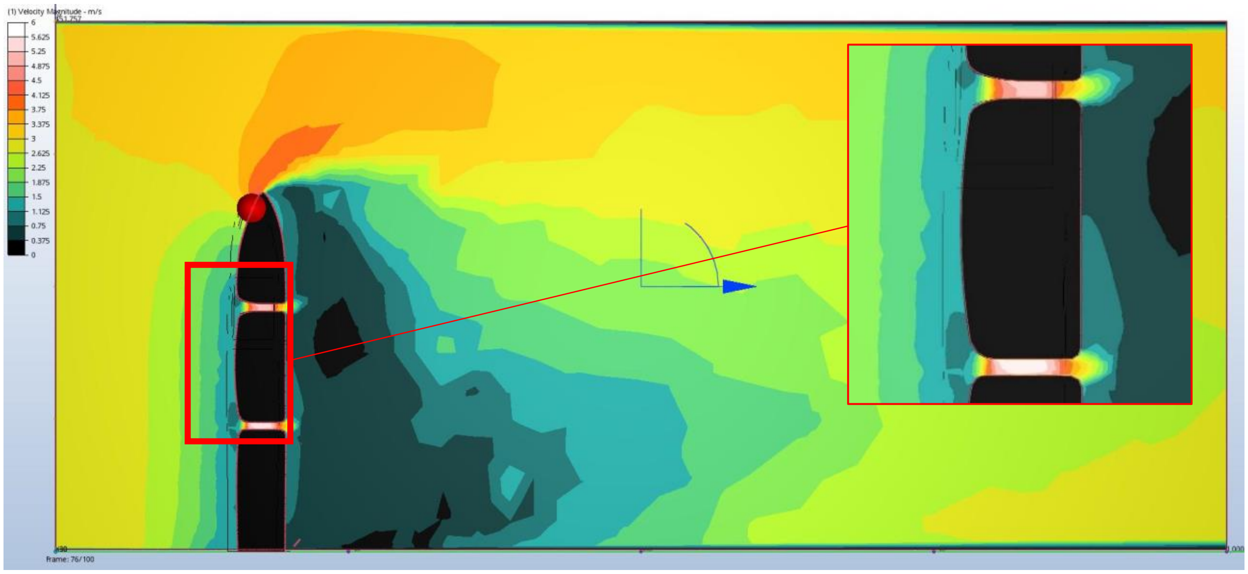


Figure 29 Section view of Original design. Air velocity testing by Autodesk CFD software. (Figure by author)

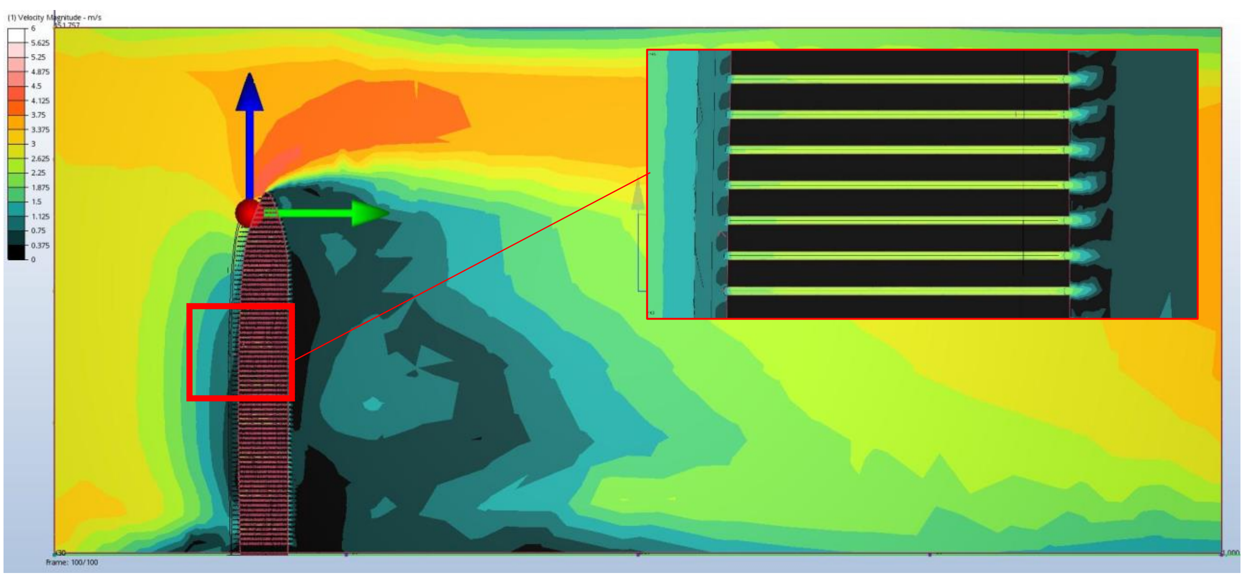


Figure 30 Section view of Proposal design. Air velocity testing by Autodesk CFD software. (Figure by author)

The first finding from comparing the result of the two models is the air velocity is about double in the original penetration while in the new idea, the air velocity is not changed inside the penetration. For generating wind energy, the air velocity I the most important factor and the main reason of this difference can be the difference in the shape of the intake.

Another finding is about the low air velocity zone at the back of the building which is longer in the original building. The lower air velocity can be a sign of lower pressure which lead to more drag force. Also, at top of the building, the air velocity is higher in the proposal design. This finding can be considered as the capacity of the building for passing the wind portion form the penetration which tells that the proposal idea is less capable for this purpose.

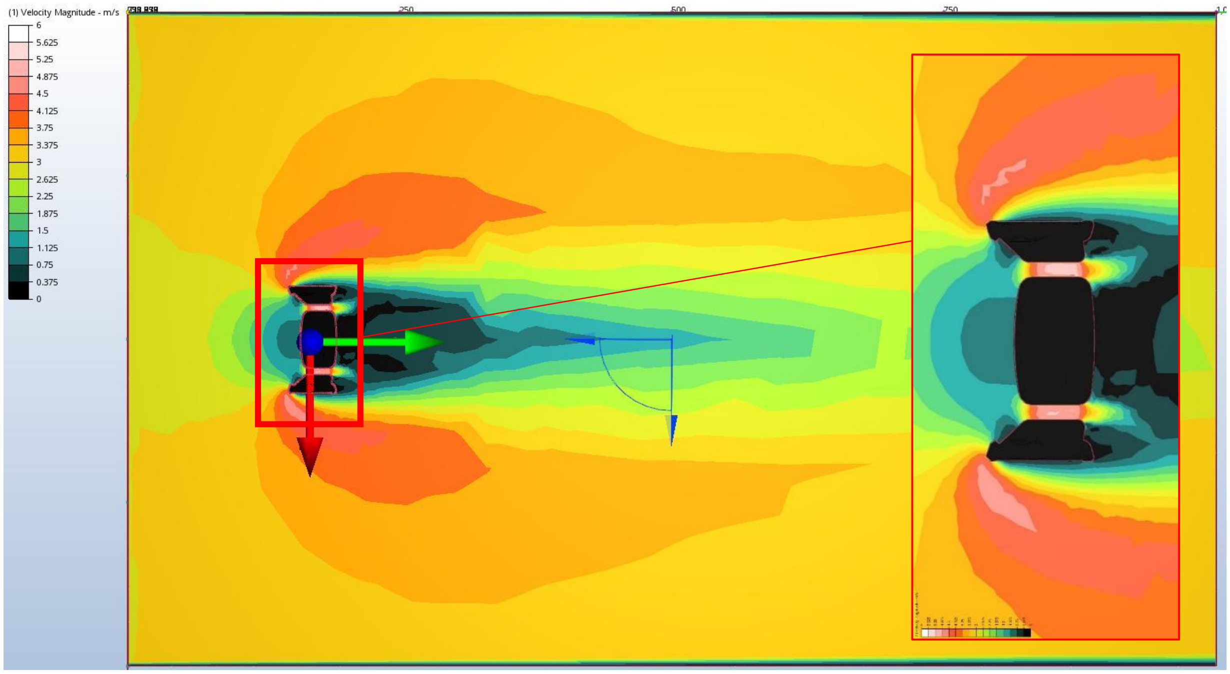


Figure 31 Plan view of Original design. Air velocity testing by Autodesk CFD software. (Figure by author)

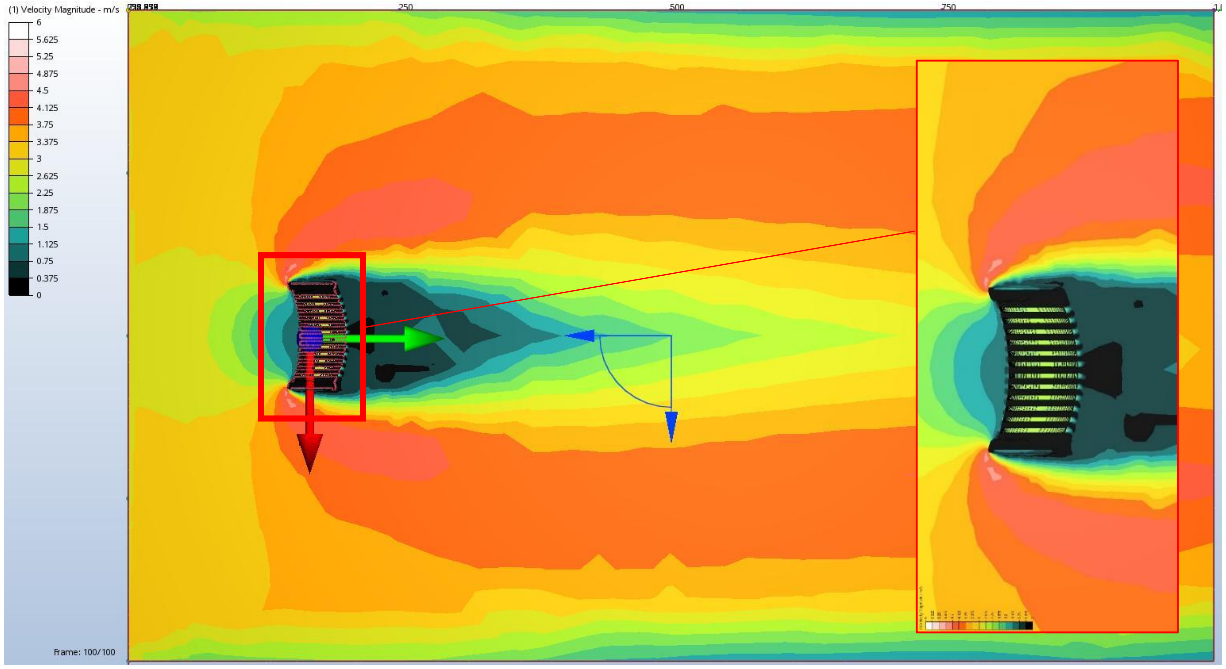


Figure 32 Plan view of Proposal design. Air velocity testing by Autodesk CFD software. (Figure by author)

In the plan view is also clear that the area of the low velocity is longer in the original building. In contrast, the area of high velocity around the building is bigger and longer in proposal design. Meanwhile, the original design demonstrates the more capability for wind penetration through the holes.

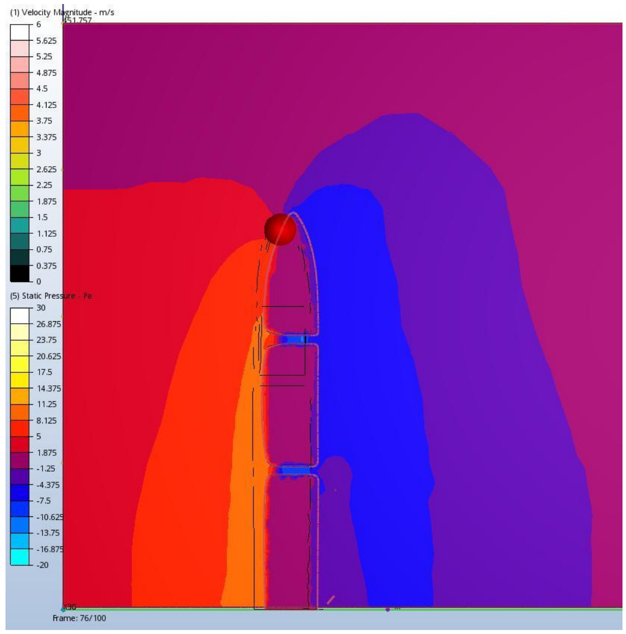


Figure 33 Section of original design. Air Pressure testing by Autodesk CFD. (Figure by author)

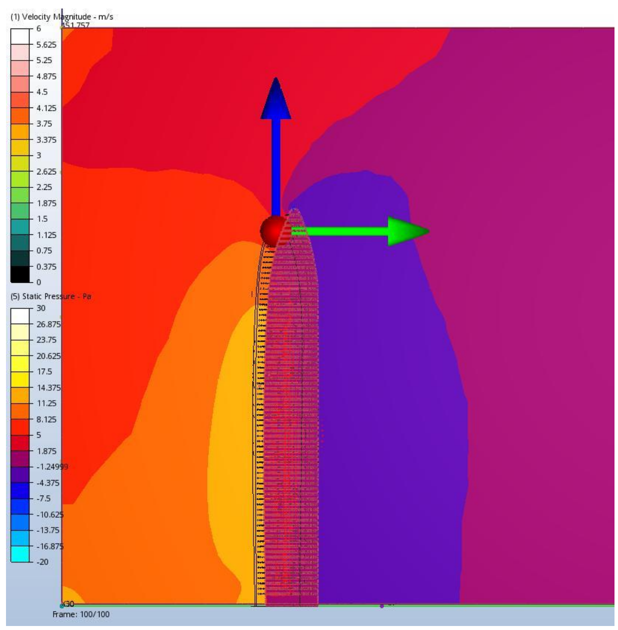


Figure 34 Section of proposal design. Air Pressure testing by Autodesk CFD. (Figure by author)

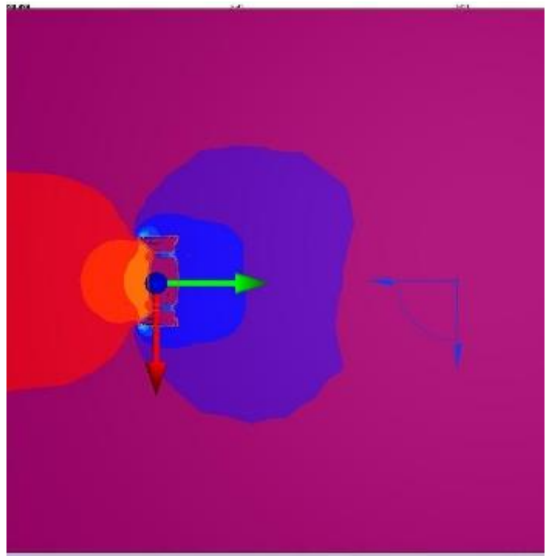


Figure 35 Plan view of original design. Air Pressure testing by Autodesk CFD. (Figure by author)

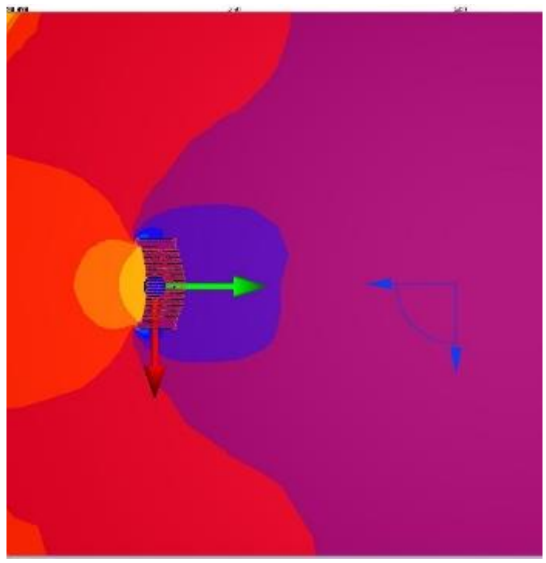


Figure 36 Plan view of proposal design. Air Pressure testing by Autodesk CFD. (Figure by author)

After studying the pressure graph, the finding shows that the positive pressure is bigger in front of the proposal design, while the negative pressure is bigger at the back of the original design. The higher positive and negative pressure shows more drag force in that specific area and is considered as a negative impact.

It also clear that in the proposal idea, there is the big zone in front of the building which has slightly more pressure. This means that the pressure difference between two sides of the building is higher and the building can have a bigger impact on surrounding areas.

10.1. Optimizing the proposal design

The first run for the CFD simulation shows that the proposal design is not a proper alternative for the original building due to low air velocity in the holes.

To optimizing the design, the first consideration is the shape of the intake to use the venture effect to amplifying the air velocity. This is the same technic that is used in the original building but on a large scale.

Figure 37 shows the 2 different alternatives that is considered for the further study.

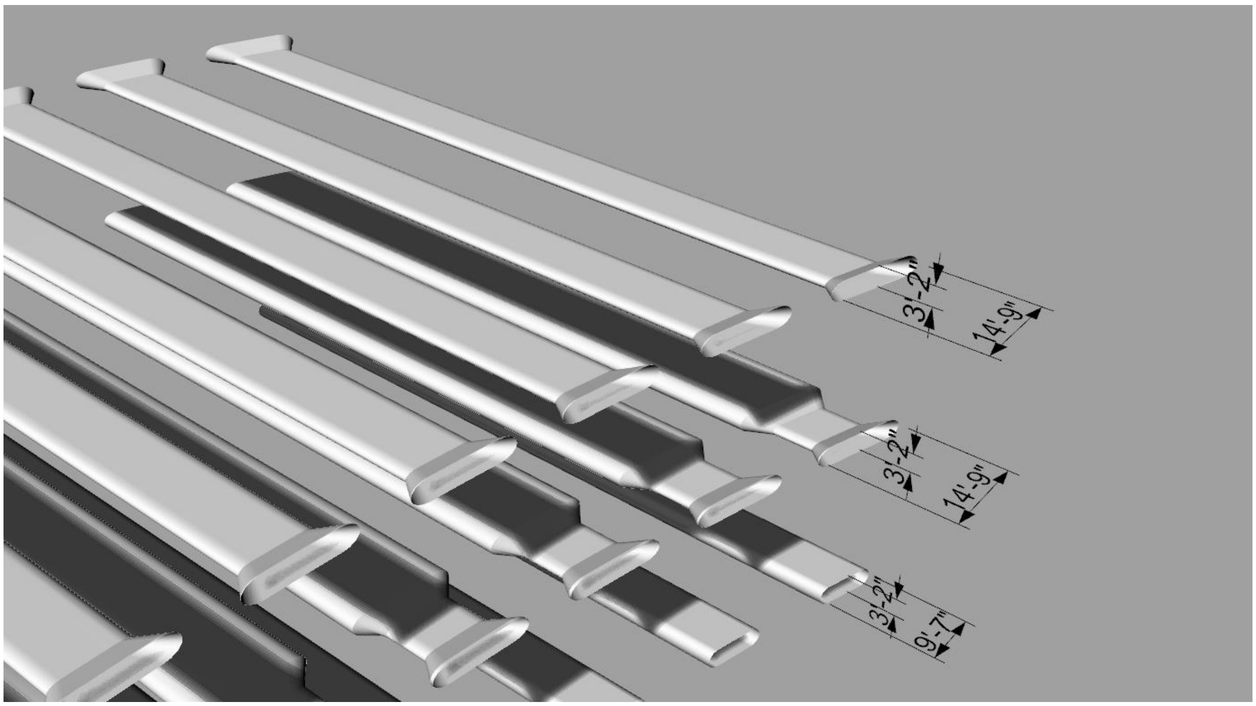


Figure 37 Three different intake shape considered for optimization. (Figure by author)

Because the channels are located between the floors, there is a limitation in the height of them. Instead of that, they are more flexible to manipulate in width. As a result, for the first alternative, just the width of the intake gets 1.5 times bigger. For the second alternative, after the intake shape, the whole width if the channel gets 1.5 times.

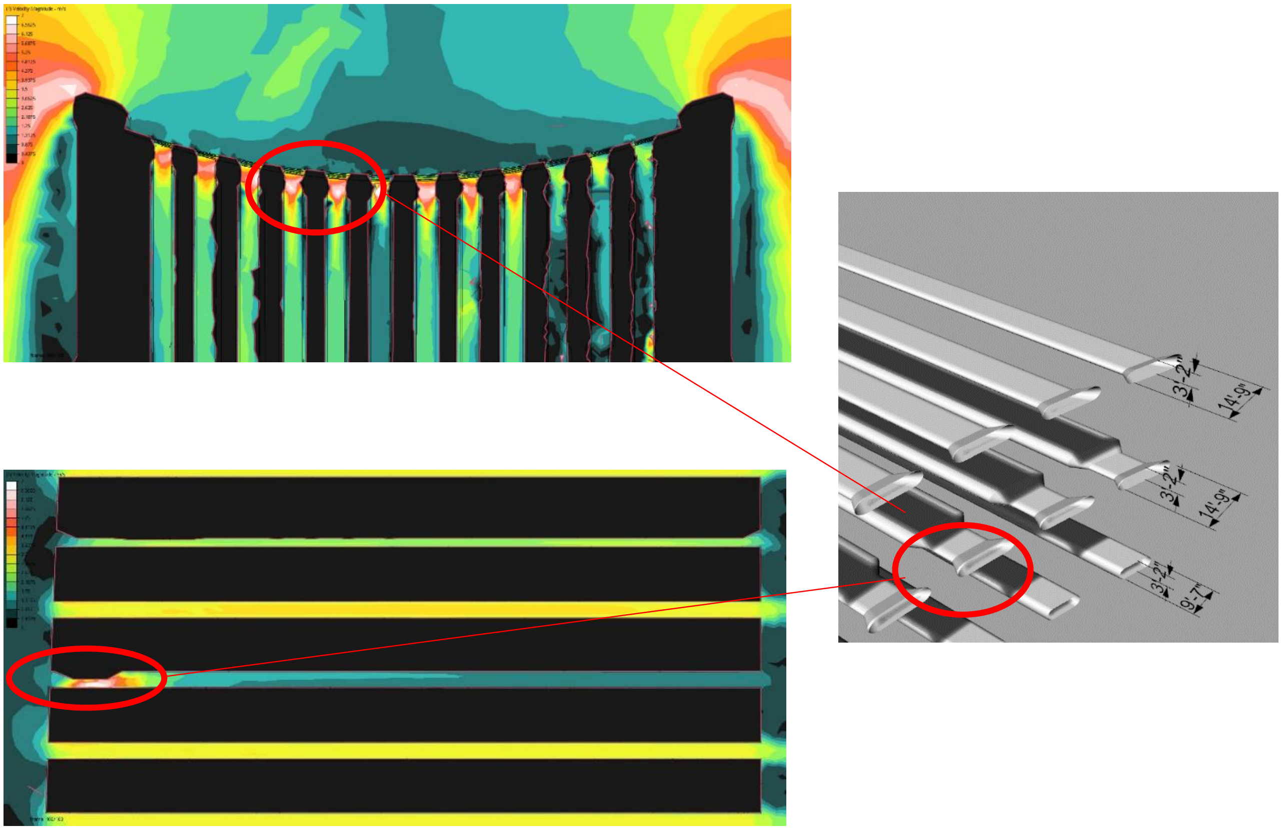


Figure 38 The optimize intake shape is successful to amplifying the air velocity. top plan view, bottom section view. (Figure by author)

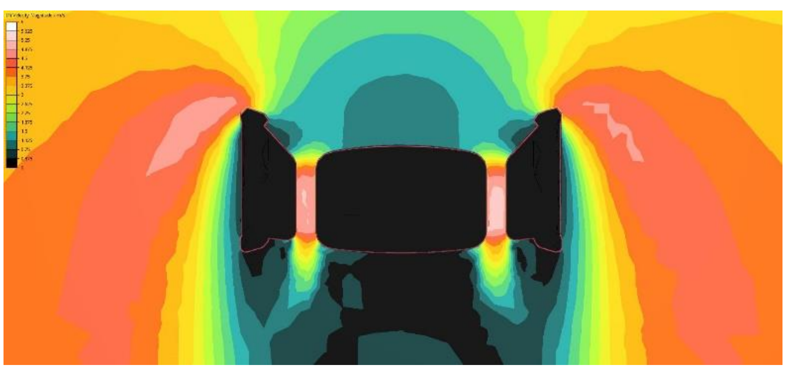


Figure 39 Original design air velocity in plan view. (Figure by author)

It's clear that changing the shape of the intake has a direct influence on the air velocity. Because of saving time for simulation, the modification of the intake shape just applied on a row of the channel. The air velocity at the point of the changing is exactly the same with the original design air velocity on the holes which is double the intake air. Also, the after the narrow part, the air velocity is really low which can show that all the wind energy is condensed at the specific point.

It worth to mention that in the plan view, in some channels there or some odd air flow shape which is happened because of the resolution of meshing. The size of the penetration is really small for the software for simulation and some part of them are missing.

Also, it’s visible the first alternative that the intake size is bigger and the rest of the channel is smaller is not successful at all due to low air velocity along the channel.

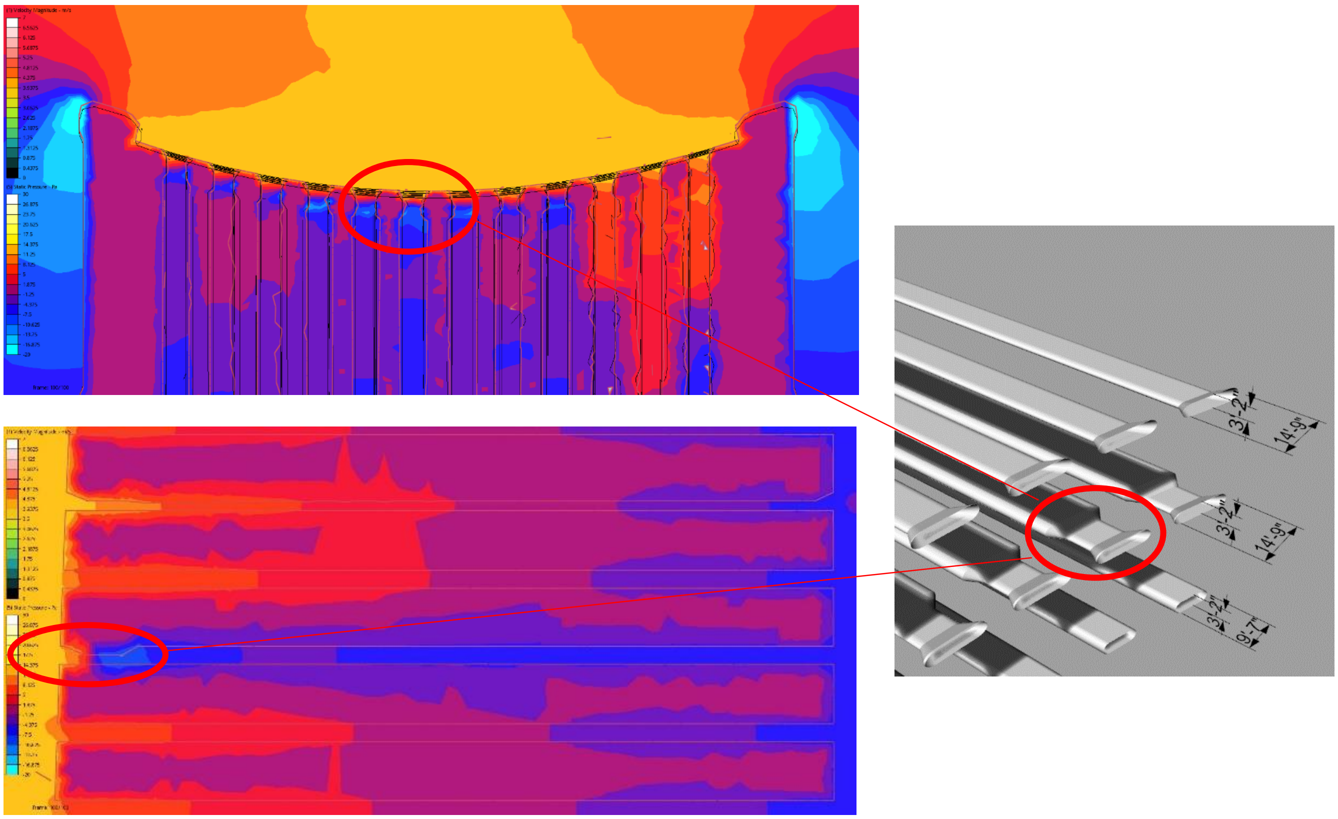


Figure 40 The air pressure difference in section and plan view for the optimized intake shape. (Figure by author)

The studying about the pressure zones shows that there is a considerable pressure difference in the modified shape intake. This point will be a perfect place for generating the wind power by devising the wind turbine. It shows that the all difference pressure area that is spreader in the non-modified shape, just concentered at the intake point.

11. Wind tunnel test

After doing the CFD test, the wind tunnel test is considered to evaluate the digital simulation result in the real environment. For doing this test, two physical models made by CNC machine out of the foam block. After sanding the surfaces, all the holes recreate by hand over the proposal model with the hot sting.

Figure 41 The physical model made by CNC machine on the left and creating the penetration on the model on the left. (Photo by author)

The wind tunnel is located in University of Arizona Architecture school for the House Energy Doctor program. Usually, the wind tunnel chamber has a cone shape profile to increase the air velocity at the specific space. But the wind tunnel that is used for this research has a rectangular profile shape that makes it possible to test the big size physical model without amplifying the air velocity.

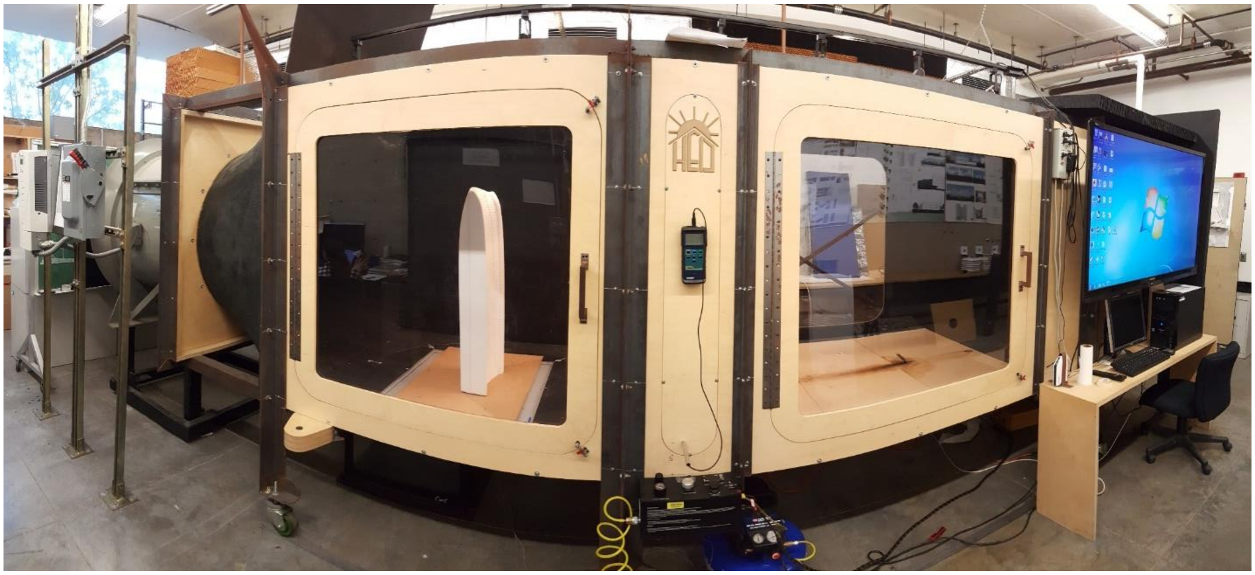


Figure 42 House Energy Doctor Wind tunnel. (Photo by author)

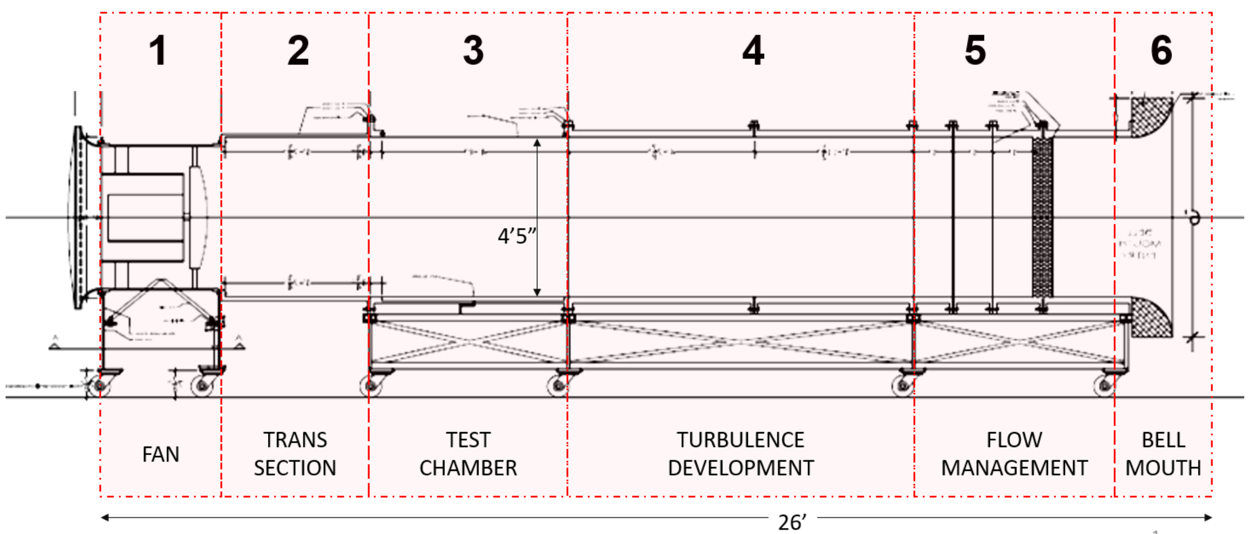


Figure 43 Wind tunnel sections. (Figure by author)

By running the fan from section 1 in.... the air suck into the section 6 as an intake. The honey cone mesh in section 5 creates the laminar airflow for the tunnel and this air flow push the smoke towards the model in section 4. The model is placed in section 3 for visual studying the smoke pattern around the model. This test, like the CFD simulation, is done in the laminar air flow situation.

11.1. Research design variables

The scale that considered for the testing is in the 1/300 scale. This specific scale is selected to be able to simulate the penetration size. The holes in the model are ¼” which in reality are 6’1/4”. This dimension is used instead of the of 3’2” x 9’7” Which was not possible to fabricate the hole less than ¼” by the CNC machine.

The two physical model with the same scale tested in the wind tunnel to see the difference between two different design can influence on the wind pattern around the building.

Figure 44 The final physical model for the wind tunnel test. (Photo by author)

The smoke is used to clarifying wind pattern and turbulence around the building. To make the smoke, the Glycol pump with 20 psi pressure into the bide with the heater at the end that generates smoke. This smoke is carrying with the wind flow and reveal the air pattern around the building. On of the most important factor to test the model is the air velocity. According to the figure 45, the Reynold factor should be greater than 2000 for this test.

The air velocity considered 0.4 m/s to satisfy the Reynolds number. To determine the air velocity, the fan speed set to 5.0 Hz according to the chart.

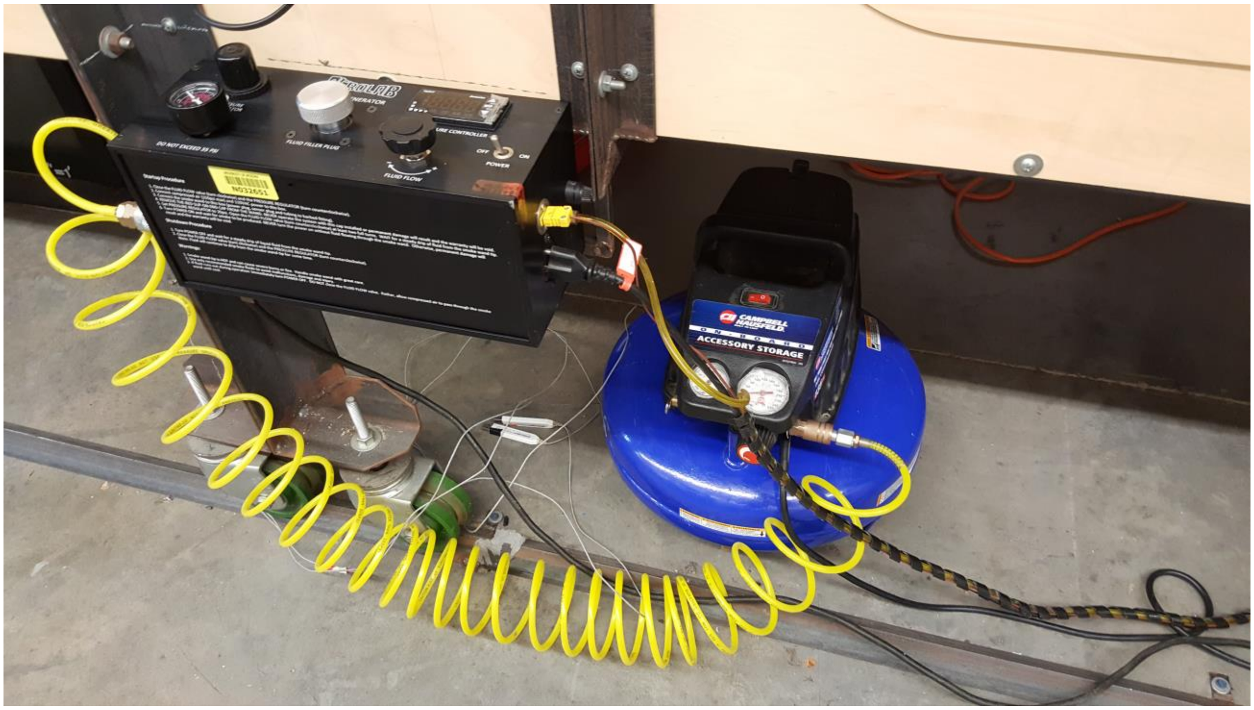


Figure 45 The compressor pressure 20 psi. (Photo by author)

The Reynolds number for **flow around bluff bodies** such as building exteriors, R_B , shall be greater than 20,000.

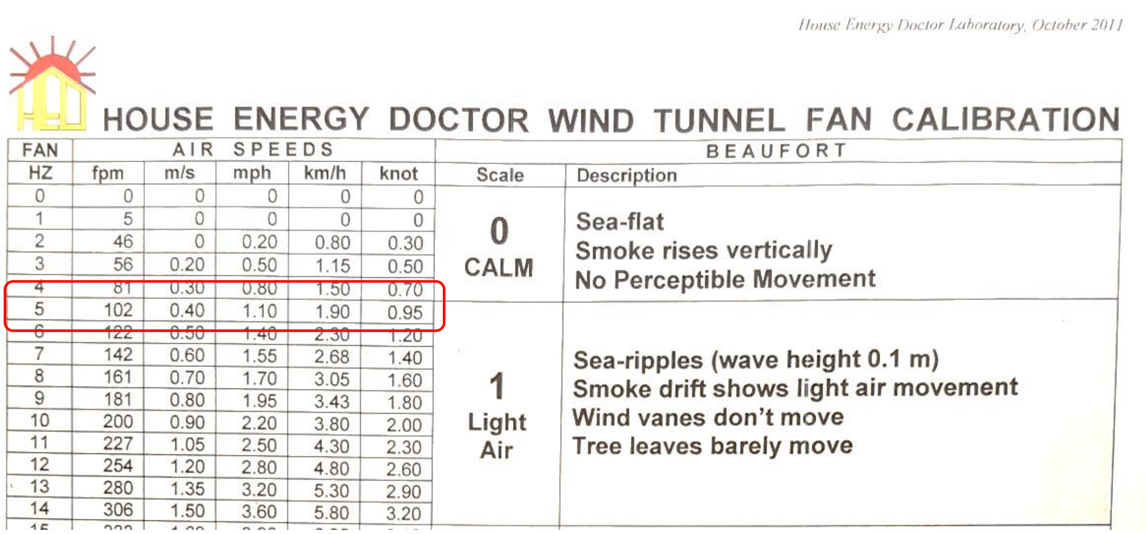
EQUATION:

$$R_B = L_B\, U_B / v \qquad (15)$$

WHERE: L_B is the typical building dimension (m),
U_B is the typical approach velocity (m/s),
v is the kinematic viscosity of the air (1.7×10^{-5} m^2/s)

Figure 46 Reynolds number [115]

Figure 47 Fan speed set on 5.0 Hz. (Photo by author)



House Energy Doctor Laboratory, October 2011

HOUSE ENERGY DOCTOR WIND TUNNEL FAN CALIBRATION

FAN	AIR SPEEDS					BEAUFORT	
HZ	fpm	m/s	mph	km/h	knot	Scale	Description
0	0	0	0	0	0	0 CALM	Sea-flat Smoke rises vertically No Perceptible Movement
1	5	0	0	0	0		
2	46	0	0.20	0.80	0.30		
3	56	0.20	0.50	1.15	0.50		
4	81	0.30	0.80	1.50	0.70		
5	102	0.40	1.10	1.90	0.95	1 Light Air	Sea-ripples (wave height 0.1 m) Smoke drift shows light air movement Wind vanes don't move Tree leaves barely move
6	122	0.50	1.40	2.30	1.20		
7	142	0.60	1.55	2.68	1.40		
8	161	0.70	1.70	3.05	1.60		
9	181	0.80	1.95	3.43	1.80		
10	200	0.90	2.20	3.80	2.00		
11	227	1.05	2.50	4.30	2.30		
12	254	1.20	2.80	4.80	2.60		
13	280	1.35	3.20	5.30	2.90		
14	306	1.50	3.60	5.80	3.20		
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		

Figure 48 According to the fan calibration chart, the air velocity is 0.4m/s. (Photo by author)

11.2. Performance variables

The final result according to the visual observation are:

The turbulence pattern is stronger and bigger behind the original design which shows more negative pressure at the back side of the building. The denser pattern in the proposal idea is part of the smoke that passes through the penetration. This part of the smoke passing from the sides of the building for the original design.

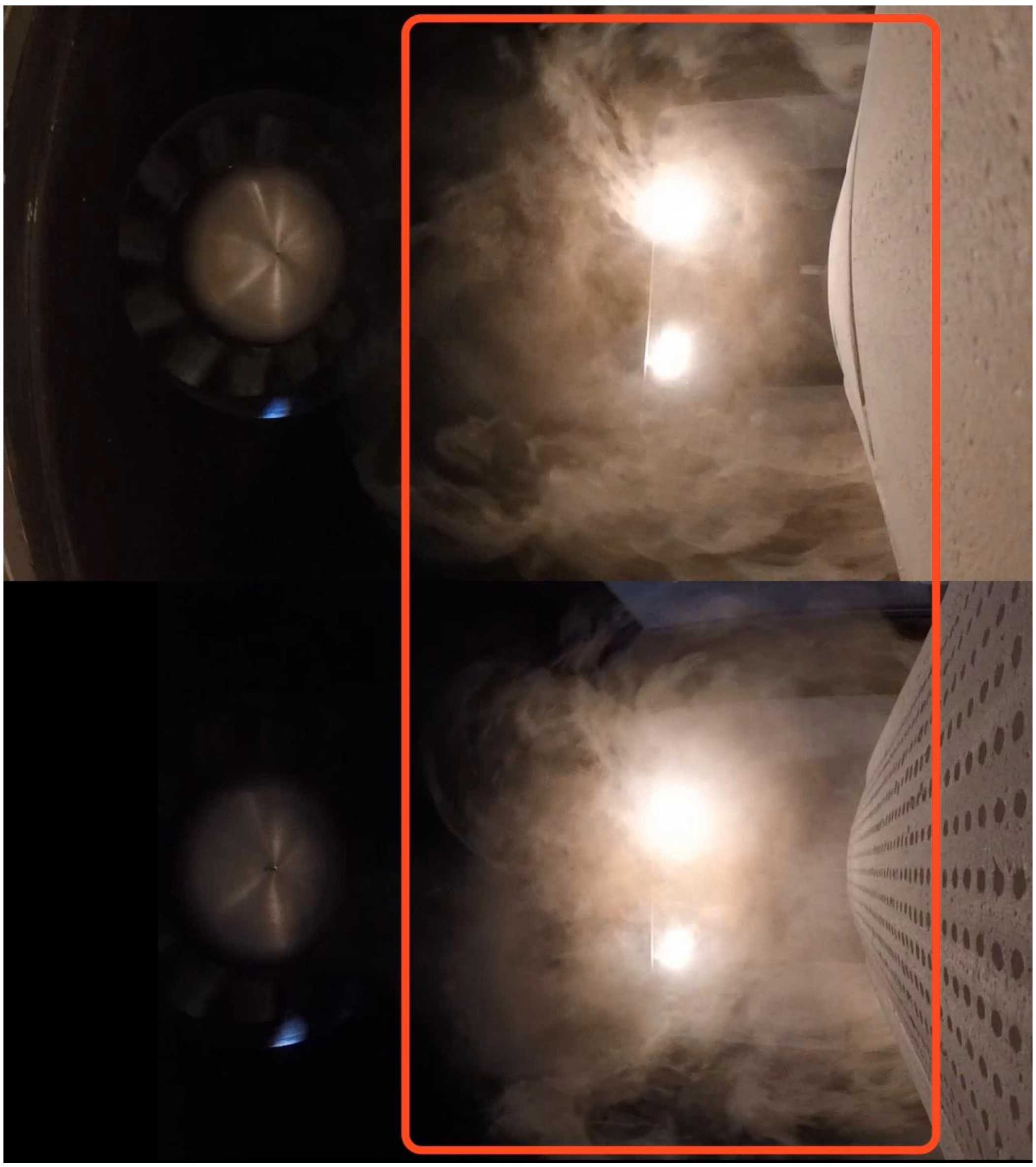


Figure 49 Original building on top vs proposal idea on bottom. The vortex shedding in the back of the building. (Photo by author)

The concave shape of the building is successful to capture the most portion of the wind. But, in the original design most part of the wind passes from top of the building and in the proposal design the wind is more capable to passing thought the building.

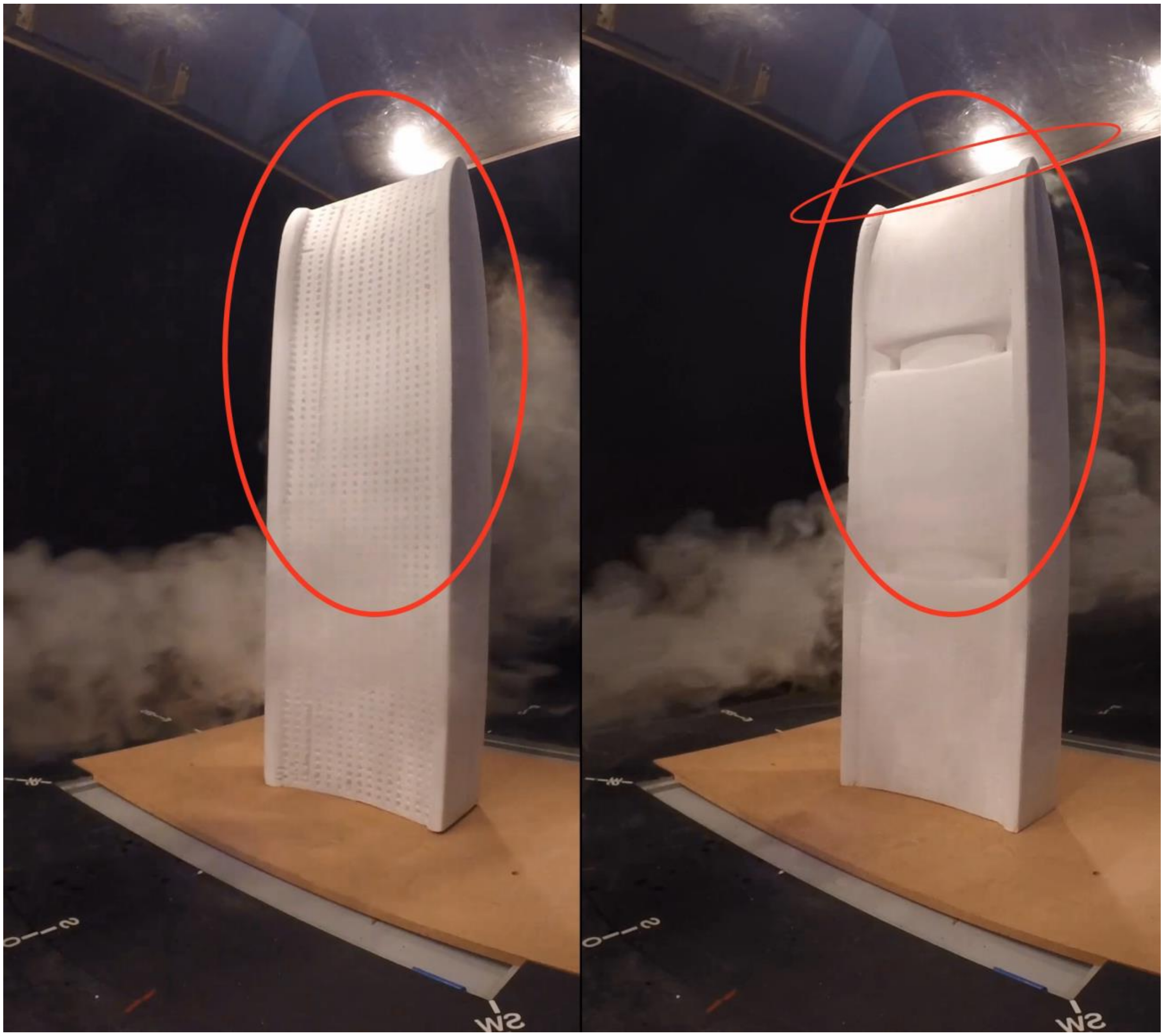


Figure 50 Original building on the right vs proposal idea on the left. The wind passing capacity. (Photo by author)

In the proposal design, it’s visible that the top part of the building is more successful for harvesting the wind which is moving vertically. Although the size of the hole is much bigger in the model that is representing in the original design, the portion of the smoke that pass through the holes is hardly visible.

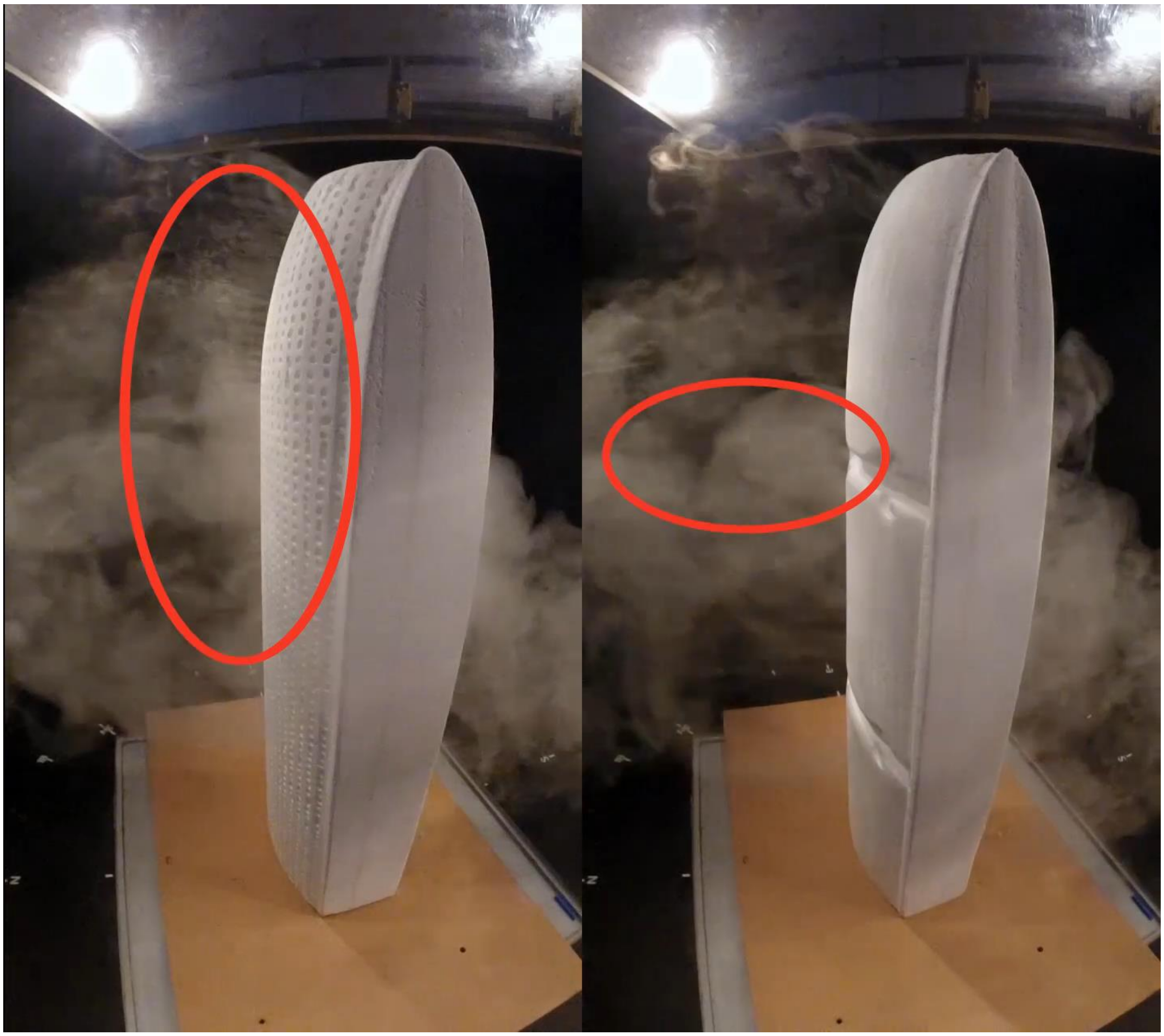


Figure 51 Original building on the right vs proposal idea on the left. The wind passing capacity. (Photo by author)

The most part of the wind passes through the middle of the building. This finding can show that probably it's better to devise the turbine in the middle of the building instead of the sides of it in the original design. As it's clear, in the proposal design, the back of the building is foggier which shows more portion of the wind can pass through the penetration.

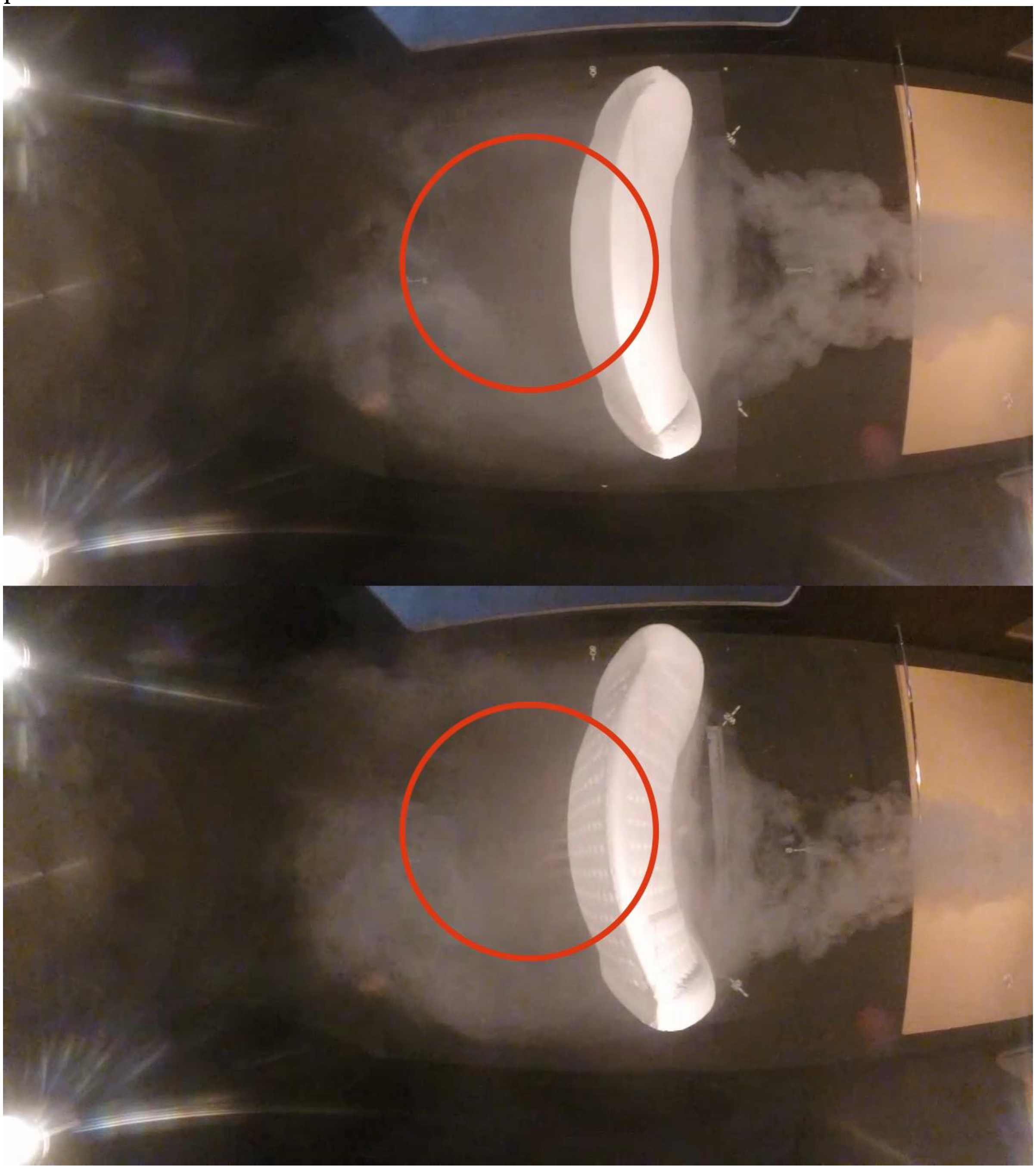


Figure 52 Original building on top vs proposal idea on bottom. The wind passing capacity. (Photo by author)

The proposal design showing better performance for an angled wind flow which is important for this kind of the design which it's not possible to match the inlet orientation with wind direction.

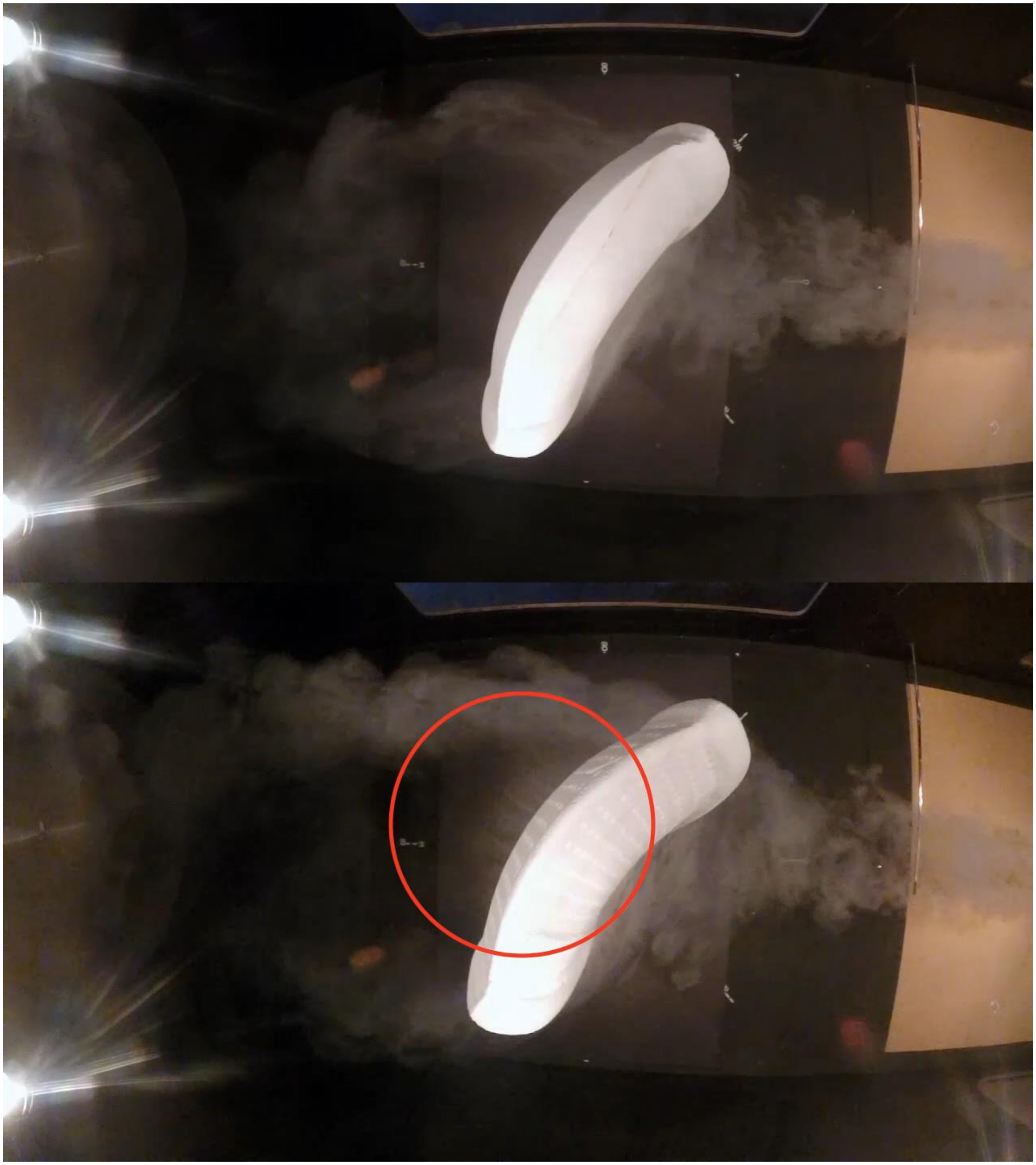


Figure 53Original building on top vs proposal idea on bottom. The wind passing capacity for the angular wind. (Photo by author)

To figure out which design can stand more against the wind, a simple test is done. The fan speed increased till the model collapse. For the original model at the speed of 0.9 m/s and for the proposal idea at the speed of 1.35 m/s the models collapse. Although this test is not accurately determined the drag and lift forces, it can give us the idea that the proposal design can stand better against the wind and needs less structural weight rather than the original design.

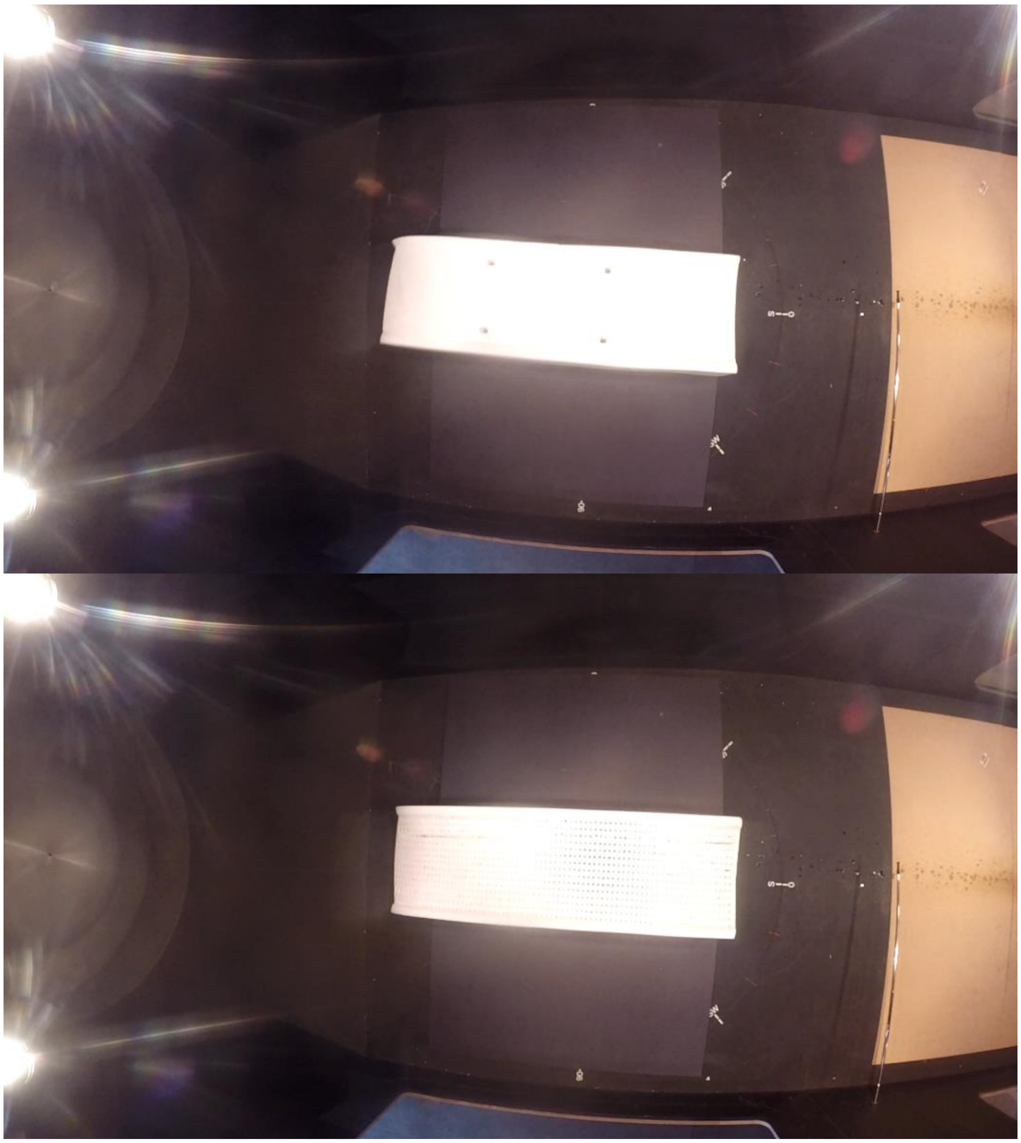


Figure 54 Original building on top vs proposal idea on bottom. Testing the resistance of the models against wind. (Ph by author)

12. The new idea in practice

After doing different types of the tests, it revealed new proposal can have a better performance for reducing the drag force on the structure and increasing the wind harvesting capacity. But also, it's important to mention devising many holes for the high-rise building without wasting space is not an easy task. In reality, there are some unused spaces in the building that have the potential to be utilized and they not only can save the budget for optimizing the spaces using, but also can be beneficial like generating energy for the building.

These spaces can be between the floors and dropped ceiling or inside the raised floor which also accessible from inside and can reduce the cost of maintaining.

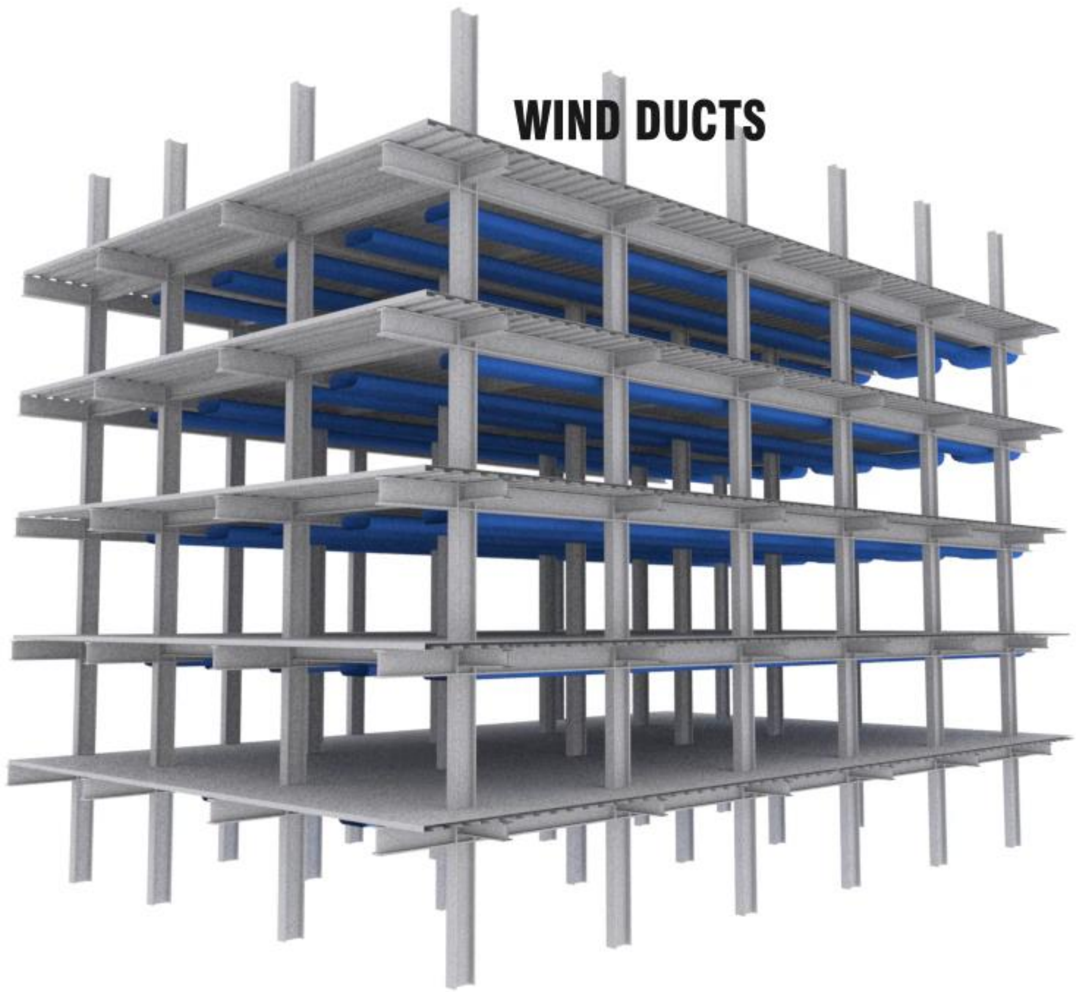


Figure 55 The final proposal configuration. (Figure by author)

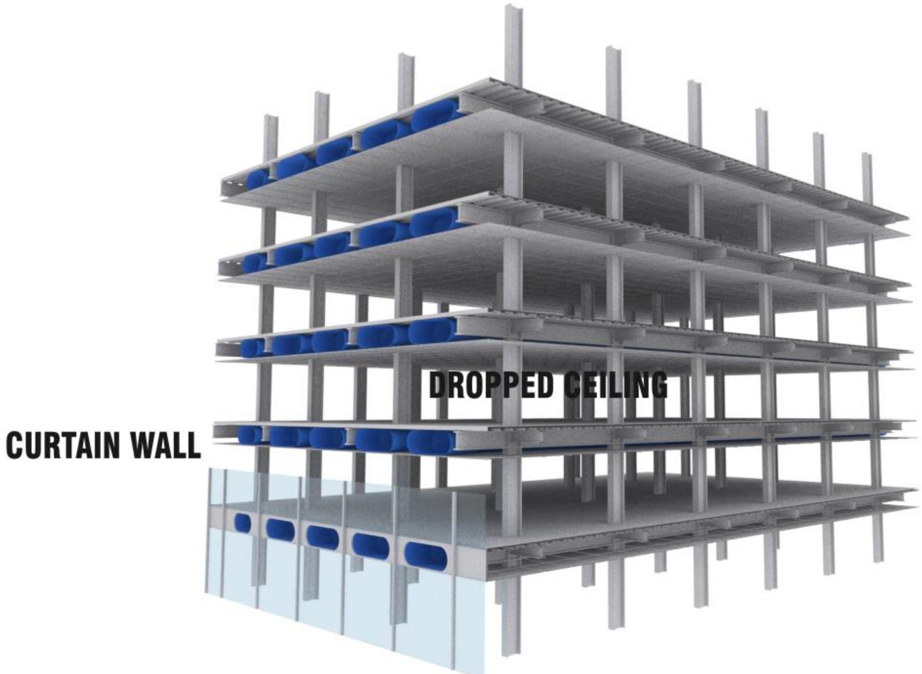


Figure 56 The final proposal with the other components. (Figure by author)

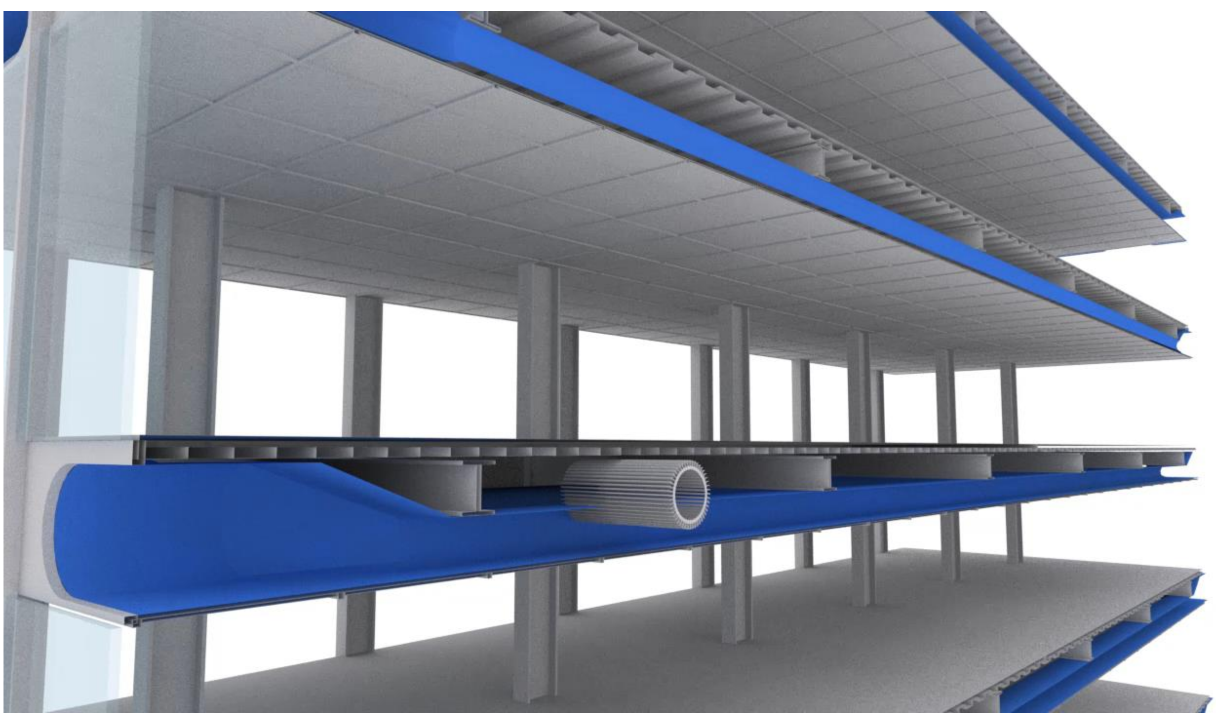


Figure 57 The HAWT that can be placed between the flooring system and wind duct. (Figure by author)

13. Test conclusion

After the CFD simulation with Autodesk Flow Design software and reviewing the findings, it’s clear that the proposal design idea has less drag coefficient in comparison to the original building. This achievement was the first goal of the research to reducing the wind impact over the building. Another evident for this achievement is gained during wind tunnel test that shows the proposal design would collapse in higher wind speed in comparison to the original building. Although the author was expected more difference for the drag force, the slightly drag force reduction can save the considerable amount of money for designing the building structure.

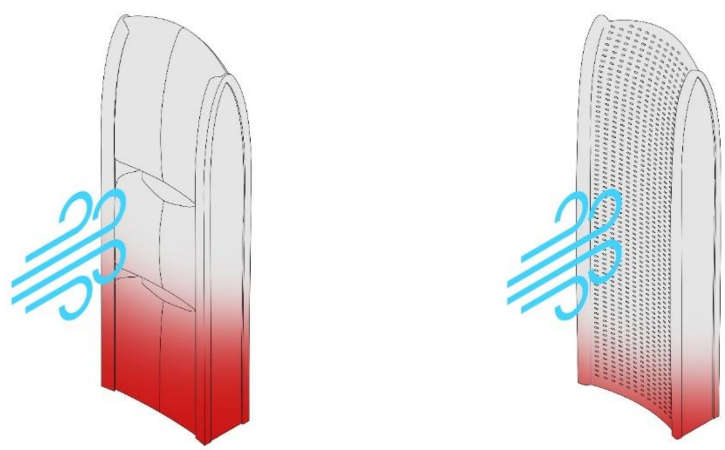


Figure 58 Two ideas in terms of the drag force. (Figure by author)

Another important issue is the difference of air velocity inside the holes. As it was expected, the bigger holes are more capable of harvesting the wind portion and because of the bell shape of the intake, they can amplify the air velocity which is the most important variable in terms of the wind energy generation. In contrast, the air velocity inside the smaller penetration is less than the bigger one.

The second CFD simulation with “Autodesk CFD” software shows by changing the intake shape, it’s possible to change the air velocity and it’s possible to amplify the air velocity even in the smaller intake.

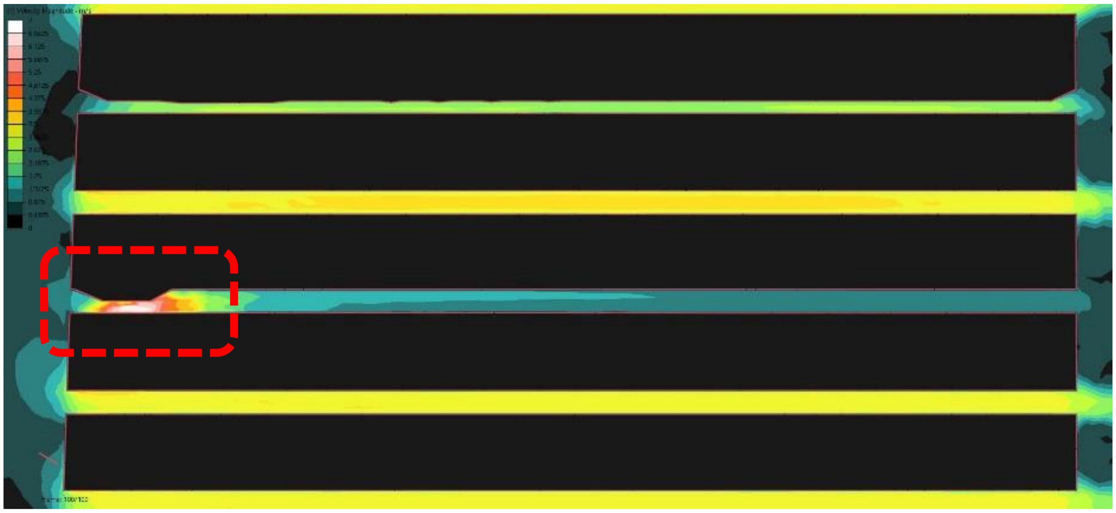


Figure 59 Section view of the modified intake shape in the proposal design. (Figure by author)

In the best situation, there is a same amount of the air velocity in the proposal design and the original design and in the normal situation we cannot amplify the air velocity. If the air velocity is the same with prevailing wind in the proposal design, according to the wind power generation equation, the potential for increasing the wind energy generation will be between 2.5 up to 20 times more than the original building.

In the normal scenario, the original building has the potential to amplify the air velocity 3 times, but the overall intake area is 20 times less than proposal design. As a result, the proposal design can generate 2.5 more energy and by considering the best scenario, the modifies intake shape in the new design can generate 20 times more energy.

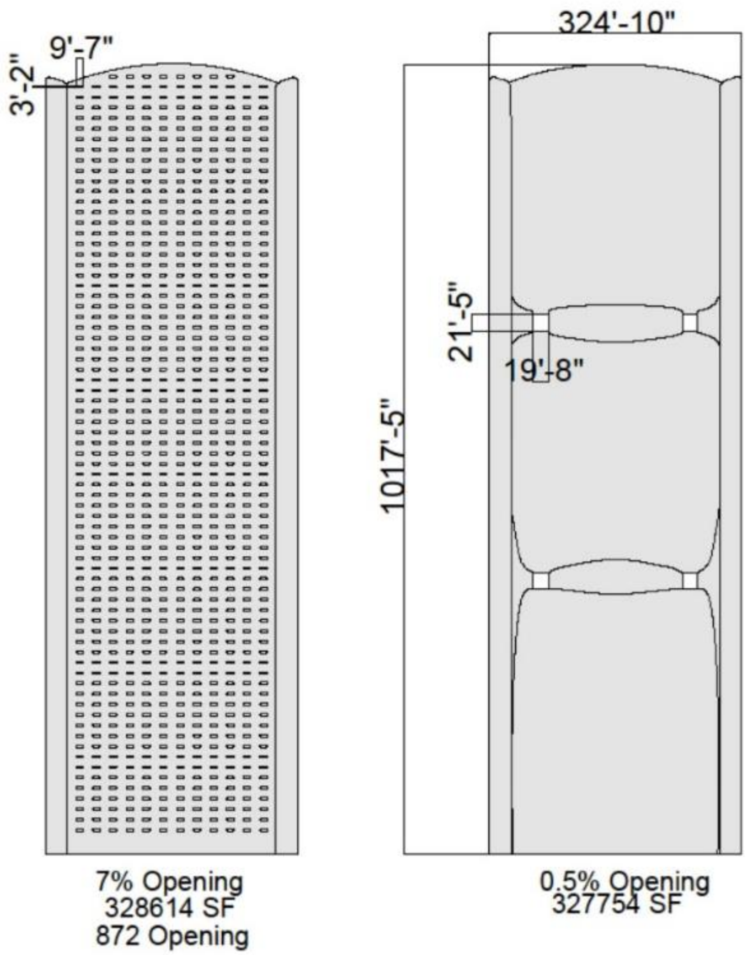


Figure 60 The models specifications. (Figure by author)

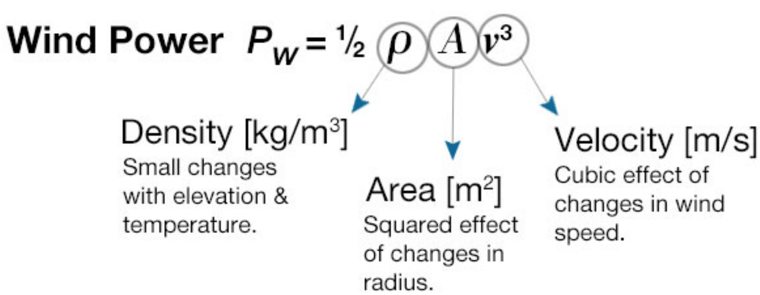


Figure 61 wind power equation. (Figure by author)

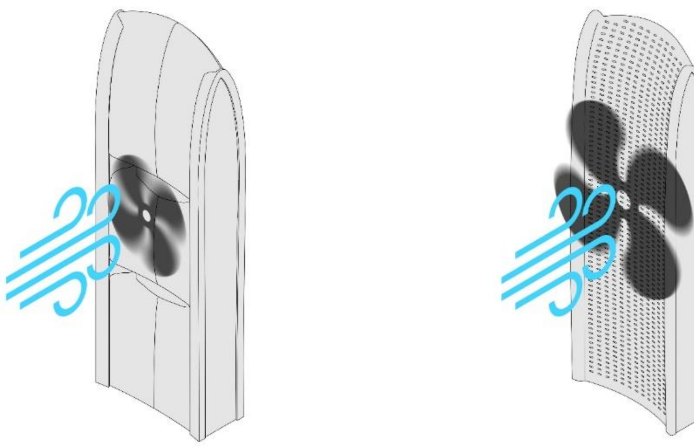


Figure 62 Two ideas in terms of the energy generating. (Figure by author)

The other import finding is the potential of wind harvesting in both designs. To get more energy from the wind, it's necessary to maximize the wind harvesting and the proposal design is more capable in this terms. During wind tunnel test it was visible that some portion of the wind passing above the building in the original design. In the proposal design, because of the more penetrating, there is a higher opportunity for harvesting wind.

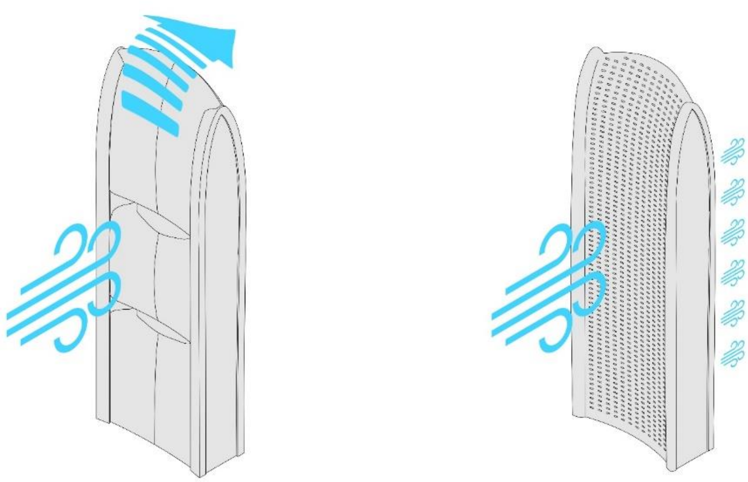


Figure 63 Two ideas in terms of the wind harvesting. (Figure by author)

The possibility of harvesting wind from the different angle is important for the fix wind turbines that are integrated into the building. The wind tunnel shows that the proposal design idea is more capable of harvesting the wind from the different angle.

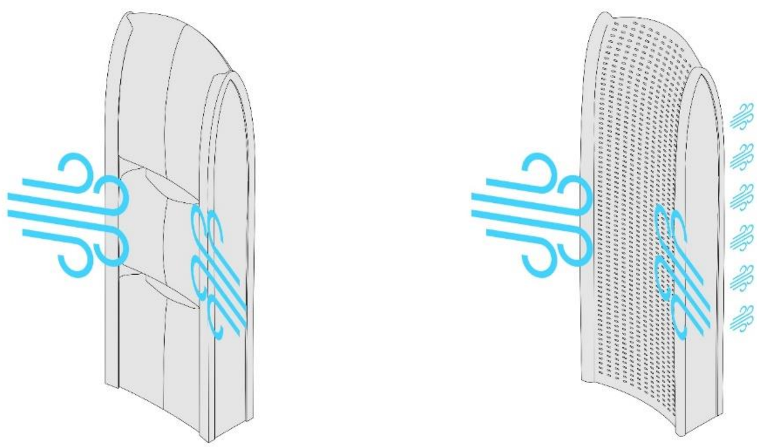


Figure 64 Two ideas in terms of the wind harvesting for angular wind direction. (Figure by author)

The most important disadvantage of the proposal design could be the difference in the lift force on the building. The CFD simulation shows that the wind speed around the building is higher in the proposal design idea which can cause more lift force on the building. This issue can also be considered as a negative impact on the pedestrian comfort level which higher wind speed would cause discomfort situation for the pedestrian.

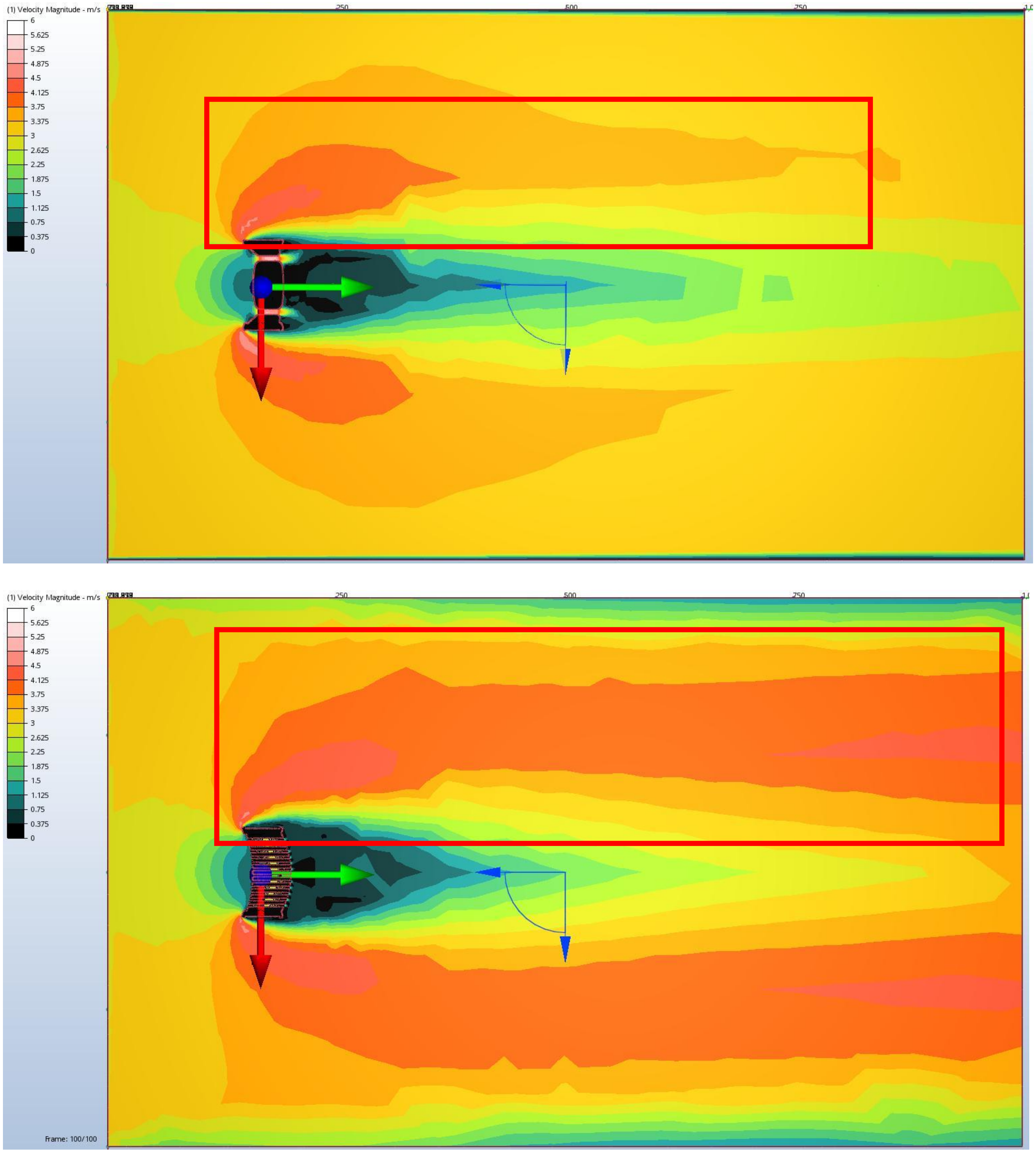


Figure 65 Top the original design, bottom the proposal design. Air velocity in plan view. (Figure by author)

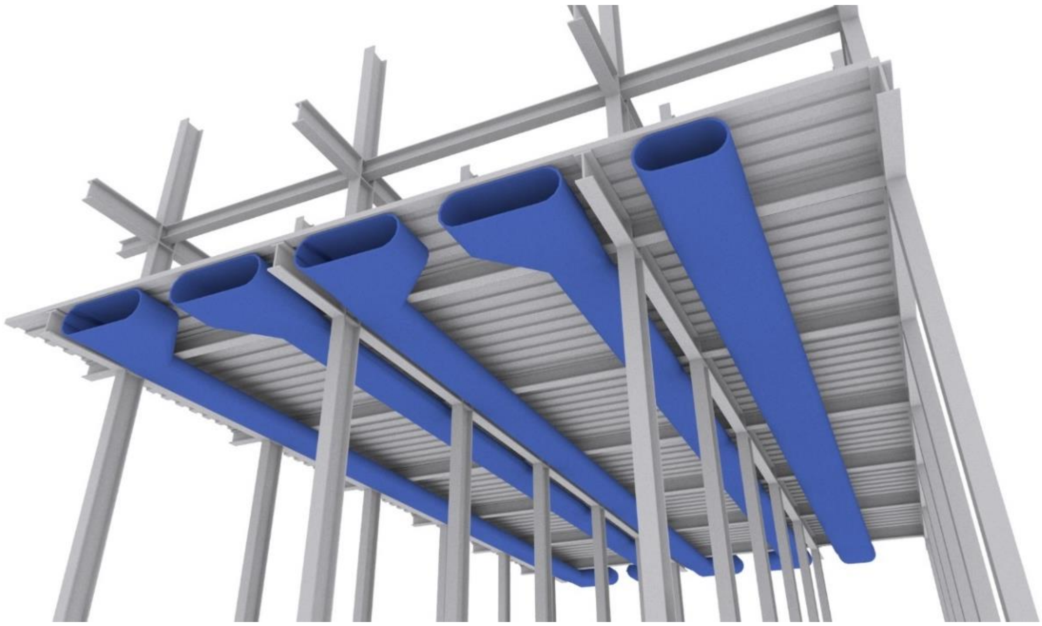


Figure 66 The proposal design installation potential. (Figure by author)

As an overall conclusion, the proposal idea can be beneficial by reducing the cost of the structural material for the building, increasing the wind harvesting capacity and wind energy generating and the compatibility to the conventional design strategies for the building.

On the other hand, by increasing the number of the wind turbines, the maintains issue become important. Although the smaller turbine is simpler to run and maintenance and easier to access, the high number of them can be a problem. Meanwhile, for devising the small turbine in the dropped ceiling or raised floors, the special consideration is needed in terms of the structural and mechanical system design.

14. Further field of study

This research is a basic and fundamental study of the potential of wind harvesting in the high-rise building. During doing this research to optimizing the wind harvesting capacity in the high-rise building with different ideas comes aside of the main research that needs further studies.

One of the most important aspects of the penetration would be the pattern or the grid of holes. It’s clear that each part of the building, top-bottom or side-center, has different potential for wind harvesting and further research will clarify that which pattern will have better performance in comparison to the regular pattern.

Another issue that needs more attention is the shape of the wind duct and the intake or outlet shape. The CFD simulation shows changing the shape of the intake can have a noticeable effect on the performance of the system.

One of the major problems of the system can be vibration which causes unwanted noise production. The vibration is produced in specific frequencies which directly related to the wind speed. By changing the wind speed, it's possible to control the vibration and noise production that further study for designing dynamic intake shape can control the unwanted disturbing effects.

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