A Literature Survey on Integration of Wind Energy and Formal Structure of Buildings at Urban Scale

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Abstract. Providing the needed and indispensable steady, quality and safe energy is one of the most important issues today. Wind energy is one of the most important renewable energy source. Wind energy has found uses much more in water pumping and obtaining electricity in rural areas until last years. Today, wind energy has taken its place in the energy sector as an alternative source of energy production. High-density building arrays within a city, the combination of indoor and outdoor spaces with different purposes effect wind flow and acceptable wind comfort. In urban areas, wind energy and wind comfort are important requirements. Not only in new urbanisation areas but also for existing urban areas and city centers acceptable wind comfort plays an important role among and around buildings. When viewed from this angle, the aim of this study is enlightening the building aerodynamics, wind effect and wind energy in urban environment, and also giving information about how to analyze the wind comfort and design criteria in dense urban areas.

Keywords: Wind energy · Wind comfort · Building's formal structure

1 Introduction

Displacement of air mass due to differences in temperature and pressure in the atmosphere is defined as the wind. Wind energy that is transformation of solar energy is the conversion of kinetic energy of air mass to mechanical energy [1].

With the urbanization process, the more number of long and narrow streets surrounded by buildings is being to be seen in the construction area of largest cities. The development of these street canyons has brought out the problems related to pollution in recent years. These areas at the pedestrian level called space generally acts as external living space. Therefore, in the plan and design process, to ensure the

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acceptable wind environment at the pedestrian level areas, it is very important to evaluate the ventilation potential and performance [2].

Traditionally, analysis and assessment of wind environment firstly based on wind tunnel tests. Today, numerical modelling (Computational Fluid Dynamics-CFD) that offers the advantages of computer capability is widely accepted. If optimization design will be carried out and if the effect of environmental impact on urban development will be assessed, owing to the fact that these test are very expensive and they require long time, numerical modeling is preferred to wind tunnel testing [3].

Over the past few decades, wind tunnels has emerged as an empirical tool to simulate the natural wind and to identify the wind power acting on the structure in the simulated air flow using models of small scale. The boundary layer wind tunnel model test has become the most reliable method to identify the wind-induced loads and structural response to these loads of high-rise buildings. With the development of advanced data collection, correct aerodynamic model test is possible with widely accepted high frequency force balance technique and instantaneous wind pressure integration. Both of these aerodynamic testing techniques has the advantage of the usage of lightweight but relatively rigid building model [4].

In recent years, the use of fluid dynamics (CFD) in the wind engineering has progressed rapidly. Currently this approach, that is known as the computational wind engineering is recognized as one of the most important research areas. The rapid growth of computational wind engineering applications is expanding the scope of wind engineering as shown in Fig. 1 and covering a variety of phenomenon from micro-climate around the human body to medium-scale climate in urban areas [5].

In computational wind engineering, a wide range of issues has studied with different perspectives. In the study of Murakami et al. [5], applications that are related to human space around buildings and environmental problems including the following conditions is mentioned.

- Wind environment in the building complex.
- Thermal and dynamic effects of the wind on the human body.
- Pollutant distribution around a building.
- Thermal comfort in outdoor [5].

In many studies, wind load analysis are made for combination of high-rise, low-rise or high-rise and low-rise buildings and different results obtained by using experiment and computational fluid dynamics (CFD) environment. Roberson and Crowe [6] studied the pressure distribution in a building for turbulent flow conditions experimentally. Ahmad and Kumar [7] studied the wind load on the low-rise buildings. And they examined the effect of geometry on pressure for low-rise buildings. Aygün and Başkaya [8] examined the surface pressure formed by wind flow around a high-rise building. Mendis et al. [9] studied the wind load on high-rise building experimentally and numerical according to the Australian conditions. Holmes et al. [10] searched the wind loads of high, medium and low-rise buildings for 15 different region in Asia-Pacific region.

Şafak [11] mentioned the main approaches and assumptions of static and dynamic load calculations for wind load. Huang et al. [12] made the numerical analyses of wind loads on high-rise buildings with steel construction by Computational Fluid Dynamics

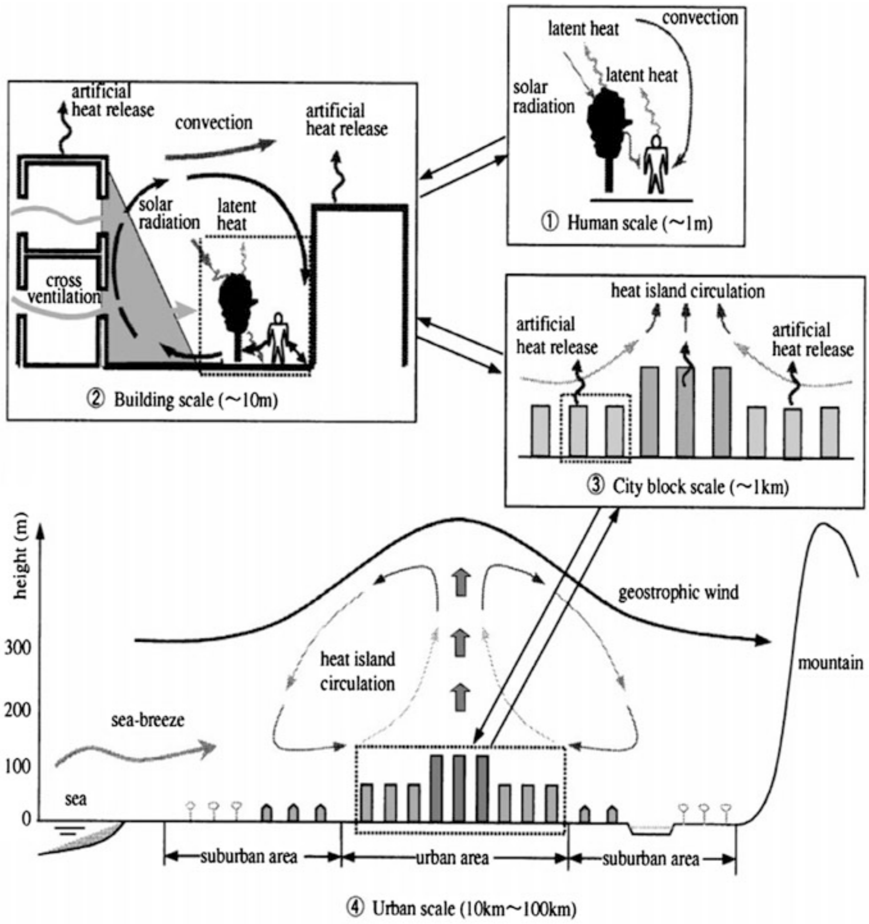


Fig. 1. Various scales related to wind climate [5]

(CFD). Liang et al. [13] studied the wind loads which effect the dynamic torsional loads on high and rectangular buildings experimentally. Huang and Chen [14] studied the wind and static loads on high-rise buildings on the basis of co-frequency pressure measurements. Tominaga et al. [15] studied the wind effects around buildings in a particular region by CFD method. Huang et al. [16] examined the RANS method analyses and kinematic simulation of wind load for high-rise buildings. Cheung and Liu [17] made the CFD analyses of ventilation process of high-rise buildings in their studies. Blocken et al. [18] examined the buildings of Eindhoven University of Technology by modelling them in CFD environment, and studied the wind loads by CFD analyses [19].

Recently, the prediction of wind environment around a high-rise building, using CFD technique, was carried out at the practical design stage. In view of this point, a working group for CFD prediction of wind environment around buildings, which consisted of researchers from several universities and private companies, was organized by the Architectural Institute of Japan (AIJ). During initial stage of that project, the working group carried out cross comparisons of CFD results for flow around a single high-rise building, building block placed within the surface boundary layer and flow within a building complex in urban area. Fig. 2 illustrates the six (a–f) test cases for these cross comparisons. They were carried out to clarify the major factors which affect the prediction accuracy [20].

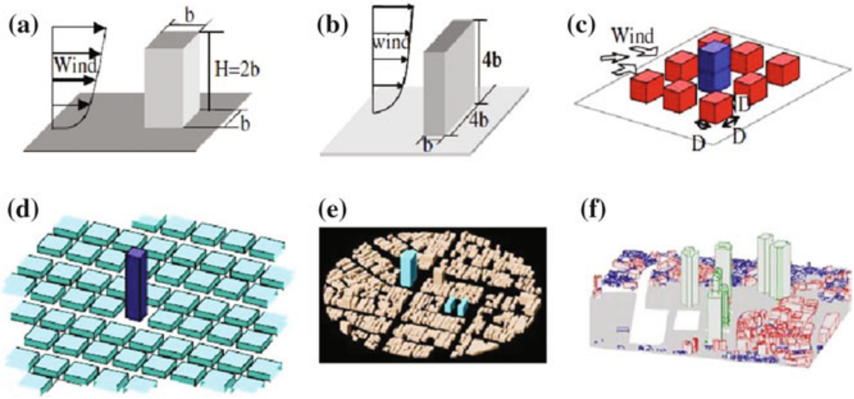


Fig. 2. Six test cases for cross-comparison. **a** The test case A (2:1:1 square prism); **b** the test case B (4:4:1 square prism); **c** the test case C (Simple city block); **d** the test case D (A high-rise building in the city); **e** the test case E (building complexes in actual urban areas (Niigata)); **f** the test case F (building complexes in actual urban areas (Shinjuku)) [20]

Because of the reasons like, reduction of surface evaporation and green spaces in cities, increasing the concrete, asphalt surfaces and structural field, meteorological parameters are changed and this cause climate change at local and regional scale. Therefore, big cities are becoming venues for their unique climate.

Increase of high-rise buildings, reduction of green space in urban areas affects the city's aerodynamics in our country, it is an important requirement that establishing a set of design criteria and standards for building wind safety and comfort and living comfort of people in urban environment.

2 Methodology

The aim of this study is to reveal the literature studies about the wind, wind energy and effects of the different form and settlement of building and external environment elements on the building aerodynamics, and also it is believed that this study will enlighten the procedures how to analyze the wind effect on the buildings in urban scale. Accordingly; first of all, introduction about the study will be given, wind energy and integration of wind energy and building aerodynamics will be explained. After that, results of the study will be explained.

3 Literature of Wind and Wind Energy

Starting from worldwide, when it is considered the causes of the formation of air movement or wind, it is seen that, they are their thermal or dynamic based pressure system, coriolis force formed by the earth's rotation, friction force formed by the roughness of earth and viscosity connected to the air flow [21]. As it is seen from Fig. 3 the records of anemograph, wind's direction and intensity is always variant. This variation feature seen in the wind's direction and intensity is called as turbulence.

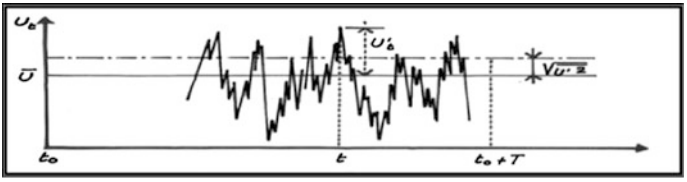


Fig. 3. An example of a anemograph record that measures the wind speed [22]

The buildings that create the urban open space make the same influence of the topography in open rural areas. There occurs a difference between flow types in open rural areas and flow types in urban areas, also wind or turbulent air movements ceased to properly pass the turbulent situation. Thus, type of air movement in urban open space scale is formed again in connection with geometric features as seen at Fig. 4 [22].

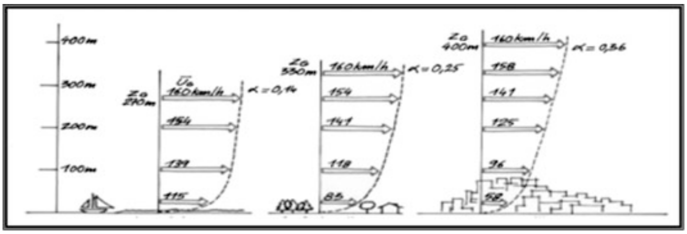


Fig. 4. Earth in the boundary layer wind speed gradients change depending on the configuration of built environment characteristics [22]

Depending on developments in the economic and social fields, based on the fact that supplying the growing energy needs of approximately 4–5% per year worldwide from fossil and nuclear sources that have harmful effects to the environment, it is need to benefit from wind energy that is clean, environmentally friendly and a local source [23].

As a result of the research it is said that the first use of wind energy in the historical process is conducted in the civilizations of China, Tibet, India and Afghanistan. The first written information about the use of wind turbines belong to the simple made horizontal-axis wind turbines in B.C. 200–300 years by Great Alexander. There are information about the use of vertical-axis wind turbines in B.C. 700s in the Persian. From Asia to Europe in the 10th century, the use of wind power developed by western countries. The first wind power, is produced by the Danish Professor Paul La Cour in 1891 [24].

Concerns about the effects of wind on the building dates back to the early human settlements. Design principles that is laid down in the design of many ancient cities as it can be understood from the coming to the fore again like principles of Feng-Shui, used for the development of ancient Chinese dynasties (wind and water), it appears to remain valid today [22].

From the summarize of the book of Aynsley, Melbourne and Vickery named Architectural Aerodynamics that constitutes an important resource about building aerodynamics; Aristotle BC 4th century in "Meteorologik" first time to discuss the mysterious winds, his student Theophratus' weather forecast methods, the ancient Greek who give the names of wind gods to the wind direction in the wind rose transfer us the importance of this issue. The principles that laid out in the book of "Ten Books on Architecture" by The Roman architect and engineer Vitruvius, in the B.C. 1st century spread to other European countries in 15th century. As well as the one who went to Europe in 1573 developed the city planning laws for Spanish cities in the South and Central America, also in world's various climatic zones, Japan, Canada, India, and other similar buildings and culture of the city is seen as designed according to local wind [22].

After the Industrial Revolution, in the city planning, in 1890 Europe, Nuremburg, taking into account the natural lighting in every room, in 1874 Sweden laws say that light and air protect is necessary to protect the health, in order to move the fumes from factories out of the city of Vienna in the 1900s, the prevailing wind is taken into account in city and regional planning. In contemporary practice of urban planning principles similar experimental, parallel to the development of digital design techniques, there are many examples [25].

4 Integration of Wind Energy and Building Form (Building Aerodynamics)

One of the main topics of building aerodynamics is revealing the characteristics of air flow that occurs in or around the building within the urban texture. As it is seen from Fig. 5, the air molecules hitting the wind above surface of the building stop when they hit the surface, change the direction by licking the surface and finally form the trace region behind the building following side surfaces by being separated from the surface of the breaking point [22].

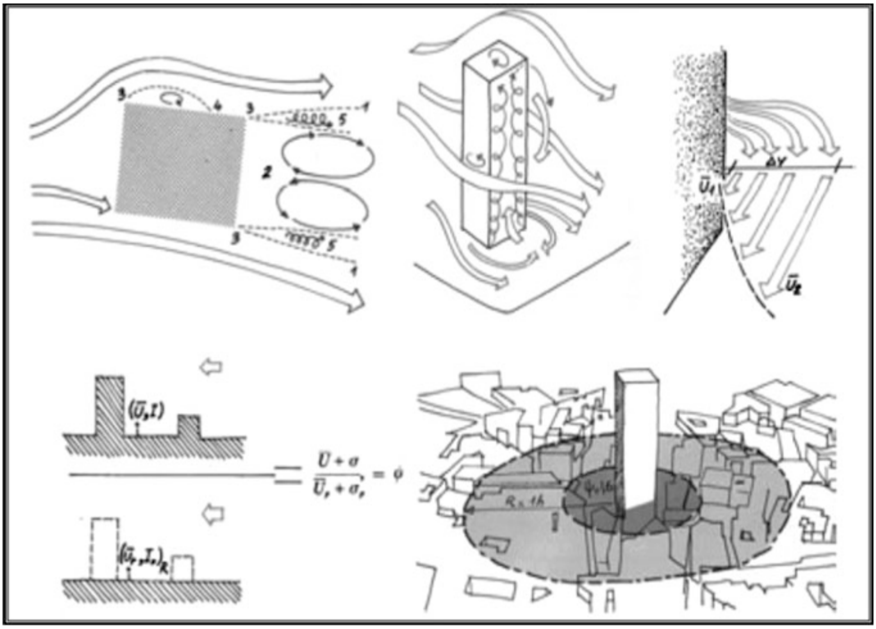


Fig. 5. The air current schemes formed around building [22]

Air molecules pushed by a unit and having different speeds form vortices. So, around the building, uncomfortable areas formed whose speed and direction is variable. This changing formation depending on the building geometry and dimensions can be solved by the work done in the design phase [22]. In this context, to reveal the relationship between building form (geometry) and wind energy, analysis is performed seen in Fig. 6.

While the airflow formed by the wind passing around the side faces of building, vortices occur as seen in Fig. 7 schematically.

Since vortex occur as variable (first one side, then other side), dynamic loads created by vortex also variable and influence on the direction perpendicular to the flow direction of the wind. Since they affect very specific and narrow frequency, vortex can be defined as sinusoidal load [26]. Wind pressure seen on the building shown in Table 1, varies depending on the topography, height, internal pressure, aerodynamic pressure and the building form [27].

High structures, are affected by vibrations caused by wind action. Therefore, wind has an important role in the structural and architectural design. There are different design strategies that enhance the functional performance of the buildings and reduce the negative effects of wind. Between these strategies, the important and effective design approach is the aerodynamic modifications in architecture [28].

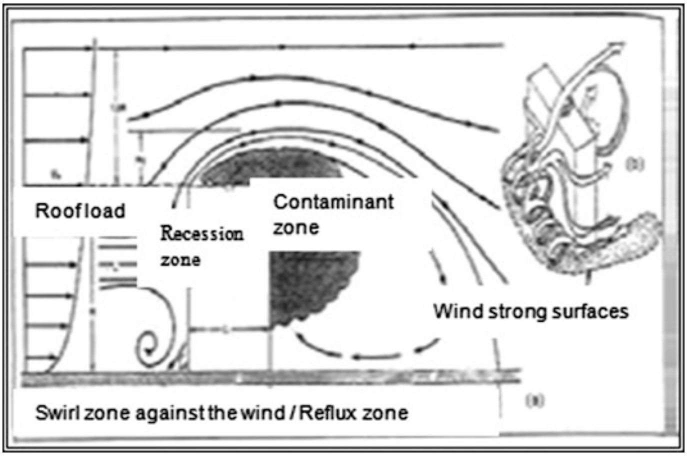


Fig. 6. Air flow around the rectangular building [22]

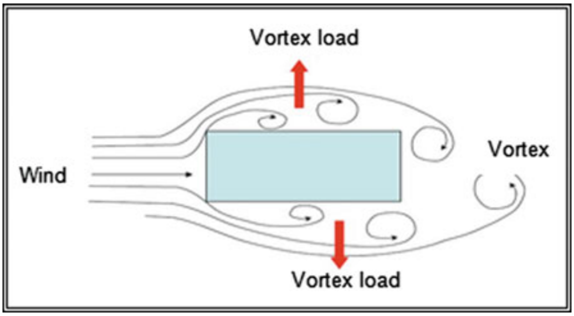


Fig. 7. The formation of vortex load [26]

Table 1. Factors affecting the building and wind interaction [27]

Factors	Impacts
Topography	Sudden changes in topography such as hills, ridges cause an increase in wind speed. Therefore, a building located near the top of a hill, will receive more wind loads than relatively the one in a flat area
Building height	If the height increase from the ground, wind speed also increase. Therefore, if building height increase, wind load effecting on the building increase
Internal pressure	The wind hitting the building causes the pressure increase (positive pressure) or decrease (negative pressure). Internal pressure change occurs by the size and frequency of the openings in the building faces
Aerodynamic pressure	Due to the aerodynamic effects (structure and interaction of wind) the highest loads occur at the roof edge. Winds affecting the structure of the front is usually lower than the wind load acting on the roof
Building form	The building form affect the wind pressure coefficient and thus wind load acting on the building

High-rise buildings, due to the increase in wind power with building height and building form, they show a more sensitive behavior against wind effect. Various forms of high-rise buildings and aerodynamic properties of these forms has been studied by many researchers. The dynamic behavior of a structure in which the face of high winds must be contained within the acceptable limits for structural design and user comfort. The building form aerodynamic is a design criteria that must be decided from the beginning of the design phase of a high-rise building [29].

According to Ilgın and Günel, the effects of wind on the structures can be controlled in two ways:

1. Significant architectural changes: Modifications that affect the architectural concept like buildings became slender with height, to gain a sculptural appearance of the structure of the top, changing the building form, creating opening in the building
2. Small architectural changes: Modifications that do not affect the architectural concept like corner modifications and settlement of the building according to the strong wind direction [28].

These two substances were examined on the following examples. Gaining sculptural view of the top of the structure as shown in the examples reduces the negative impacts of wind on buildings [30].

As it is seen in the example, Petronas Towers in Malaysia shown in Fig. 8 [31], reducing the plan section of the building by ‘changing the form’ at the high level of the building reduces the effect of wind force by varying the effect of the wind energy.

It is a known fact that, building form has a significant impact on protection of lateral resistance of the building form. If the building form is only limited by the rectangular prism, this form is exposed to effects of lateral wind. To cylinder, ellipsoid, triangular or other structure forms act less lateral force than rectangular prism-shaped structure [31].

Wind pressure acting on the building in the form of cylinder (circular) or the ellipse-shaped is reducing by 20–40% compared to the rectangular prism-shaped building [32]. Because of this, in many famous building, building forms that have favorable effects are preferred.

The Marina City Towers’ (Chicago 1964) cylinder form seen in Fig. 9a, Millennium Towers’ (Tokyo 2009) conical circular plan seen in Fig. 9b, Toronto City Halls’ (Toronto 1965) crescent-shaped form seen in Fig. 9c and U.S. Steel Building’s (Pittsburgh 1970) triangular plan seen in Fig. 9d are among the buildings that aerodynamic building forms are prepared [29].

Also, the openings created especially close to the roof section of the building facade are the aerodynamic answers of the building that reduce the negative effects of the wind affecting on the building. The Shanghai World Financial Center (Shanghai 2008) seen in Fig. 10 is one of the best examples about this subject [33].

In this section, it has been mentioned that wind has influence on the building, in order to reveal these effects, various wind tunnel experiments have been carried out. In these studies, it has been demonstrated that wind power increases with building height and form, because of this, wind energy acting on the buildings can be controlled with same aerodynamic modifications during the design stage.

Fig. 8. Petronas Towers in Malaysia [31]

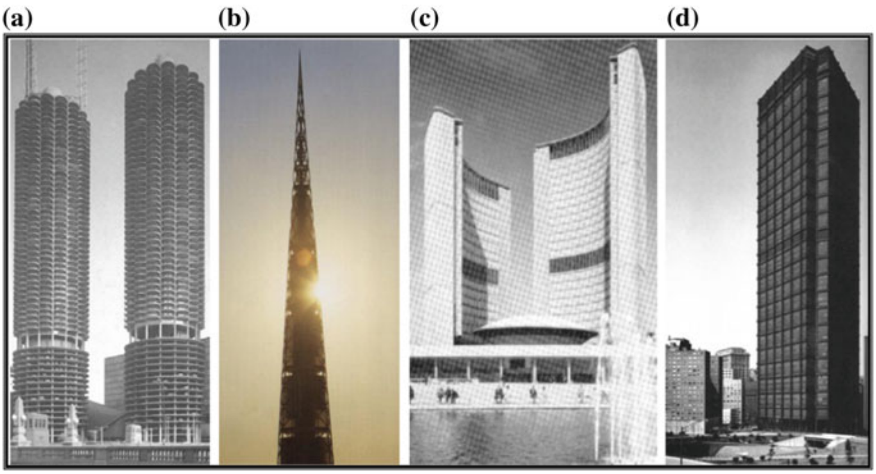


Fig. 9. **a** The Marina City Towers (Chicago 1964), **b** Millennium Tower (Tokyo 2009), **c** Toronto City Hall (Toronto 1965), **d** The U.S. Steel Building (Pittsburgh 1970) [29]

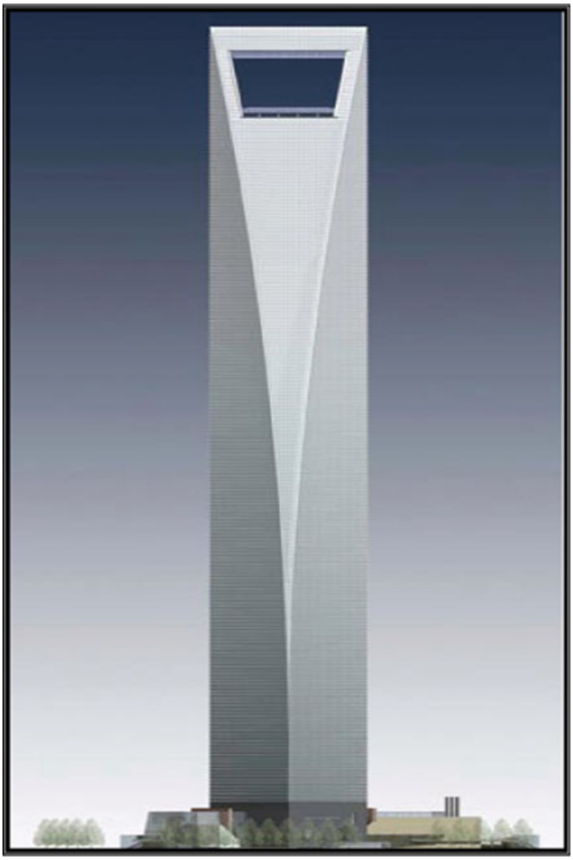


Fig. 10. The Shanghai World Financial Center Building [33]

5 Results

In a wide range, building shape, height and distance between buildings affects the direction and intensity of the wind flow. Airflow between buildings has been investigated by many researchers using different statistical analyzes. Usually, street canyons with typical architectural forms, semi-enclosed areas, the relationship between form and courtyard complex of low-rise buildings in a relatively open field wind environment were examined. Collected and stored measured data comprises information on wind direction and wind speed at different locations. Then statistical methods are used to determine the key factors defining the effects of building form on the air flow. In urban environment, information about how it is the wind flows around buildings, to decide on the best positioning and wind turbines, air pollution dispersion and pedestrian comfort has a great importance in terms of design [34].

In Fig. 11, from the schematic representation of the obstacles to the turbulence, in Fig. 12, it is included in the schematic representation of complex the flow path of the air around the building form.

System integration level and forms of architecture are discussed in different ways by different researchers. In this context, according to Çakmak [35], five relationships can be mentioned about structure-facade integration. These relationships are as seen in Table 2; remote, touching, connected, meshed and unified.

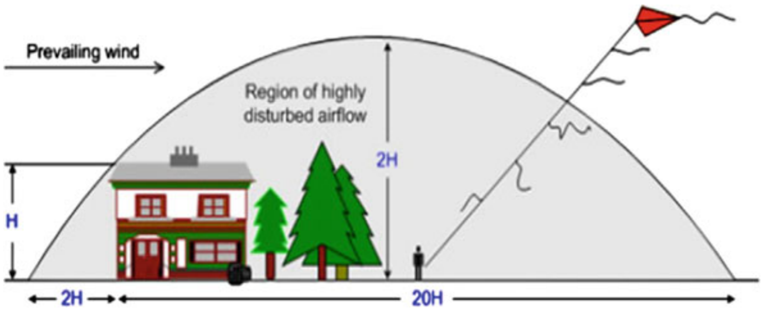


Fig. 11. Turbulence from obstacles results with high turbulent area near these obstacles [34]

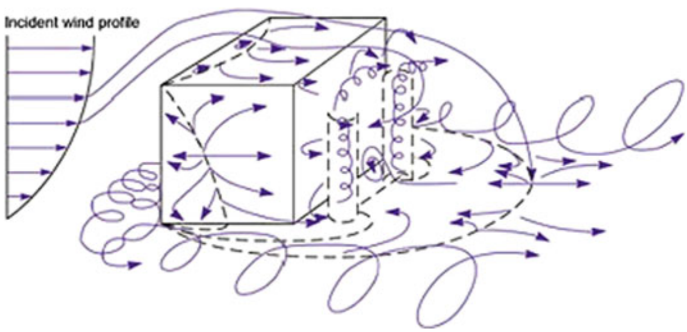
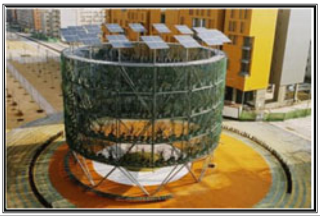


Fig. 12. Wind flow around building form creates mixed air flow path sand waves [34]

According to another aspect, integration level and shape of the building systems and ecosystems can be taken into account like ecological design and physical integration, system integration and continuous integration.

Table 2. Table showing the level of integration of building systems [35]

Integration levels	
Remote Systems are physically separated from each other and still been coordinated form	
Touching One of the system remains above the other and in the position it is touched with this system. It is only influenced by its own weight where it is	
Connected The systems are connected in various ways to each other permanently	
Meshed Systems occupy the same space	
Unified	

Ecological design is the design approach that design system is integrated with our natural environment. They deal with the building not only as a single structure but also with urban and land. The characteristics of the area where the building is discussed in the context of ecology and these properties are integrated physically, systematic and continuous.

In Bachman's study, the integration potential between architectural systems can be classified as physical integration, visual integration, performance integration and integrated integration. According to this view, architectural systems must share the same space, the coming together should be resolved aesthetically and must collaborate or complete each other in a point.

Physical integration Building components must be in harmony with each other. These components share a common volume in a building and they are interacting in different ways in this volume. Physical integration includes the basic components of the system volume and shape interactions in common. In standard application, for example, many buildings on the ground and roof sections are usually divided into separate regions: recessed lighting in the bottom section, later space for groove, in the top section, depth section supporting the above ground at the top [36].

Visual integration All components of the building are coming together to complete the visuality. This expression is available for as well as structure to the overall visual idea also, each room features and even individual components. Color, size, shape and placement properties can be used to create the desired effect [36].

Performance integration Where the physical integration is called as shared space and visual integration is shared image, performance integration is related with common functions. For example, a bearing wall serves as a shell as well as being a bearing wall [36].

Integrated integration All these integration levels seen between systems are emerging often integrated. The level in which physical, visual and performance integration are seen together is called integrated integration [36].

6 Conclusions and Suggestions

Many research studies have been conducted about wind energy and building relationships (building aerodynamics). Owing to the increase of wind speed with height and the increase of wind energy proportional to the height, it is found that wind turbines has been used in more high-rise buildings. As a result of these studies, it is put forward that wind energy has serious effects on high-rise buildings and solutions that convert negative aerodynamic effects to positive is very important in design stages.

As a result, selection of appropriate building form results in reduction of aerodynamic forces around the buildings. This method can lighten the wind response compared with the original building form. Surface roughness at the urban scale, position and height of buildings, vegetation and open space fiction, and thus the effect of the wind affects the city's pedestrian wind comfort with pedestrian comfort conditions.

The world's energy problem extending since the 1970s, development, diversification of architectural systems in recent years and existing energy resources come to the level that they cannot meet the needs of building stock make it necessary to take measures to reduce the environmental damage.

In later years with questioning the relationship between architecture and environment, it is seen that energy is a factor that is driving the design in architecture, because of this architectural systems' diversification and integration of wind energy and building is becoming important from the beginning of the design stage. In this context, buildings must be designed within the framework of a performance-based approach.

To provide environmentally conscious design and thus integration of building and wind, there are some parameters that should be taken into account from the beginning of the design process. These are;

- Climate
- The building location and geographical location.
- The usage of building.
- Intended use of the building.
- Building form.

Today, as a result of the tendency to renewable energy sources, getting the benefit of these sources has accelerated and it has been started to be used effectively by many countries. Wind energy that is leading source of renewable energy has turned into a giant energy sector especially in Denmark, Germany and Spain, Europe and the United States. The wind energy that is first limited with the application in wind farms, nowadays with technological developments is emerging in the building examples that display integration of energy generation and building. Especially in European countries and the USA, in planned high-rise buildings, the designs that building systems and wind energy examples are increasing.

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