

Study of Wind Energy Utilization in the Built Environment

Lei Pan, Baoming Chen

Shandong Institute of Architecture and Engineering, Jinan, China

Abstract: Wind energy sources have the potential to significantly reduce fuel costs, greenhouse gas emissions, and natural habitat disturbances associated with conventional energy generation. While rapid development of huge on- and off-shore wind farms continues, examples of integration in the urban environment, closer to prime consumers of energy such as buildings, remain scarce. Full integration of wind turbines into buildings can produce energy where it is consumed and can avoid transport costs. Because of the interference of buildings, mean velocities are low and turbulent levels are high in urban, aerodynamic concentrators are formed. At present there are three basic aerodynamic concentrators: diffusers, flat plate concentrators, and the bluff body. This paper attempts to analyze performances of the concentrators using CFD simulation software, to discuss the optimal wind energy field. Aiming at different shapes of buildings, this paper describes the velocity, pressure and energy distributing quantitatively, using effective turbulence models. To place the turbines on top of or alongside a building, i.e. the bluff body type, is the most attractive option. In this case no modification of the building are needed and the aerodynamic efficiency is high. The aerodynamic efficiency of the flat plate concentrator is very high, so this type of concentrator is promising. Towers of diffusers type with "Kidney" foot prints produce good wind enhancement. But the drastic adaptations of the buildings to reshape them into an aerodynamic body are large.

Keywords: wind energy , built environment , wind turbine , CFD

1. INTRODUCTION

Nonetheless every new building will add to the overall energy demand (and thus contribute to increasing atmospheric CO₂ levels) unless it is designed to a sufficiently high level of thermal energy efficiency so that it does not require space heating or air conditioning and is also able to obtain all of its hot water and electricity requirements from non-polluting renewable energy sources. One approach to this is to add more and more renewable energy power stations to supply the electricity grid network with CO₂-free electricity. This is beginning to happen and the proportion of grid electricity generated by renewable energy will no doubt steadily increase.

One way that building designers can help reduce the problem is to provide for the generation of electricity on the site (from a wind turbine or from biofuels, etc.), though this is usually only feasible in open countryside. Another approach is to use the building itself as a means of generating electricity by extracting energy from the ambient energy flows interacting with the building envelope. In the UK during the summer, the dominant ambient energy flow interacting with a building is solar energy from sunlight and in the winter, wind is dominant. Therefore, for maximum year-round renewable energy provision, both solar and wind energy should ideally be converted into energy for the building^[1].

Wind energy sources have the potential to significantly reduce fuel costs, greenhouse gas emissions, and natural habitat disturbances associated with conventional energy generation. While rapid development of huge on- and off-shore

wind farms continues, examples of integration in the urban environment, closer to prime consumers of energy such as buildings, remain scarce. Apart from the use in remote areas, the use of small wind turbines for the built environment has gained in interest. This originates from two sides^[2]:

- (1) the growing demand for renewable energy and
- (2) the increased interest among architects, project developers and local governments in sustainable and zero- or low-energy design buildings.

Full integration of wind turbines into buildings can produce energy where it is consumed and can avoid transport costs. Because of the interference of buildings, mean velocities are low and turbulent levels are high in urban, aerodynamic concentrators are formed.

2. INTEGRATION STRATEGIES

According to Panofsky and Dutton^[3], the roughness of the built environment reduces the average wind speed at about 75% of the average building height to zero. As a result, wind turbines in the built environment require buildings that are reasonably higher than the average building height. Wind turbines close to such buildings can profit from the local flow deviation since they operate in wind accelerated by the building. Buildings may play an active role in increasing the energy output and are not just used as a foundation of the wind turbine. Such integration of building and wind turbine will therefore be referred to as Building Augmented Wind Turbines (BAWT)

There are three different categories of BAWTs (see Mertens ^[4]): those situated on a building; those situated between diffuser shaped buildings; and those situated in a duct through a building. The first category can be explored in the near future; The last two categories are interesting for the far future because both building and wind turbine should be designed almost from scratch. At present there are three basic aerodynamic concentrators: diffusers, flat plate concentrators, and the bluff body, see Fig.1. All other possibilities are combinations of these three ^[5].

Table1.

ground cover	offing	lake	open plain	field	country	town	big city
$Z_{0,ref}$ (m)	0.003	0.01	0.03	0.10	0.20	0.30	1.00
α	0.107	0.13	0.146	0.205	0.25	0.28	0.33

3.ANALYSIS OF BASIC AERODYNAMICS CONCENTRATORS USING CFD SIMULATION

In order to assess the potential for fully integrating (and retrofiting) turbines into buildings, the aerodynamic performances of the three basic shapes of building forms were assessed using CFD (Computational Fluid Dynamics) Simulations.

3.1 Wind in the Built Environment

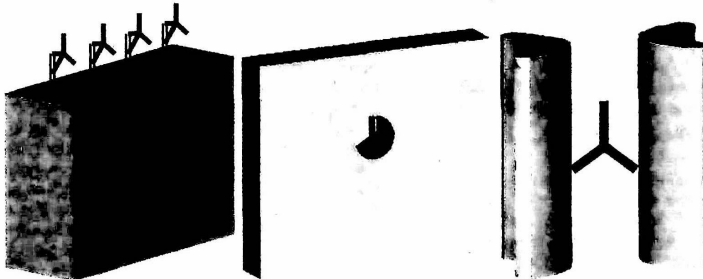


Fig 1 three basic aerodynamic concentrators

Wind speed near the ground varies observably along with the height of the aerosphere. The cause of the vertical variety of wind speed near the ground is momentum factor and thermodynamics factor. The former is derived from friction effect of ground viz. the ground roughness. The later mostly represents the relation of the aerosphere vertical stabilization. In the neutral aerosphere, the development of turbulence entirely depends on the momentum factor. At the upstream end, the mean inflow velocity profile is based on a power-law distribution ^[6]:

$$\frac{U(z)}{U(10)} = \left(\frac{z}{10} \right)^\alpha \quad (1)$$

In this, $U(z)$ is wind velocity of height z , $U(10)$ is reference wind velocity in 10m, and α is the

coefficient of wind velocity along with height. The value of α bears on the roughness of ground. If the value of α is big, and the increase of wind velocity along with height is obviously, that is to say the grade of wind velocity is big.

According to literature ^[7] the roughness of the built environment and the value of α of different grounds are shown in Table1.

This paper the wind comes from the left side, the roughness of the built environment $Z_{0,ref} = 1\text{m}$, the

reference velocity $U(10) = 4\text{m/s}$, and the value of α is 0.33. Wall boundary function condition: standard $k-\varepsilon$ model is often used in engineering, but it is only appreciable for the onflow area depart from wall. Because of the improvement of the viscosity effect of laminar flow, standard $k-\varepsilon$ model must be amended. In this paper the wall function is adopted to correct the building areas.

3.2 CFD Calculations of Different Shapes of Building Forms

3.2.1 the Bluff Body Concentrator

The reference building for the CFD calculation has a height of 20m, a width of 30m and a depth of 10m (see Fig 2). The separation wind speed at a height $(h+\Delta h)$ at a height Δh above the roof with height h can be defined in terms of the wind speed in the IBL (Internal Boundary Layer) found with relation (2) where the parameter C_r gives the change of the undisturbed wind speed to the wind speed at height above the roof.

$$C_r = \frac{u_r(h+\Delta h)}{u_0(h)} \quad (2)$$

In this, $u_x(h+\Delta h)$ is the wind speed in height of

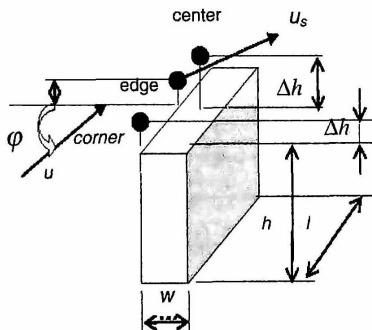


Fig 2 model of bluff body

($h+\Delta h$), and $u_0(h)$ is the wind speed of the undisturbed wind in height of h .

This paper discusses the variety of wind speed along with height at different positions on the roof of building, such as at center, edges, and corners of the building, and attempts to ascertain the turbines' proper height of setting to avoid the high turbulence and low velocities within the separation bubble. Overseas scholars have studied the problems^[8], but the problems discussed are in the case of the yaw angle $\varphi = 0$. Because there is a lean angle between the leading vane of the site and the axis of building, namely the yaw angle $\varphi \neq 0$. So this paper discusses the problem with hypothesis of $\varphi = 45^\circ$.

According to the result of the CFD calculation depicted in Fig 3 a quantitative height of 2~3m or $\Delta h/h=0.1\sim 0.2$ above the roof is enough to avoid the high turbulence and low velocities within the separation bubble. The turbines at the windward edge of the roof and the corners can utilize wind energy more effectively than at the center position. According to the Figure 3 this condition was achieved at a height

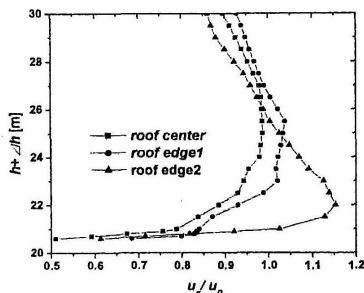


Fig 3 calculated wind speed change C_p at different height above roof

above the roof of approximately 1~3m, so the wind turbines' installation can be chosen for the corners position $\Delta h/h=0.05\sim 0.15$.

3.2.2 The Flat Plate Body

The basic design of the concentrator with a duct through the building can look like a flat plate (see Figure 4). The pressure difference between the windward and leeward side of the building initiates the

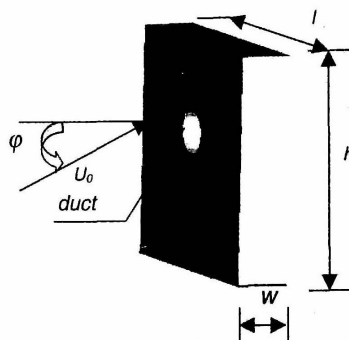
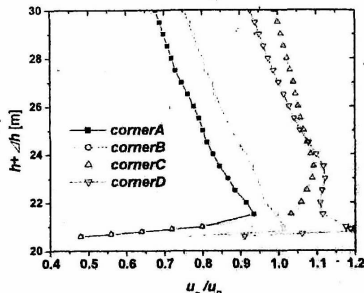


Fig 4 flat plate model

flow through the duct in the building. At the windward side there is a stagnation condition that causes the locally increased pressure to be higher than the undisturbed pressure far before the building.

The concentrator effect will only be present for small wind turbine dimensions compared to the building dimension since the wind turbine has to be located in high wind speed zones, which only exist close to the building. This limits BAWT dimensions up to 20% of the characteristic building dimension. Therefore, in mid- to high-rise buildings with a dimension of around 100m, the BAWT diameter can only be up to about 20m. This is relatively small compared to 100m rotor diameters found in conventional turbines nowadays. However the wind turbine has to be as big as possible in order to generate an appreciable amount of energy. A CFD calculation of the flow around a building, with dimensions $l, w, h \approx 120, 20, 100$ m and the diameter of the duct is 20m, in an atmospheric boundary layer showed the change of wind speed from undisturbed wind speed to the wind speed in the duct of the



building.

This paper the concentrator effect of the duct can use the parameter C_a to estimate the available wind energy in the duct at different yaw angles.

$$C_a = \frac{u_a}{u_0(h)} \quad (3)$$

Where u_a is the average wind velocity in the duct, and $u_0(h)$ is the wind speed of the undisturbed wind in the wind turbine setting height of h . Good wind enhancement over a wide range of angles of wind incidence is essential for fully-integrated turbines, since in general neither they nor the building will be able to yaw to face into the prevailing wind. Rarely in urban areas does the wind blow strongly from a single direction for the majority of the year and, in any case, the possible building orientations may be limited by the constraints of the site. So this paper wind velocity around the building at different yaw

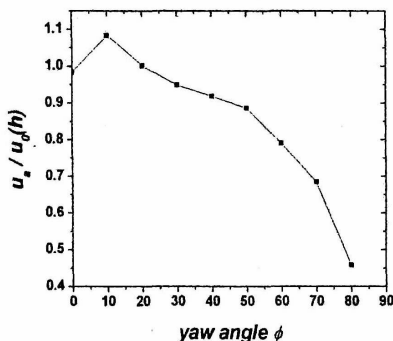


Fig 5 calculated wind speed change C_a

angles ($\phi = 0 \sim 80$) is calculated. According to the result of the CFD calculation depicted in Figure 5, the aerodynamic efficiency of the flat plate concentrator is high. The wind energy in the duct of the building can be used effectively up to the yaw angle 30–40.

3.2.3 The Diffusers

In this case buildings are positioned in such a way

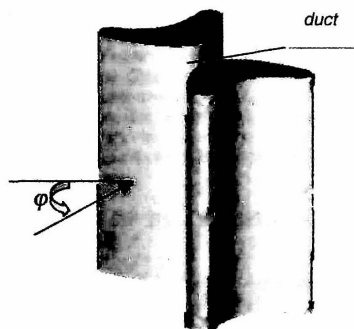


Fig 6 diffusers model

that they act as a diffuser for the wind turbine (See Figure 1, far left). In the past there was a lot of interest in the diffuser augmented wind turbine and several tests on the operating conditions and achievable aerodynamic efficiency were carried out.

All tests were carried out on horizontal axes wind turbines in ring shaped diffusers. This combination results in a high aerodynamic efficiency compared to other possibilities. The tests of Igra [9] and others [10] confirm the possibility of raising the aerodynamic efficiency in this configuration. However measurements also show the drawback of this configuration. The diffuser needs to be long in order to generate an appreciable gain in aerodynamic efficiency. The common shape of the diffuser augmented wind turbine is not very suitable for the built environment.

This paper uses CFD simulation to analyse the wind velocity yield between two diffuser tower buildings. And the paper discusses the change of average wind velocity between the buildings at different yaw angles $\phi = 0 \sim 80$ (see Figure 6).

The concentrator effect of the duct between two diffuser towers can use the parameter C_a to estimate the available wind energy in the duct at different yaw angles (see Function 3). Where u_a is the average wind velocity in the duct, and $u_0(h)$ is the wind speed of the undisturbed wind at the top of the building with height of h . According to the result of the CFD calculation depicted in Figure 8, the aerodynamic efficiency of the diffusers concentrator is higher than that of the flat plate concentrator. Towers of diffusers

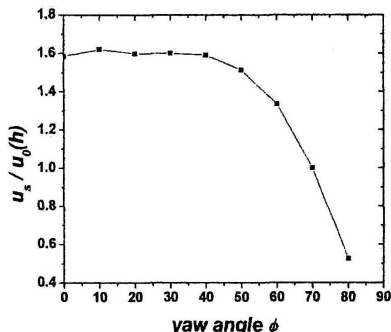


Fig 7 calculated wind speed change C_a

type with "Kidney" foot prints produce good wind enhancement. The wind energy in the duct of the building can be used effectively up to the yaw angle 50–60.

4. CONCLUSION

Wind energy sources have the potential to significantly reduce fuel costs, greenhouse gas emissions, and natural habitat disturbances associated with conventional energy generation. Full

integration of wind turbines into buildings can produce energy where it is consumed and can avoid transport costs. Because of the interference of buildings, mean velocities are low and turbulent levels are high in urban, aerodynamic concentrators are formed. This paper attempts to analyse performances of the concentrators using CFD simulation software, discusses the three basic aerodynamic concentrators wind energy field.

(1) Considering the necessary modifications of the building to encourage good flow properties for the wind turbine to place the turbines on top of or alongside a building is an attractive option. In this case no modifications of the building are needed and the aerodynamic efficiency is very high. According to the result of the CFD calculation, for the yaw angle $\varphi = 45^\circ$, a quantitative height of 2~3m or $\Delta h/h = 0.1 \sim 0.2$ above the roof is enough to avoid the high turbulence and low velocities within the separation bubble. The turbines at the windward edge of the roof and the corners can utilize wind energy more effectively than at the center position.

(2) The flat plate concentrator type is promising, the aerodynamic efficiency is also very high, but the building will generally need several adaptations. In this paper, for the flat plate building, wind energy in the duct of the building can be used effectively up to the yaw angle 30~40.

(3) The diffuser shaped buildings can also effectively use the wind energy in the built environment. Towers with "Kidney" footprints produce the best wind enhancement. The wind energy in the duct of the building can be used effectively up to the yaw angle 50~60.

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