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Improving the performance of wind turbines in urban environment by integrating the action of a diffuser with the aerodynamics of the rooftops

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Abstract

We investigated the effectiveness of combining the concentration effects generated by a dual-pitched roof and a diffuser-shaped wall mounted over a Darrieus turbine, which is rooftop mounted with horizontal shaft running close to the roof ridge. A2D CFD study was carried out in three steps: (1) we predicted the turbine basic performance with and without a convergent-divergent diffuser in a infinite and undisturbed domain; (2) the behavior of the concentration system on the rooftop were simulated in a simplified urban contest; (3) we improved both the operating conditions and the domain geometry to make them more similar to realistic urban environments. The simulations are performed by means a fully URANS since both the turbine aerodynamic forces and the urban wind field are simulated. Results show that by integrating the actions of rooftop and diffuser a significant power increasing is obtained in skewed winds. Moreover, the diffuser allows a drastic abatement of torque fluctuations.

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*Keywords:*wind turbine; urban environment; rooftop; diffuser;augmentation; skewed wind.

1. Introduction

The feasibility of harnessing the wind source in urban environment has been widely investigated and is one of the most attractive topic for researchers. Mertens [1] exposed the problems deriving from low average wind speed, high turbulence, low tip speed ratio (imposed by noise limits) and dimensional constraints (due to visual integration). Moreover, economic analysis [2, 3] of traditional wind energy conversion systems in urban environment, showed that the investment pay-back time is often greater than

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the machines' life. From this, the importance of enhancing power conversion, in particular by placing turbines in the high-wind zone generated by buildings concentration effects, usually close to the rooftop [4-7]. So the building aerodynamics (governed by height, roof shape and sloping) can play an important role in determine the real power production. Vertical axis wind turbines (VAWT), in respect to horizontal axis wind turbines (HAWT), because of their low turbulence sensitivity, small dimensions, absence of any yaw control, low noise can be considered the most suitable technology for urban wind exploitation [8-10]. Furthermore, experimental studies [11, 12] highlighted significant performance improvement of H-Darrieus turbines in skewed winds, that are typical of built environments.

The adoption of a diffuser could theoretically be greatly effective. However, the installation of diffuser augmented HAWTs for urban micro generation, could lead to technical (active yaw control need, high weight [8]) and safety issues. On the other hand, omni-directional guide vanes with augmentation effects are an attractive alternative for VAWTs and some prototypes have been designed: drag based VAWTs such as Zephyr [13] or PAGV (power augmentation guide vane) Sistan Turbine [14] or the ODGV (omni directional guide vanes) Darrieus [15]. A visual integrated turbine for urban environments is Crossflex [16], a flexible blades troposkine VAWT that can be sited on ridges and corners of buildings with advantages in terms of structural solidity, modularity, flow concentration induced by a cowling design.

For tidal applications, considering the one-directional flow and absence of visual impact's concerns, several ducted type diffusers for vertical axis turbines(VATT) have been investigated. Ponta and Dutt [17] performed experiments to evaluate the advantages of a convergent-divergent channel coupled to a H-type VATT. The diffuser allowed flow acceleration and regularization, which could lead to higher power production, turbine's downsizing, higher rotational speed and to self-regulating behavior. The CFD study of Malipeddi and Chatterjee [18] (that inspired our diffuser geometry) showed that a VATT placed inside of a convergent-divergent diffuser can produce higher power and a significant torque ripple reduction.

The present work concerns a 2D CFD study of the performance of a H-Darrieus VAWT, which is mounted on a dual-pitched roof with the shaft close and parallel to the ridge. The feasibility of accumulate the concentration effects of both the sloped roof and a half convergent-divergent diffuser mounted over the turbine is investigated. Differently from the past and current literature, in which disk actuator or Blade Element Momentum theories are used to predict the turbine behavior [19, 6], we adopt a novel and challenging methodological approach, since both the turbine aerodynamic forces and the wind behavior trough the buildings of a realistic urban environment are calculated by solving URANS equations.

Nomenclature

ρ	[kg/m^3]	air density
Ω	[rad/s]	wind turbine angular velocity
C_P		power coefficient, $C_P = \dfrac{P}{\frac{1}{2}\rho U_\infty^3 2Rh}$
h	[m]	length of the turbine blades
P	[W]	power
R	[m]	turbine radius
TSR		tip speed ratio, $TSR = \dfrac{\Omega R}{U_\infty}$
U_∞	[m/s]	free stream wind speed at a reference height (in the inlet boundary to the domain)

2. Validation of the model

The validation of the computational model is performed for the 1.2 kW Windspire [20], a commercial 3 blade H-Darrieus VAWT. We have chosen this turbine for three reasons: (a) the availability of experimental data in open field, that avoid the need to correct wind tunnel data to take into account blockage effects; (b) a large aspect ratio (blade length/diameter is 5) that entails a moderate influence of 3D aerodynamics (as blade tip losses), allowing 2D results to fit the experimental data; (c) the solidity is similar to that of our turbine, and typical of medium-solidity VAWTs used in urban areas. The CFD software is Ansys FLUENT v.15. All of the computational grids are composed of two grid levels: a fixed sub-grid with the external dimensions of the flow domain, and a dynamic sub-grid that includes the VAWT geometry and allows a relative motion with respect to the fixed grid. The study is based on URANS (Unsteady Reynolds Averaged Navier-Stokes) implicit model. We adopted the k-ω SST turbulence model because of its aptitude in cases involving high adverse pressure gradients and therefore smooth surface separations [21]; the model has proved to be particularly efficient for VAWTs due to its ability to simulate in more detail the vortices that are seen during dynamic stall at low TSR than the k–ω and k–ε models [22]. Grids are hybrid structured-unstructured (unstructured grids with the adding of regular quad element layers all around the walls to better predict the boundary layer phenomena). Wall distance from the first layer of cells is set to keep $y^+ < 5$ for all the simulation conditions.

Load is controlled by passive stall: for wind speed ≤ 10.6 m/s (rated speed) TSR is kept to 2.3, for higher wind speeds the turbine speed is kept constant. Fig. 1 shows a comparison between calculated and experimental power and C_P versus wind speed measured at the hub height. Except for very low wind speeds (that imply really low *Re*) and very high wind speeds (that involve stall), the numerical results overcome the measured data for less than 20%, that is reasonable considering that the power measured is the electrical one and the CFD model doesn't include tip losses and the interferences of shaft and struts.

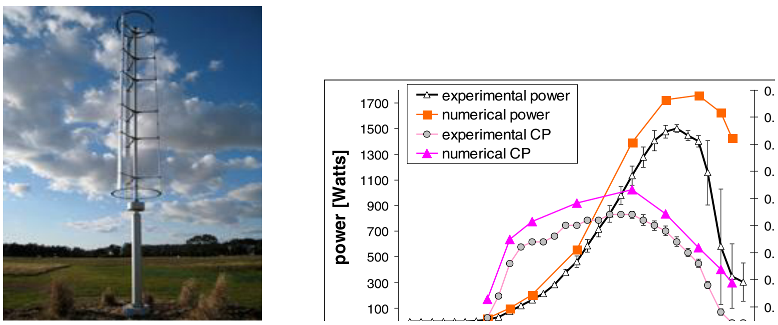


Fig. 1. (*left*) Windspire 1.2kW VAWT; (*right*) comparison between experimental performance [1] and predictions obtained for the Windspire turbine with ANSYS Fluent CFD software.

3. Basic performance of the turbine inside the diffuser

The turbine we adopted has the same airfoil and diameter (NACA0015;D=2.436m) of Crossflex [16], but solidity is higher and the three blades are straight. As a first step of the study the basic operations of the turbine with and without a convergent-divergent diffuser have been predicted in an infinite and undisturbed domain with uniform wind speed at the boundary inlet. The diffuser has the characteristic ratios (inlet area/throat area; convergent length/D; divergent length/D) found by Malipeddi and Chatterjee [18]; the throat length is T=D+2e, where e=0.067D, as suggested by Coşoiu et al. [23]. Fig. 2 (*a* and *b*) shows how the streamlines are modified by the action of the diffuser; in particular it should be noticed that the convergent walls prevents the flow diverges towards the outside of the rotor while there is approaching, realigning the flow before it passes through the blades or even - at the beginning and at the end of upwind - making it to converge towards the center of rotation. The effects of the diffuser are also depicted in Fig. 2 (*c* and *d*) for a wind speed of 7.5 m/s and a TSR of 2.75. Thanks to the diffuser the turbine processes a greater flow rate, as confirmed by the higher absolute flow velocity that occurs in the throat (including the downwind region). This is responsible for the higher torque generated by the blade during its downwind path (C_P graph of Fig. 3).However, in upwind two opposite actions can be observed: a torque increasing at both the ends of the path and a torque decreasing at the path midway. The later is due to the lower flow velocity entailed by the blockage of the turbine and by the large distance separating the blade from the throat. The former is due to the directional change of the rotor inflow already mentioned above, and explained in Fig. 3 for a blade azimuthal position of 40°. In particular, it can be seen that with the diffuser the flow approaches the blade with a larger angle of attack (angle between the flow apparent velocity and the blade chord) that causes a higher pressure difference between the suction and the pressure sides of the blade, and consequently a torque increasing.

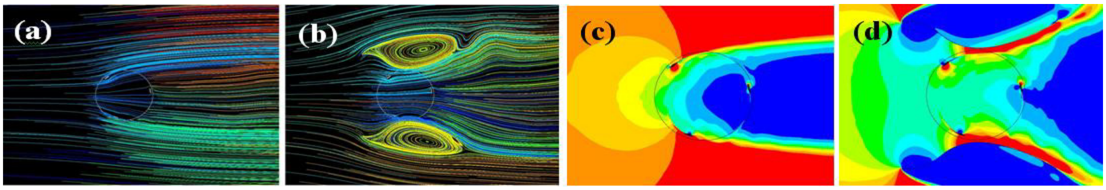


Fig. 2. streamlines in the turbine region in the case without diffuser (*a*) and in the case with diffuser (*b*); velocity field without diffuser (*c*) and with diffuser (*d*). Color scale: 2÷8 m/s.

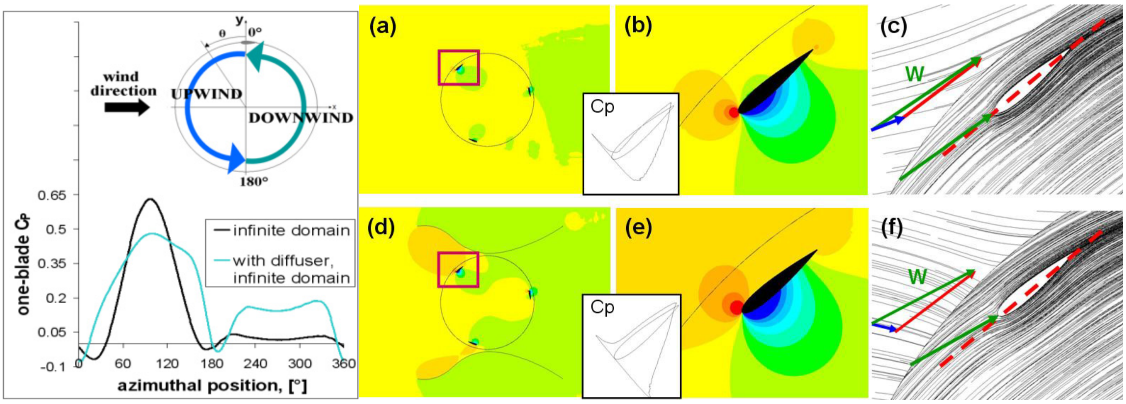


Fig. 3. (left) one-blade instantaneous C_P during one revolution calculated with and without diffuser at TSR=2.75; static pressure (a, b) and streamlines (c) for the blade at 40° without diffuser; static pressure (d, e) and streamlines (f) for the blade at 40° with diffuser. The streamlines on the rotating mesh are the relative ones, thus they indicates direction of air apparent velocity, W; red and blue arrows indicate blade velocity and air absolute velocity.In the white boxes: pressure coefficient diagrams.

4. Performance of the augmentation system

We simulated to mount the turbine and the diffuser-shaped wall (one half of the diffuser studied in the infinite domain) on a dual-pitched roof with a slope of 18°, that is the average slope of the Italian roofs. The aim is to verify if the resulting augmentation system has a better performance than the single concentration effect of the roof. The study has been performed in the two steps described in the following.

The simulations are initialized for steady conditions, then 75 revolutions are simulated: 50 with a large time-step corresponding to 2° azimuthal (in order to allow the development of a stable far wake), 25 revolutions with a finer time-step (0.5°). All grids are hybrid with resolutions that are chosen in agreement to the literature (~ 130.000 cells for the rotating mesh including the blades; 270.000 cells for the overall simplified domain; 450.000 cells for the overall realistic urban domain).

4.1. Simplified domain

In order to focus the analysis on the mutual interactions between roof and diffuser, avoiding any other effect or disturbance, an extremely simplified domain has been chosen, as depicted in Fig. 4. This domain is not representative of a realistic urban context since the inlet wind speed is supposed uniform (without a vertical gradient) and its direction is exclusively horizontal (i.e., any vertical components that may be induced by the building height or by others upstream buildings are neglected).

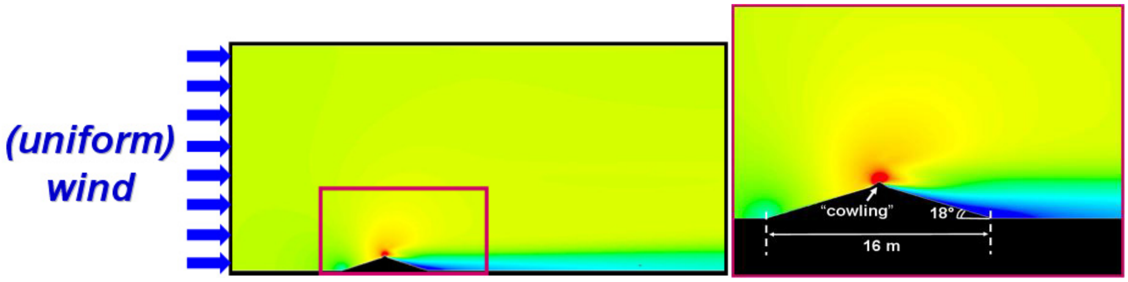


Fig. 4. dimensions of the simplified domain, and velocity field.

At the first we verified the usefulness of adopting a cowling similar to that conceived for Crossflex (actually the original one is a 3D device with structural, aesthetic and flow augmentation purposes). In our case a power increasing of 5.5% is achieved by means of the cowling, that seems intensify the concentration effect of roof and diffuser by addressing the flow towards the blade with a larger attack angle (see pressure maps and streamlines on Fig. 5 for a comparison). The graph reported in Fig. 5 resumes and compares the performance obtained for the basic operations of the turbine (in an infinite domain with and without diffuser) and for the turbine mounted on the roof (with and without the diffuser-shaped wall) versus TSR for a wind speed of 7.5 m/s.

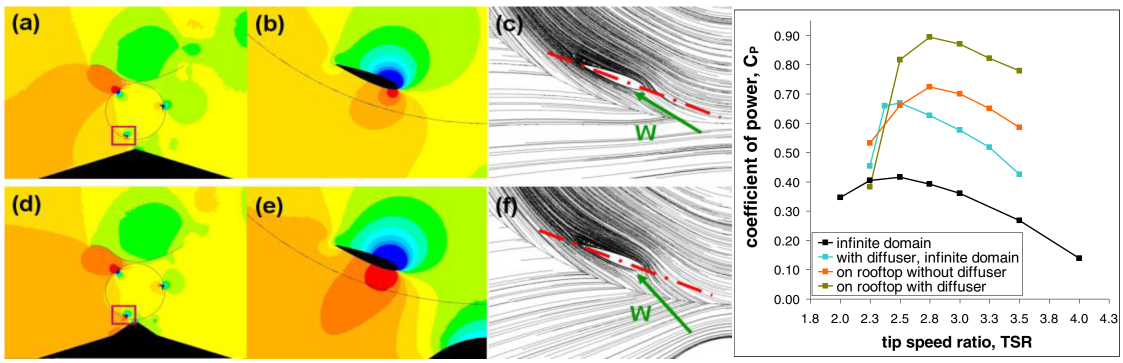


Fig. 5. static pressure and streamlines for the blade at 158° without cowling (a, b, c) and with cowling (d, e, f) for awind speed of 10.6 m/s; (right) C_P versus TSR predicted for a wind speed of 7.5 m/s

Ata wind speed of 10.6 m/s (that we consider the nominal wind speed for our turbine) the diffuser alone improves the power production of 60%, the roof alone improves of 65%, whereas the integration of roof and diffuser-shaped wall gives an overall gain of 103%. As expected, the optimal TSR increases (from 2.50 to 2.75) due to the higher flow rate processed by the turbine.

4.2. Realistic urban context

The performance of the augmentation system (dual-pitched roof plus diffuser-shaped wall) is therefore simulated in the realistic urban domain shown in Fig. 6. The building height, H, is 16.6m; the length and height of the overall domain are 377m and 263m, respectively. The exponential law of Hellman for the inlet wind velocity is used with a coefficient of 0.35 (typical of urban and suburban zones). As reference height we chose the height at the base of the roof where the turbine is mounted; the wind reference speed at the inlet boundary corresponding to the reference height is used to calculate the turbine C_P.

Since the building is significantly higher than the upstream buildings, the wind approaches the roof with a strong vertical speed component (skewed wind). Despite the advantage predicted with the simplified domain, we found that in this case the cowling leads to a power loss of 11.6%. Fig. 6 (on the right) shows that in skewed wind conditions the cowling generates excessive blockage, becoming an obstacle to the oncoming flow. For this reason we removed the cowling from the rooftop.

As resumed in Fig. 7, we found that the diffuser-shaped wall allows a power increasing of 44% for a reference wind speed of 6.0 m/s and of 50% for a reference wind speed of 10.6 m/s; to achieve the same gain without diffuser the turbine should be raised of at least 1 m (to meet higher wind speeds above the rooftop). Another important advantage given by the diffuser is a drastic reduction of torque fluctuations.

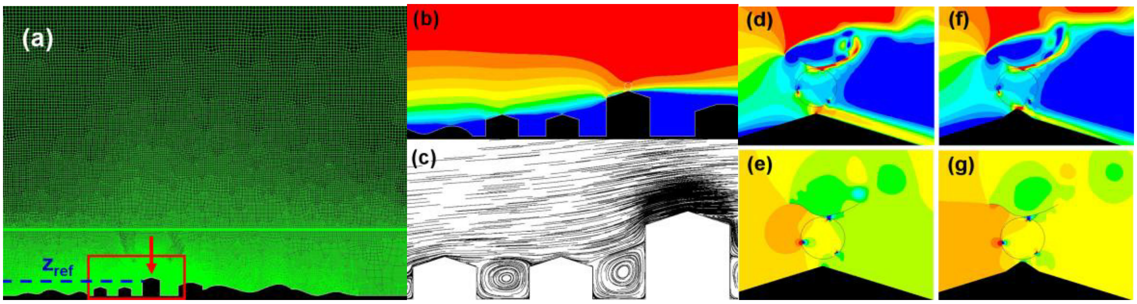
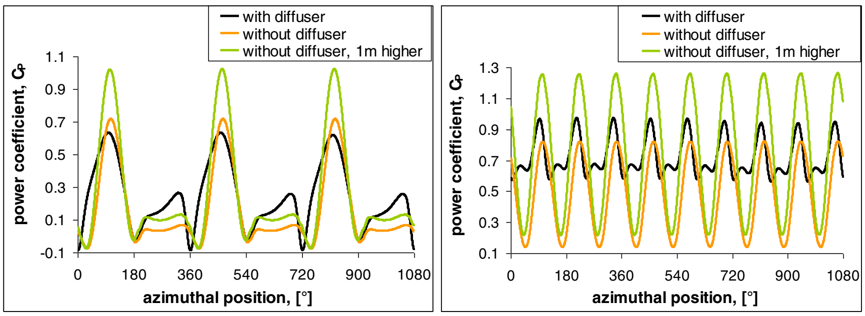


Fig. 6. (a) grid for the realistic urban context, arrow indicates the roof where the turbine is mounted; (b) velocity field [1÷12 m/s] and (c) streamlines, predicted without the turbine operation (steady flow conditions); (d, e) velocity and static pressure without cowling; (f, g) velocity and static pressure with cowling.



C_P at different ref. wind speeds

Reference wind speed	6.0 m/s	10.6 m/s
turbine on rooftop with diffuser	0.78	0.72
turbine on rooftop without diffuser	0.54	0.48
turbine on rooftop without diffuser, 1m higher	0.74	0.75

Fig. 7. instantaneous C_P during last 3 revolutions for one blade (left) and for the turbine (top), wind speed 10.5 m/s; (right) C_P.

5. Conclusions

We performed a 2D CFD study to verify if a convergent-divergent wall arranged over a VAWT turbine placed closely parallel to the ridge of a dual-pitched roof can be useful to improve the wind concentration effect of the building. Our principal finding are summarised below.

The combination of a dual-pitched roof and a diffuser-shaped wall allows to obtain a power increasing of 40% ÷50% with respect to the only action of the roof. To obtain the same gain without the diffuser the turbine would need to be placed higher above the rooftop in order to meet higher air velocity, with a consequent worsening of visual impact and safety. Another advantage due to the diffuser is a great mitigation of the torque ripple that implies lower fatigue loads and lower vibrations. However, the horizontal positioning of the turbine deletes an important advantage of VAWTs: the omnidirectional wind harnessing. Thus the actual yearlypower production is related to the wind direction distribution in the particular location: significant energy gain can be obtained only if a prevailing wind occurs, and in this case the installation building need to be chosen to ensure the ridge perpendicularto the prevailing wind.

The paper demonstrates the potential of a fully URANS approach to predict the effectiveness of this type of solutions, providing an insight in the physical phenomena that helps to explain the performance improving. So, by analysing static pressure field and streamlines features around the blades two causes for the torque gainare recognised: in upwind the diffuser acts guiding the flow to an optimum angle before it interacts with the rotor blades; in downwind the diffuser increases the flow absolute velocity.

As regards the methodological approach, we found that it is wrong to consider a computational domain oversimplified or neglect vertical components of the wind speed since some geometric details of the augmentation system that can provide satisfactory results in simplified conditions may instead lead to a significant power decreasing in realistic contexts. Therefore, after the analysis of the performance of the turbine inside a diffuser in an infinite domain, it would seem more effective to investigate directly the system behaviour for two or three urban scenarios representative of realistic situations and criticism.

6. Copyright

Acknowledgments

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Biography

Stefania Zanforlin has experience in CFD tools applied to internal combustion flows (reciprocating engines) and external flows (wind turbines). Her recent activity on wind turbineshas regarded: assessment of micro-generation potential in urban environments, performance prediction of offshore turbines on floating platforms, investigation of aerodynamic interactions between vertical axis turbines.