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INCREASING PERFORMANCE OF VERTICAL AXIS WIND TURBINES

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Abstract: *The research presented in this work addresses the performance of Vertical Axis Wind Turbines (VAWT). The aerodynamic performance of the turbine is measured by the power coefficient (Cp) which is calculated by simulating the flow around the entire turbine with Computational Fluid Dynamics (CFD). The analysis is focused on evaluating the effect on the performance of the turbine for three different cases. In the first case, flows with different turbulence intensities are simulated. The turbulence intensity is increased from almost zero to 40% which leads to an increase of the Cp of about 27% for small turbines. In the second case, we change the camber of the blade during a quarter of the rotation of the VAWT. The proposed morphing methodology increases the Cp by 46%. In the third case, the placement of a small turbine on the frontal windward corner for three different building heights is studied. The Cp is increased by 80% on the highest building compared to the baseline case of the turbine in an unperturbed flow.*

Keywords: *Vertical Axis Wind Turbine, Computational Fluid Dynamics, Power Coefficient, Turbulence Intensity, Morphing Blade, Roof-mounted Turbines*

1. Introduction

VAWTs extract power as the airfoil blade generates a torque due to the lift force while rotating. For Darrieus or H-Type VAWT the axis of rotation is perpendicular to the flow direction, which leads to complex aerodynamics because the angle of attack of the blade is continuously changing. In this paper, mainly micro-scale VAWTs defined as an installed power of less than 2.5 kW [1] are investigated but we also examine a large 500 kW turbine.

Micro-scale turbines are mainly interesting for urban applications. Wind flow over a single building offers some locations where the wind accelerates considerably and therefore provides a greater potential for energy extraction by a wind turbine. Nevertheless, in dense urban locations, the wind is both slower and more turbulent. The complexity of this wind flow is due to the presence of the buildings themselves and their various effects on the wind flow's aerodynamic behavior. In this paper, the turbulence intensity of the flow is analyzed as it has been shown that it is able to increase the performance of the turbine. Experimental results reported in [2] show that the power coefficient can increase by 20% when the turbulence intensity is increased to 14.8%. A larger turbine is also analyzed and compared with field studies available in [3].

CFD has emerged as the most common tool to conduct design and analysis of the aerodynamic performance of VAWT [4]. It is cost effective and accurate but is still computationally expensive and cannot be used for all analyses. This paper will first show that the effect of the turbulence intensity on the Cp is well captured. CFD is then used to model a morphing blade simulation. The blade shape has a dominant effect on the wind generated turbine torque. In section 3, a case study is presented when the blade changes its shape during the rotation cycle. Finally, the location of a micro-scale turbine on the roof of a building is also studied. It is clear that the building has an enormous influence on the flow speed which requires dedicated analysis. Very accurate but computation expensive LES simulations were performed in [5] to examine the flow on the roof on cuboid buildings of different sizes and different wind directions. Though, the frontal windward corner was not recommended for placement of wind turbines while the other two windward corners showed significantly higher velocities, in this work we only investigate the frontal windward corner.

This paper is organized as follows. Section 2 discusses the effect of turbulence intensity on the Cp value for a small and a large turbine. Section 3 presents the results of a test case of a morphing blade and section 4 reports on the effect of the building height on the performance of a small turbine placed on the corner of the building.

2. Effect of turbulence intensity

Turbulence intensity (Iu) is a measure of the wind turbulence. It is defined as the standard deviation of wind speed over the mean wind velocity. Turbulence intensity decreases with increasing wind speed but the wind in an urban environment will typically have values of turbulence intensity ranging from 20% to 30%. In this section, the effect of Iu on the performance of a VAWT is examined using CFD. Computational results based on a commercial CFD code (Star CCM+) using full URANS calculations of the turbine are performed. To demonstrate the accuracy of the approach wind tunnel results are reproduced numerically. A two-bladed H-type Darrieus turbine of diameter 0.5 m and swept area of 0.4 m^2 is simulated. The two NACA0018 blades rotate at angular speeds of 1200 rpm. The free stream wind speed is 10 m/s. The details of the computational methodology are reported in [6]. Numerical values of the power coefficient are compared with experimental measurements from [2] as shown in Figure 1.

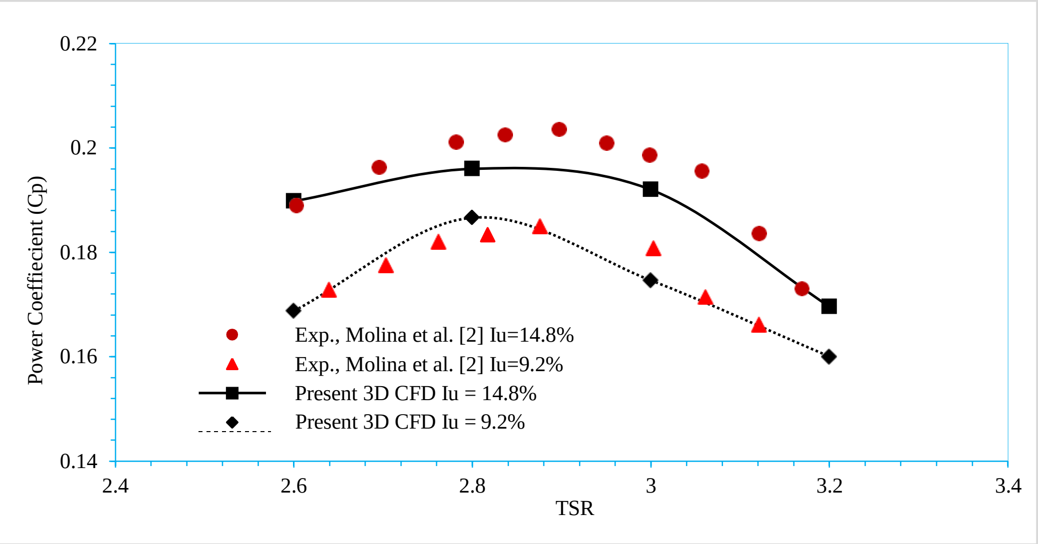

Fig. 1. Cp comparison between CFD results and experimental measurements of Molina et al. [2] for a small 0.5 m diameter turbine

The Figure 1 shows a good comparison for both values of the turbulent intensity of the flow. At Iu=9.2% the highest numerical Cp values of 0.187 is very close to the experimental value of 0.185. At Iu=14.8%, the numerical Cp values of 0.196 is a little less than the experimental value of 0.203, nevertheless the overall trend is well captured. Note that the higher turbulent intensity Iu=14.8% leads to an increase in Cp of 4.8%. We now perform the same simulation for different values of Iu ranging from 0.7% to 40%. Table 1 provides the numerical Cp values for each simulation at different Iu values. We can see a significant increase in the value of Cp from 0.175 at Iu=0.7% to Cp=0.222 at Iu=20%. This increase in Cp is about 27%, which is quite significant. However, the Cp does not increase for Iu values larger than 20% as shown in Table 1.

Table 1: The obtained Power coefficient against different intensity levels

Turbulence Intensity (%)	0.7	9.2	14.8	20	30	40
Power Coefficient (Cp)	0.175	0.177	0.192	0.222	0.229	0.230

We now investigate a larger turbine. The large turbine also has two NACA 0018 blades but the rotor diameter is 35 m. The swept area of this turbine is 850.5 m^2. Note that much of the literature is only addressing small turbines which are often less performant. Figure 2 reports the CFD results for the Fine Mesh (20 million elements) and Medium Mesh (15 million elements) as well as field measurements data. First, note that the Cp for this turbine reaches 0.33, which is higher than for smaller turbines. Note also the importance of the mesh size. The Medium Mesh is not able to capture the correct Cp at low Tip Speed Ratios (TSR). Therefore, the Fine Mesh is used to study the effect of the turbulence intensity on this large turbine. Figure 3 reports that the same Cp is obtained for three different turbulent intensity ranging from Iu = 1%, 15% and 30%. This work does show that small turbines can benefit from an increase in turbulence intensity but not large turbines. Indeed, the Cp can increase by as much as 20% but large turbines do not see any effect of the turbulence intensity.

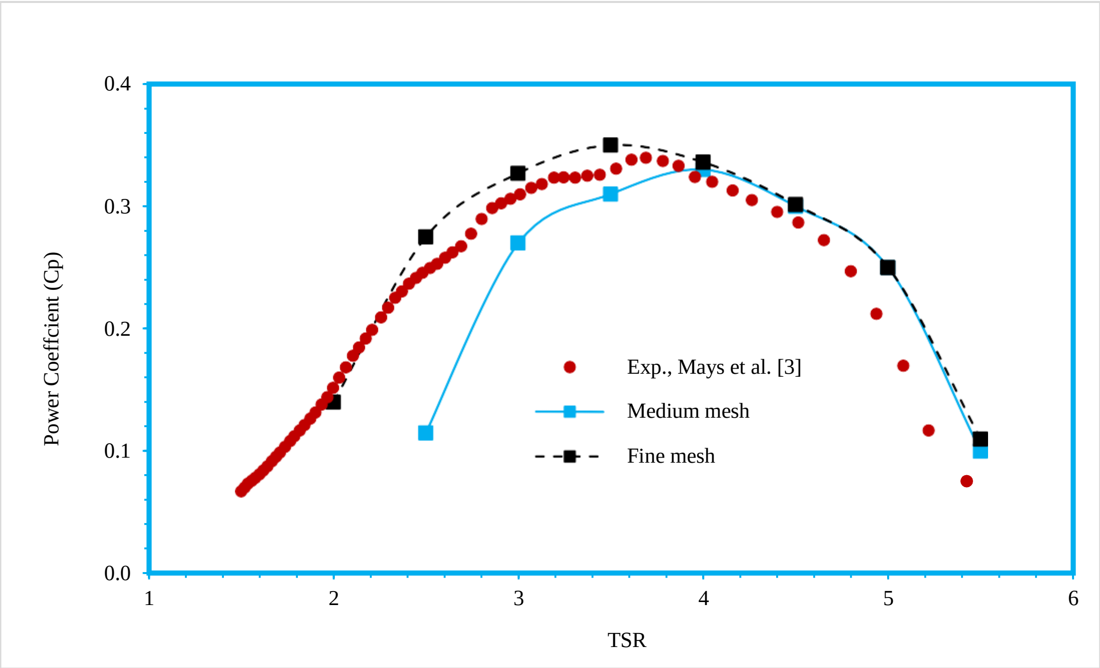

Fig. 2. Cp comparison between CFD and experimental data [3] for a large turbine 35 m diameter turbine

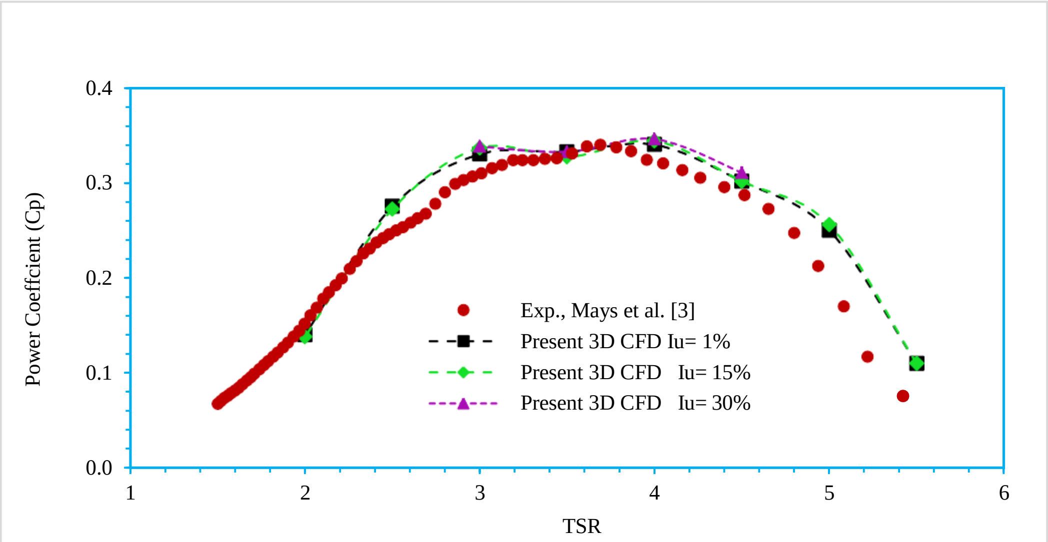

Fig. 3. Effect of the turbulence intensity on the Cp of a large turbine

3. Effect of blade morphing

The blade of a VAWT has a significant effect on the performance of the turbine. As the turbine rotates the angle of attach of each blade changes. If this angle reaches a large value, dynamic stall of the blade can occur which creates a large change of the forces on the blade. One interesting techniques to control the dynamic stall situation is to change the blade geometry by changing its camber. The overall benefit is that the performance of the turbine is improved. Robust and well controlled morphing airfoils have been designed. In particular, Pankonien et al. [7] have designed an airfoil mechanism that controls the trailing edge as shown in Figure 4. The baseline shape is a NACA 0012 airfoil. The inward shape is the trailing edge flexed with a deflection of 13.4 degrees.

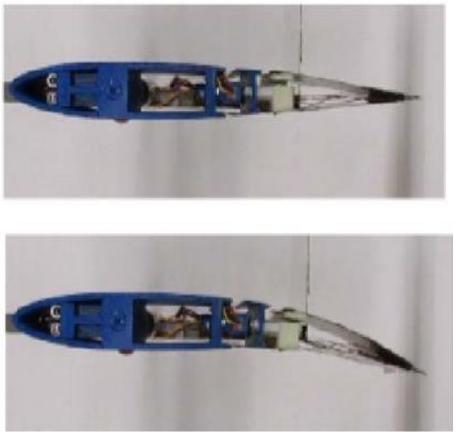

Fig. 4. The Synergetic Smart Morphing Aileron (SSMA) designed by Pankonien et al [7]; top) baseline shape, bottom) inward shape

A numerical simulation of a turbine with a single blade is performed to calculate the Power Coefficient. Details of the simulation are reported in [8]. The blade rotates at 90 RPM at TSR 3.17. The turbine has a rotor diameter of 5.395 m and the wind speed velocity is 8 m/s. A two dimensional simulation with a mesh of 416 000 elements with a time step of 2.222E-4 s equivalent to 3000 time steps per rotation is performed. The Cp for this baseline case is reported in Figure 5 as the solid line. The average Cp after 15 cycles is 0.096. When the blade is in the first quadrant, the Cp increase and as it reaches the 80 degrees azimuthal angle it start falling. In the second quadrant, which in Figure 5 is identified as a blue dash lined box, the Cp is negative and undergoes many fluctuations as vortices are shed over the blade. In quadrant 3 and 4, the Cp is smooth with maximum values around 270 degrees. For this specific case, it is suggested to morph the blade to control the complex flow which may be due to dynamics stall that occurs in the second quadrant. Therefore, a simple morphing strategy is investigated such as to only morph the blade very rapidly at the start of the second quadrant and keep its inward shape until the azimuthal angle of 180 degree, which is the end of the quadrant. The resulting Cp which is reported as the dashed line in Figure 5 shows two spikes, one upward at 90 degrees and one downward at 180 degrees. The spikes are related to the morphing motion. The first is when the blade changes from the baseline to the inward shape and the second is when the shape is changed back to the baseline position. Once the inward shape is fixed during the second quadrant, we can see from the Cp curve that only small vortices are shed. The Cp is only slightly negative. The performance of the turbine in this quadrant is significantly improved. The average Cp for the entire cycle is also increase to 0.14 due to this approach. This represents a 46% increase, which demonstrated the high benefit of a morphing approach. Table 2 reports the average CP for both cases.

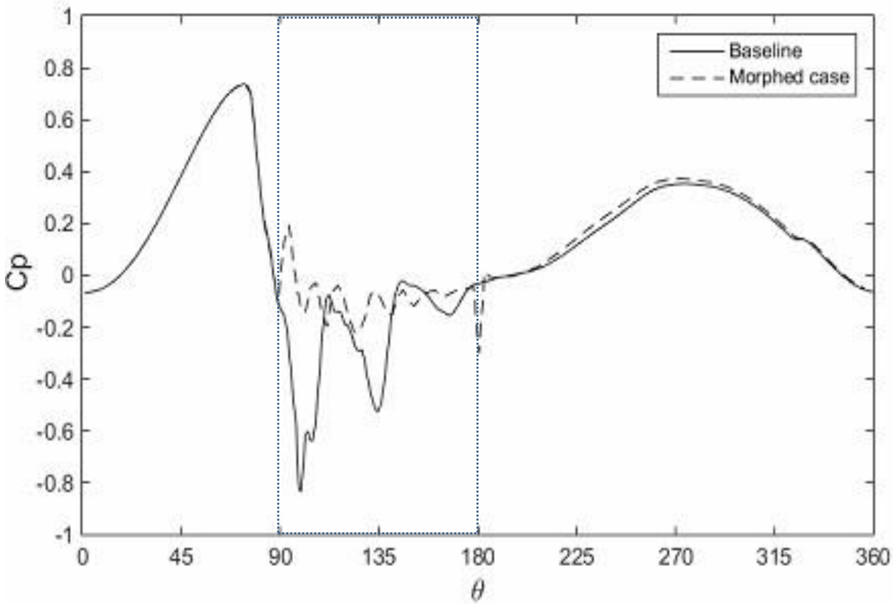

Fig. 5. Power Coefficient versus azimuthal angle for a turbine with the baseline blade and the morphing blade

Table 2: Average Cp values for baseline and morphed cases

Case	Cp
Baseline	0.096
Morphed case	0.140

4. Effect of building size

The study in section 2 indicates that small turbines, which are interesting for urban applications, would benefit from the high turbulence intensity in urban areas. But the best location to place a vertical axis wind turbine on a single building is not yet fully identified. It is well known that the wind flow over a single building offers some locations where the wind accelerates considerably, providing a greater potential for energy extraction by a wind turbine. Nevertheless, Drew et al. [9] reported that 38 building-mounted wind turbines in the UK performed below expectations during field tests. The study found that the wind speed data used for assessing these small wind turbines' performance was obtained from low-resolution wind speed databases that do not accurately reflect the local changes in wind resources. Thus, it is clear that a need to understand the different effects of wind flows disturbed by buildings on roof-mounted wind turbines' performance is required to have the turbines perform adequately. Herein, CFD analysis is performed on a roof-mounted VAWT.

It was shown that placement of a VAWT on the side of a building can led to a 120% increase of the Power Coefficient compared with the reference value [10]. Numerical and experimental analysis in [11] also show that the performance of a Savonius turbine placed above a small 5 m high structure increases the performance by 60%. Furthermore, investigating the placement on a 30 m cubic building, a new design, based on drag type blades with 120-degree arcs, led to a Cp of 0.25, which was significantly better than the original Savonius turbine but remained quite modest [12]. On the same building configuration, the placement of a Darrieus turbine in the middle of the roof edge facing the wind gave a max Cp of 0.40 [13]. By varying the placement of this turbine on the same building for different wind direction, the best result was a Cp of 0.54 [14]. In this section, we investigate an H-type Darrieus placed on the frontal windward corner, the corner facing the wind as shown in Figure 6.

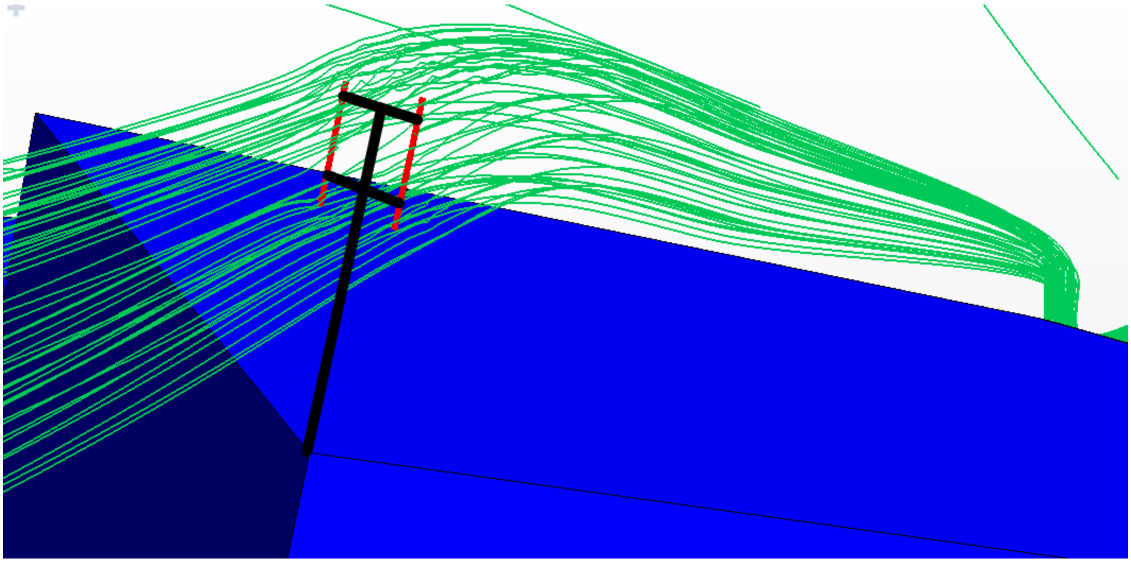

Fig. 6. Placement of a small VAWT on the corner of the building when the wind is facing this corner

It is clear that the building has an enormous influence on the flow speed, which requires dedicated analysis. The size of the building also has a significant effect on the performance of the turbine. We perform CFD simulations using STAR CCM+ to understand the effect of the building size. To do so, a two-bladed H-type VAWT is used with the turbine's diameter (D) and height (H) of 1 m, which provides an aspect ratio (H/D) of 1. The NACA 0018 airfoil section is used for the blades with the chord size (c) of 0.06 meters. This geometry gives the turbine's solidity (σ=nc/D, where n is the number of blades) equal to 0.12. Simulations have been done for three different building heights: 100 ft (30.48 m), 200 ft (60.96 m), and 300 ft (91.44 m). To eliminate the reverse flow effect, the computational domain has the building placed at a 5H distance from the inlet, 10H from the outlet, 5H from the sides, and 10H at the top, where H is the height of the building. The velocity inlet and pressure outlet boundary conditions have been used for the inlet and outlet faces of the domain, respectively. The wall boundary condition is used for the ground and surfaces of the building, and the symmetry boundary condition is used for the other boundaries. In this study, the turbine is placed on the roof-top corner of the building. The distance between the roof and the bottom of the turbine is 1.8 meters. To change the value of the Tip Speed Ratio ($TSR=R\omega/U_\infty$, where R is the turbine radius and ω is the angular velocity of the turbine) in this study, the angular velocity is changed.
Since the wind turbine operates in the atmospheric boundary layer, a velocity profile is defined for the inlet boundary to account for this effect. In this profile, the wind velocity is a function of the height of the building, defined as follows:

$$V_Z=V_{mid}(Z/H_t)^{0.31} \tag{1}$$

In this equation, V_{mid} is referred to the wind velocity at the middle plane of the turbine, Z is the height from the ground, and H_t is the height from the ground to the center plane of the turbine. The inlet velocity profile describing the atmospheric boundary layer is depicted in Figure 7—this velocity profile is used firstly for the building height of 100 ft. Therefore, the V_{mid} was considered as 9.3 m/s. Moreover, the same velocity profile is used for the taller buildings, i.e., 200 ft and 300 ft.

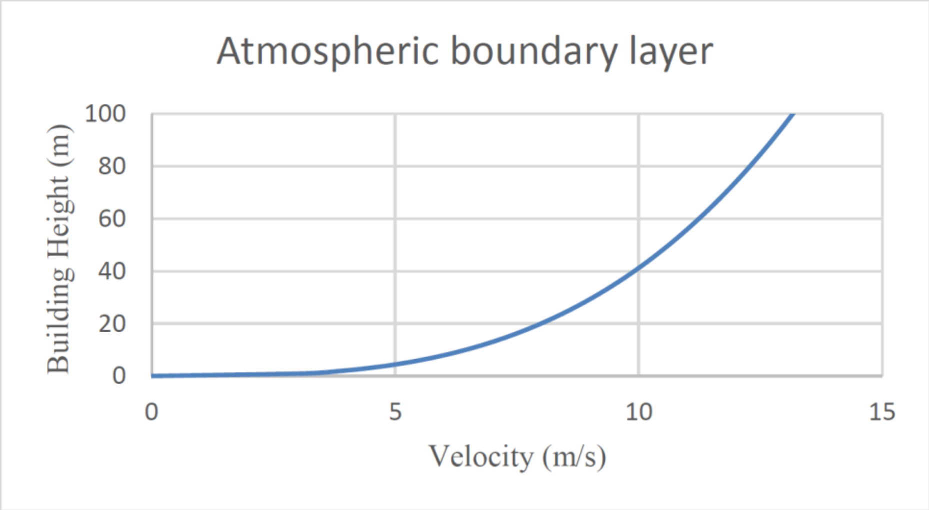

Fig. 7. Velocity profile showing the atmospheric boundary layer

To solve the equations of motion and capture all flow field features, a commercial CFD solver named STAR CCM+ is used. The SIMPLE algorithm (Semi-Implicit Method for Pressure Linked Equations) is utilized to couple the pressure-velocity equations. For the convection term, a second-order upwind scheme is used. In this study, a time step that is equal to 0.48° rotation of the blade per time step was used. Simulations continued until the moment coefficient, and the power coefficient became stable. The stability here is defined as less than 1% changes in the power coefficient in two consecutive rotations of the VAWT.
Figure 8 shows the moment coefficient (C_M) for the building height of 100 ft at a TSR of 5, where the max power is attained. This Figure depicts 16 rotations of the VAWT, where it has been stable at the 10th rotation. Moreover, Figure 9 compares the C_M of the turbine for different building heights at the TSR values that the maximum power is obtained. For comparison, one rotation of each turbine is shown at the rotation number when the results have been their stable state. This figure shows the 15th rotation of the VAWT for the 100ft building height. However, since the velocity is increased for higher buildings and the time step is decreased for them due to the higher rotational velocity in which the maximum power occurs, the 15th rotation does not have the same time for taller buildings. This graph shows that the highest value of the moment coefficient is higher for taller buildings.

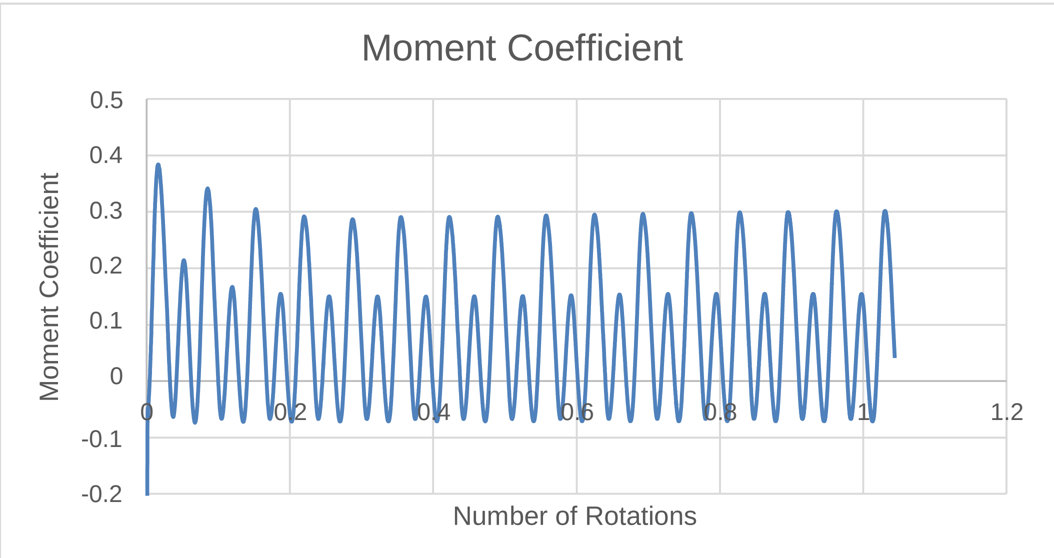

Fig. 8. Moment coefficient for the 100 ft height building at the TSR of 5 in which the maximum power for this building is obtained

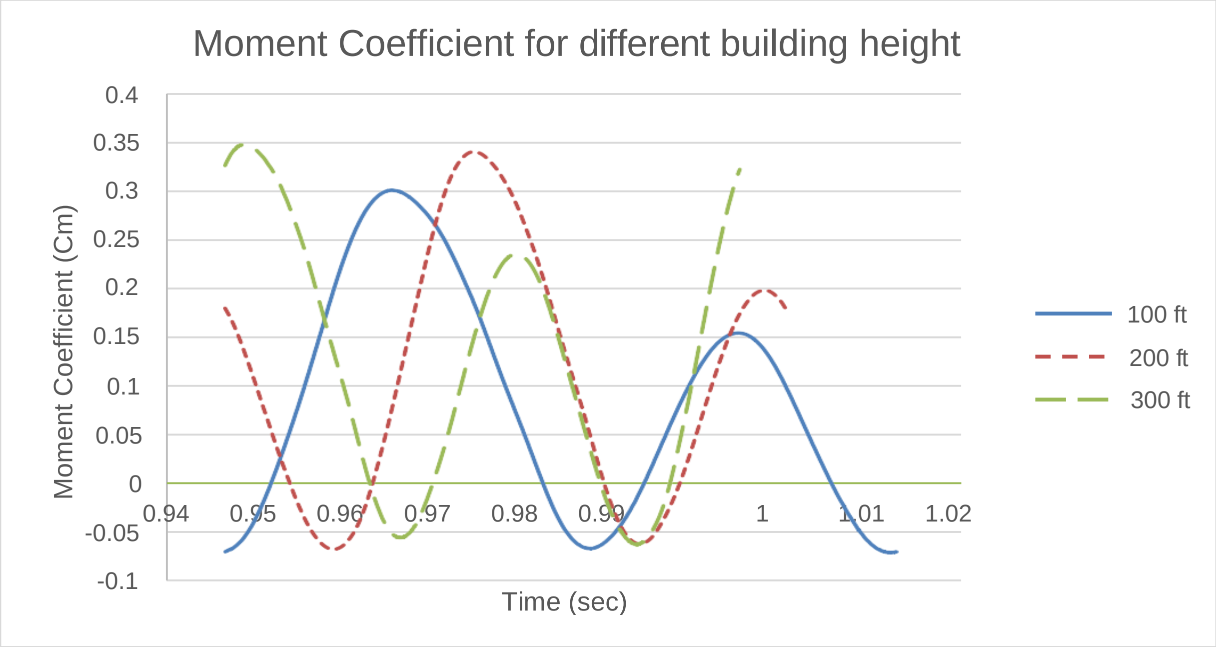

Fig. 9. Comparison of the instantaneous moment coefficient for different building heights at the TSR values for which the maximum power is generated

Figure 10 shows the power coefficient for different building heights at varying values of TSR. It shows that the maximum Cp is increased for taller buildings, while the maximum Cp occurs at lower TSR values for taller buildings. It is important to mention that since the velocity is increased for taller buildings, the values of TSR are decreased. However, the maximum Cp is obtained at higher rotational velocities for taller buildings. The Cp is increased from 0.426 for the turbine on placed on the building of height 100 ft to 0.578 for the turbine installed on the building of height 300 ft. This increase is significant and improves the performance of the turbine by 36%.
Table 3 shows the maximum power values for different building heights. The following equation is used to calculate power.

$$P_{Turbine} = C_P \, 0.5 \rho A_S U_\infty^3 \tag{2}$$

where ρ is the air density, U_∞ is the free stream velocity, and A_S is the swept area equal to the turbine diameter multiplied by the blade span. Since the power is proportional to the velocity cubed, taller buildings can generate more power due to the higher velocity on the roof-top and higher Cp values. This table shows that the maximum power for the 200 ft building is increased by 134% in comparison to the 100 ft building height results. On the other hand, the maximum power for the 300 ft building is increased by 260% and 54% in comparison to the 100 ft and 200 ft building height results, respectively. The increment rate of power from 100 ft to the 200 ft building height is 282 W, which is almost the same as the 266 W from 200 ft to 300 ft building height. It shows that although the building height increased equally, the power increment just slightly decreases.

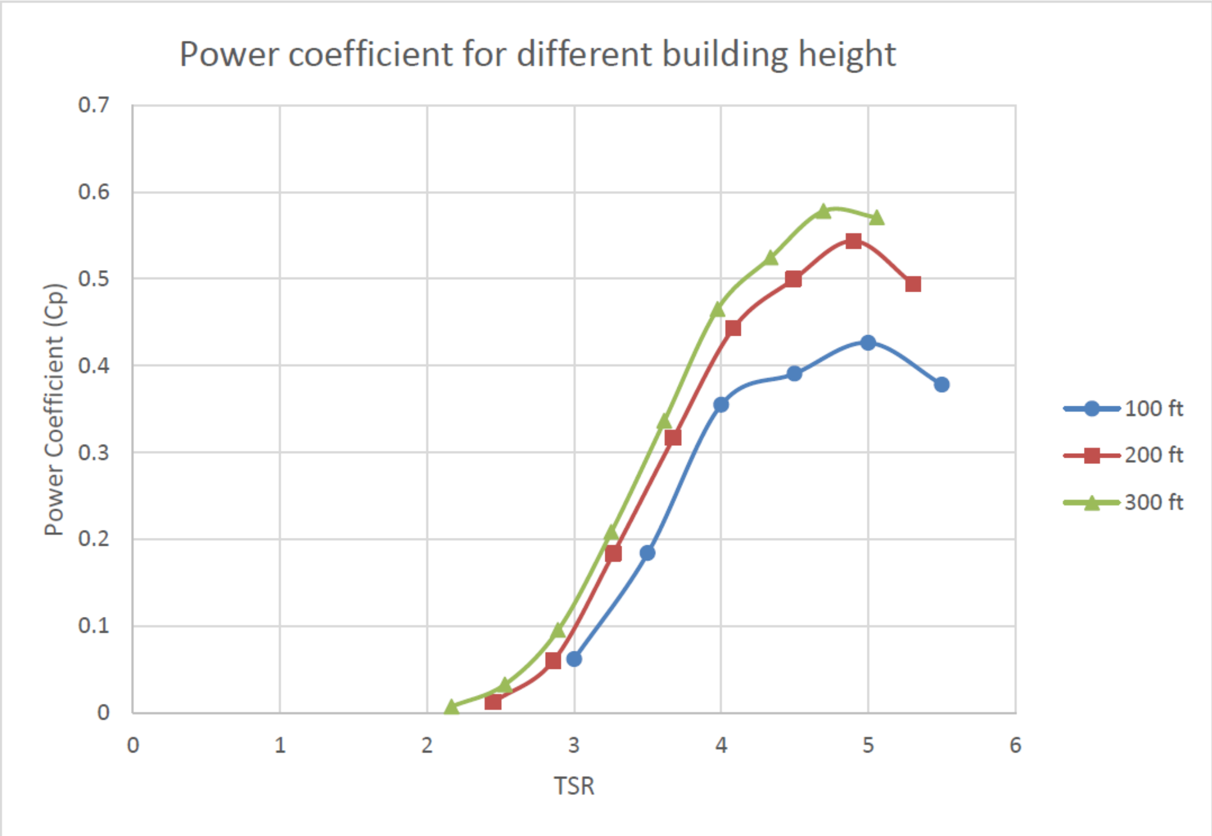

Fig. 10. Power coefficient (C_P) for different building heights to varying values of TSR

Table 3: Maximum power generated for different building heights

Building Height (ft)	TSR value for maximum power	Maximum Power (W)
100	5	210
200	4.89	492
300	4.69	758

5. Conclusions

This paper presents CFD investigations related to unsteady simulations of vertical axis wind turbines. The analysis is focused on evaluating the effect on the performance of the turbine for three different cases. In the first case, we show that the turbulence intensity can increase the Cp about 27% for small turbines. In the second case, we illustrate that a morphing blade can increase the Cp by 46%. In the third case, we show that when placing of a small turbine on the frontal windward corner the Cp of that turbine is increased by 80% compared to the baseline case without a building. These studies show that the Cp can reach high values and can lead to very performant VAWTs, in particular for urban installation.

Acknowledgments

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References

[1] Peacock, Andrew, D. Jenkins, M. Ahadzi, A. Berry, and S. Turan. "Micro wind turbines in the UK domestic sector." *Energy and Buildings* 40, no. 7 (2008): 1324-1333.

[2] Carbo Molina, Andreu, Tim De Troyer, Tommaso Massai, Antoine Vergaerde, Mark Runacres, and Gianni Bartoli. "Effect of turbulence on the performance of VAWTs: An experimental study in two different wind tunnels." *Journal of Wind Engineering and Industrial Aerodynamics* 193 (2019): 103969.

[3] Mays, I. D., C. A. Morgan, M. B. Anderson, and S. J. R. Powles. "Experience with the VAWT 850 demonstration project." *Proceedings of European Community Wind Energy Conference* (1990): 482 – 487.

[4] Barnes, Andrew, Daniel Marshall-Cross, and Ben Richard Hughes. "Towards a standard approach for future Vertical Axis Wind Turbine aerodynamics research and development." *Renew Sustain Energy Rev* 148 (2021): 111221.

[5] Kono, Takaaki, Tetsuya Kogaki, and Takahiro Kiwata. "Numerical Investigation of Wind Conditions for Roof- Mounted Wind Turbines: Effects of Wind Direction and Horizontal Aspect Ratio of a High-Rise Cuboid Building." *Energies* 9, no. 11 (2016): 907.

[6] Belabes, Belkacem, and Marius Paraschivoiu. "Numerical study of the effect of turbulence intensity on VAWT performance." *Energy* 233 (2021): 121139.

[7] Pankonien, Alexander M., Cassio T. Faria, and Daniel J. Inman. “Synergistic smart morphing aileron.” Paper presented at the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, Massachusetts, April 8-11, 2013.

[8] Minetto, Robert Alexis Leonczuk, and Marius Paraschivoiu. “Simulation based analysis of morphing blades applied to a vertical axis wind turbine.” *Energy* 202 (2020): 117705.

[9] Drew, Daniel R., Janet F. Barlow, Tim T. Cockerill, and Maria M. Vahdati. "The importance of accurate wind resource assessment for evaluating the economic viability of small wind turbines." *Renewable Energy* 77 (2015): 493-500.

[10] Xu, Wenhao, Gaohua Li, Xiaobo Zheng, Ye Li, Shoutu Li, Chen Zhang, and Fuxin Wang. "High-resolution numerical simulation of the performance of vertical axis wind turbines in urban area: Part I, wind turbines on the side of single building." *Renewable Energy* 177 (2021): 461-474.

[11] Liu, Xiran, Dan Zhao, and Nay Lin Oo. “Numerical prediction of the power coefficient improvements of three laterally aligned Savonius wind turbines above a forward-facing step.” *Journal of Wind Engineering and Industrial Aerodynamics* 228 (2022): 105112.

[12] Larin, Patrick, Marius Paraschivoiu, and Cevdet Aygun. “CFD based synergistic analysis of wind turbines for roof-mounted integration.” *Journal of Wind Engineering and Industrial Applications* 156 (2016): 1-13.

[13] Victor, Samson, and Marius Paraschivoiu. "Performance of a Darrieus turbine on the roof of a building." *Transactions of the Canadian Society for Mechanical Engineering* 42, no. 4 (2018): 341-349.

[14] Allard, Marc Alexandre, and Marius Paraschivoiu. "Power enhancement CFD based study of Darius wind turbine via roof corner placement." *Journal of Renewable and Sustainable Energy* 14, no. 3 (2022): 033301.