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An Innovative Method for Enhancing the Local Wind Potential around the Vertical Axis Wind Turbines at Low Potential Regions

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Abstract: *This study presents an innovative method for improving the local wind power potential around a vertical axis wind turbine (VAWT). The idea is an external simple structure constructed by four vertical cylinders with a square arrangement which is embedded around the VAWT. The ratio of the cylinders diameter to the virtual VAWT rotor diameter, d/D, varies between the 1/10 and 1/4. On the other hand, the ratio of the corresponding gap space between the two adjacent cylinders of the external structure to the rotor diameter, G/D, is considered 1.5 and 2.0. The obtained numerical results show that existing of the considered external structure around the VAWT develops a region with an enhanced velocity magnitude around the turbine rotor. In addition, it is revealed that maximum 27.6%, 24.3%, and 23.6% enhancements in the wind flow potential are obtained corresponding to the undisturbed wind flow of 1, 2, and 3 m/s, respectively.*

Keywords: *External structure, Turbulence intensity, Vertical axis wind turbine, Wind potential*

1. Introduction

Small scale wind turbines are popular devices for converting the wind kinetic energy to electricity in residential and non-residential buildings not only at developed countries but also at developing countries. They are made in two different forms; vertical axis and horizontal axis having the output rates less than 10 kW, usually. In comparison to horizontal axis wind turbines (HAWTs), vertical axis wind turbines (VAWTs) are able to generate the power regardless to wind direction which is a great advantage. Although, most of the wind power generations are regarding to large scale HAWTs with several 100 kW, but the use of small scale wind turbine shows an increasing role in power generation. Several studies have been performed on the small scale wind turbines, particularly on the VAWTs not only by numerical and computational methods but also using different experiments. Some of them will be reviewed in this section. Yang et al. [1] presented an innovative method to evaluate the VAWT performance with deflectable blades for ocean and tidal energy applications. It was demonstrated that construction of the turbine blades in the deflectable form increases a downstream blade power output and reduces an upstream blade resistance. The effects of the VAWT blade number on the aerodynamic force are investigated by Li et al. [2].They showed that increasing the number of blades decreases the power coefficient. In addition, it was found that depending to the wind potential; turbines with two and five blades have higher output energy for higher and lower potential regions, respectively. The unsteady wake effect between two adjacent VAWTs is investigated using CFD simulations by Zuo et al. [3]. They found that with increasing the distance between the two adjacent turbines, the power coefficients for both upstream and downstream turbines increase due to reduction in wake effect. Li et al. [4] conducted on the aerodynamic forces on a straight bladed vertical axis wind turbine using the wind tunnel test. They showed that the aerodynamic forces were maximum when the blade passes through the upstream region. In the other work, Posa et al. [5] studied on the wake structure of a single VAWT with a wind tunnel test and also using the particle image velocimetry (PIV) technique. They compared their obtained results with those of the large eddy simulation (LES) method. It was indicated that the tip speed ratio is an important parameter in determining the characteristic of VAWTs wakes at high Reynolds numbers. Wekesa et al. [6]

published a work on the turbulence effect on the aerodynamic performance of a small scale VAWT. They revealed that turbulent flow increases the kinetic energy on the small wind turbines at low speeds and decreases its efficiency at wind speeds near the furling speeds. Investigation on Darrieus type straight blade VAWT with flexible blade is presented by Liu and Xiao [7]. They compared the aerodynamic characteristics of the flexible blades with those of the rigid blades. It was found that at small tip speed ratio, the energy extraction enhances with flexible blades in comparison to those of the rigid blades. Performance of the small scale VAWT with variable amplitude blade pitching was performed by Jain and Abhishek [8]. It was demonstrated that the variation in the amplitude of dynamic blade pitching allows for the maximum power extraction for a wide range of tip speed ratios. Ahmadi-Baloutaki et al. [9] investigated on the interaction between the VAWTs in array configurations. They indicated that when turbines are positioned in side-by-side arrangement with counter-rotating condition, the aerodynamic performance over the sum of the isolated installation will be improved, slightly. In addition, they demonstrated that the downstream turbine output power becomes maximum when the stream wise distance between the upstream pair and downstream turbine and the distance between the pair of upstream turbines become three rotor diameters and one rotor diameter, respectively. Performance of a VAWT with the modified trailing edge of the blade is presented by Lin et al. [10], numerically. The maximum thrust of the turbine was found 0.38%-2.31% greater than that of a straight blade in their study. Ahmadi-Baloutaki et al. [11] conducted on the upstream wind turbulence effect on a VAWT performance. They generated an upstream wind turbulence intensity in the range of 5%-10%. It was revealed that compared with nearly smooth flow case, the performance of the VAWT under turbulent upstream flow increases the power output.

Although several valuable attempts have been done for improving the VAWTs performance, however, most of the published works were focused on the blades design. Despite the previous researches, this study is not considering the blade shape effect on the VAWT performance. In the other words, the present study is focused on the wind potential enhancement around the VAWT in order to provide higher wind speed for better VAWT operation.

2. Problem Description And Computational Details

In the present study, the interaction between an external structure constructed by four circular cylinders embedded around a virtual VAWT rotor and the wind flow is investigated, numerically. Figure 1 illustrates a schematic of the under consideration innovative idea. It is assumed that the height of the cylinders is enough longer than the rotor height to avoid the tip effects of the cylinders on the rotor performance. Therefore, computations are performed in two dimensions. In general, the VAWT rotor rotates due to aerodynamics interaction between the wind flow and turbine blades. On the other hand, at regions with low wind potential, the net output of the VAWTs is usually insufficient for residential and commercial demands. Therefore, in such regions, VAWTs with higher capacities are preferred for a specific value of the electricity generation. Embedding of the introduced external structure leads to an interaction between the wind flow and circular cylinders before meeting the wind with the rotor. This interaction develops a jet-like flow around the rotor and consequently enhances the wind potential in this critical region. One of the advantages of this external structure is minor difference of its efficiency with respect to wind direction. That is, in each wind direction, the wind potential within the structure increases. However, the level of this increasing may be affected with wind direction. It is worth mentioning that this study investigates the interaction between the undisturbed wind flow and external structure in order to find the enhanced wind potential around the turbine rotor. In other words, the aerodynamic interaction between the wind flow and turbine blades is out of the scope of this study. In order to determine enhanced wind potential around the virtual turbine rotor using the computational fluid dynamics tool, a two dimensional rectangular flow domain according to figure 2 is defined. The constructed physical domain has dimensions of (30d+G) × (20d+G) in which "d" is the cylinders diameter of the structure and "G" is the gap space between the cylinders. The center of the virtual VAWT is set at (10d+G/2, 0) so that the external structure and virtual turbine are concentric. Here, the diameter of virtual VAWT rotor is "D". The coordinate's origin is imposed on the mid-point of the inlet section. Computations are performed for d/D=1/10, 1/5, and 1/4 and G/D=1.5 and 2.0 under the undisturbed wind velocities of U=1, 2, and 3 m/s corresponding to low potential regions data. Regarding the boundary conditions, a uniform undisturbed wind velocity is considered for incoming flow, convective boundary condition, $\frac{\partial u}{\partial t} + U\frac{\partial u}{\partial x} = 0$, is imposed to the outlet section in which U and u are the incoming velocity (or undisturbed wind velocity) and stream wise velocity, respectively, and symmetric condition is used for the sides of the flow domain. In addition, no slip boundary condition is adapted to all surfaces of the structure.

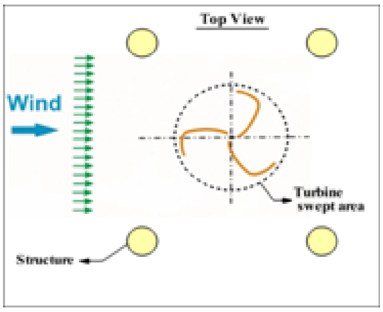

Figure1. *Schematic of the under consideration innovative idea*

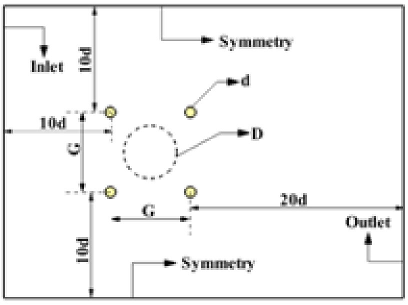

Figure2. *Physical flow domain applied in this study*

The governing equations for incompressible, unsteady, Newtonian, and constant fluid properties are as,

- Continuity equation,

$$\nabla.\vec{V} = 0 \tag{1}$$

- Momentum equation,

$$\rho\frac{D\vec{V}}{Dt} = -\nabla p + \mu\nabla^2\vec{V} \tag{2}$$

in which, V, p, t, ρ, and μ are velocity vector, pressure, time, density, and dynamic viscosity, respectively. Here, the applied operator notation is defined as,

$$\nabla = \frac{\partial}{\partial x}i + \frac{\partial}{\partial y}j \tag{3}$$

In the present study, in order to model the turbulence quantities, RNG k-ε model (Yakhot and Orszag, [12]) is carried out. Although this turbulence model is very similar to standard k-ε, however, there are some benefits regarding to this model comparing to standard scheme. For example, i) it has an additional term in its dissipation equation that is supported to improve the accuracy for rapidly strained flows, ii) the effects of swirl on turbulence is included in the RNG model which enhances its accuracy for swirling flows (Dewan, [13]). The equations of RNG k-ε may be found in various textbooks (for example; Dewan, [13]).

In order to solve the governing equation, the momentum equations are discretized using the second order upwind scheme while for the discretization of the turbulence equations, first order upwind scheme is carried out. For coupling the pressure-velocity fields, the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) (Patankar, [14]) is applied. The discretized equations are solved implicitly by means of the finite volume method. In addition, the convergence of 2D velocity components is established at each time step by controlling the residuals of all equations which are defined to be solved by setting their variations less than 10^{-7}.

The wind potential per swept area of the virtual VAWT at each location is assessed using the following equation (Jain, [15]),

$$\frac{P}{A} = \frac{1}{2}\rho U^3 \tag{4}$$

in which P, A, ρ, and U are wind power, turbine swept area, air density, and undisturbed wind velocity.

The sensitivity of the virtual VAWT power to wind speed is determined by (Jain, [15]),

$$\frac{\Delta P}{P} = 3\frac{\Delta u}{U} \tag{5}$$

in which, Δu, and ΔP are change in wind speed, and change in wind power, respectively.

Table 1 shows details of the applied grid numbers for all computed cases. In order to ensure that the applied grid resolutions are sufficient to capture the turbulence scales and consequently the independence of the obtained results to grid number, several grid resolutions are tested for all cases. Figure 3 presents a sample of the grid independence results for d/D= 1/10, G/D=1.5 and undisturbed wind velocity of 3 m/s. The obtained results showed a very small sensitivity to the grid numbers between “Grid 3” and “Grid 4”. Therefore, “Grid 3” is considered in the case of d/D= 1/10, G/D=1.5. Details of “Grid 1” to “Grid 4” can be found in table 2.

Table1. *Details of applied grids*

	d/D=1/10		d/D=1/5		d/D=1/4	
	G/D=1.5	G/D=2.0	G/D=1.5	G/D=2.0	G/D=1.5	G/D=2.0
Cell No.	24980	33878	36054	43756	40592	43756
Face No.	38051	51537	55131	66819	62043	66819
Node No.	13068	17656	19074	23060	21448	23060

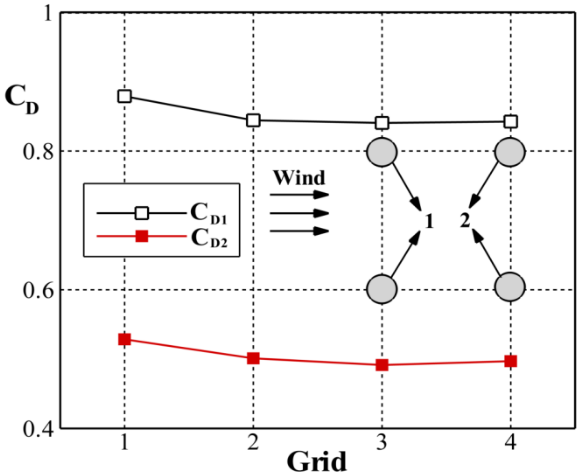

Figure3. *Results of the grid size independence study*

Table2. *Details of applied grids for grid size independence study*

Grid No.	Cell number	Face number	Node number
1	16628	25290	8659
2	19970	30384	10411
3	24980	38051	13068
4	34228	52214	17983

For validation of the obtained numerical results, the numerical method applied in the present study is validated for the flow around a single circular cylinder at Re=3900. The validation study showed excellent agreement between the present validation data with that of the previous studies. Table 3 compares the obtained validation results with different researches for the flow around a single cylinder at Re=3900. It should be said that the Reynolds number in validation study is calculated based on the undisturbed wind velocity and the single cylinder diameter.

Table3. *Comparison of obtained results in the present study for drag coefficient with that of the previous studies at Re=3900*

Author	C_D
Alkishriwi et al. [16]	1.05
Mani et al. [17]	0.99
Wornom et al. [18]	0.99
Lysenko et al. [19]	1.18
Kravchenko and Moin,[20]	1.04
Luo et al. [21]	1.01
Zhang et al. [22]	1.001
Ouvrard et al. [23]	0.94
D'Alessandro et al. [24]	1.02
Present study	1.04

3. Results And Discussion

In this section, first of all, effects of wind-structure angle on the velocity field will be discussed, briefly. Figures 4 (a) and (b) illustrate the stream wise velocity distributions for d/D=1/5 and G/D=1.5 at two different wind-structure angles of 90° and 45°, respectively. In both situations of 90° and 45°, the regions with high wind potentials within the structure are demonstrated with vertical and horizontal rectangles, respectively. In the case of 90°, as seen, points with high wind potential are mainly collected in the two vertical rectangles which are near the first and second columns of the cylinders. In addition, for wind-structure angle of 45°, these points with high potentials are mainly collected in two horizontal rectangles in which one of them is near the upper cylinders row and the other one is near the lower cylinders row. Further examination of the velocity field for both wind-structure angles of 90° and 45° reveals that once a vertical axis wind turbine with minimum three blades is embedded in the center of this external structure, at each situation, at least one blade will be located within the rectangles. Therefore, it is easy to imagine that at each wind-structure angle and three-blade vertical axis wind turbine situation, the net output of the turbine will be increased. Therefore, without consideration of the wind-structure angle, the obtained results from this study are presented for only 90° in the following.

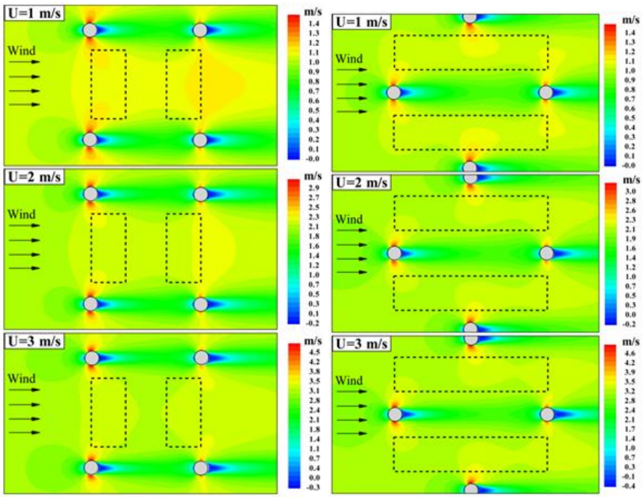

Figure4. *Distributions of the velocity field around the external structure for d/D=1/5 and G/D=1.5 under three different undisturbed wind speed of U=1, 2, and 3 m/s at two wind-structure angles; (a) 90°, (b) 45°*

Figure 5 demonstrates distributions of time-averaged stream wise velocity along the axis passing from the center of the virtual VAWT center in the stream wise direction for d/D=1/10, 1/5, and 1/4 in G/D=1.5. Variations are plotted for three undisturbed wind velocities of U=1, 2, and 3 m/s. Here, the velocity magnitudes and stream wise coordinate are normalized with undisturbed wind velocity and cylinder diameter, respectively. In general, passing the undisturbed wind flow from the external structure cause to an interaction between the wind flow and circular cylinders. The effect of this interaction is development of regions with enhanced velocity magnitudes. First interest location is realizable just after the primary column of the cylinders. The other one is located just after the second column of the cylinders. It is worth mentioning that the concept of primary and secondary columns may be understood with respect to their location on the stream wise coordinate. The location of first enhanced velocity is particularly important from this perspective that this location is very close to the turbine rotor. Therefore, turbine blades meet with enhance wind speed and consequently, the net output of the VAWT increases. However, several parameters are effective on the rate of this velocity enhancement. Some of them are related to geometrical parameters of the external structure such as the arrangement, diameter, and shape of the cylinders as well as the gap space between two adjacent cylinders. In this study, these parameters are generalized by introducing the non-dimensional parameters such as d/D and G/D. As seen from figure 5, for all d/D values, at the meeting point, the rate of velocity enhancement is higher for lower value of the undisturbed wind velocity. On the other hand, for each individual undisturbed wind velocity, the level of this enhancement increases by increasing the d/D.

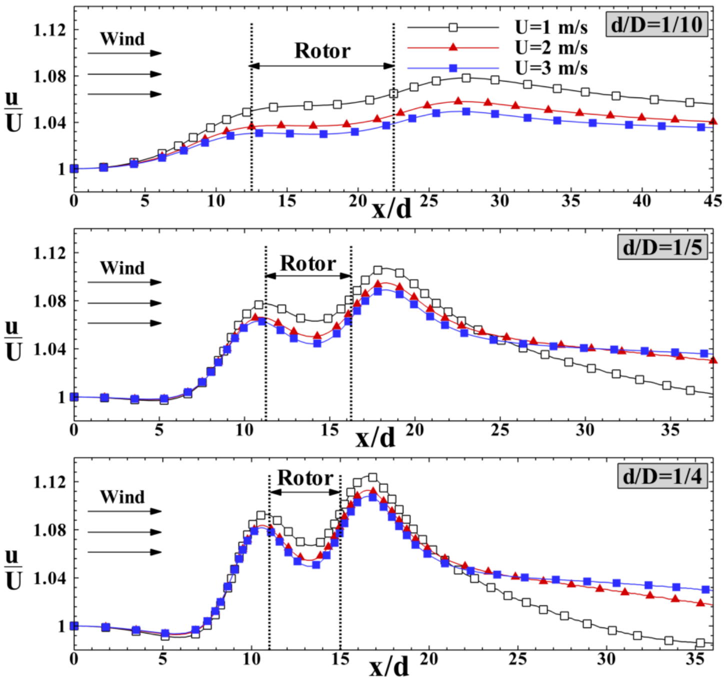

Figure5. *Distribution of the wind velocity along the axis passing from the center of the structure in streamwise direction for d/D=1/10, 1/5, and 1/4 in G/D=1.5 under three different undisturbed wind speed of U=1, 2, and 3 m/s*

As mentioned before, one of the effective parameters on the introduced external structure is the ratio of the cylinder diameter to the VAWT rotor diameter (d/D). That is, increasing the d/D increases the structure performance. However, very small values of d/D may be led to an increase in the turbulence intensity around the turbine due to vortex shedding process. Although, the VAWTs performance is not sensitive to turbulence intensity of the wind flow, but, due to dynamic nature of the turbulence phenomenon, the higher rates can reduce the lifetime of the turbine parts. To better understand, figure 6 presents distributions of turbulence intensity along the axis passing from the center of the virtual VAWT center for d/D=1/10, 1/5, and 1/4 in G/D=1.5. Variations are plotted for three undisturbed wind velocities of U=1, 2, and 3 m/s. It is clearly seen that at the meeting point, the rate of turbulence intensity is higher for U=1 m/s compared with those of the U=2 and 3 m/s. However, at the meeting point, the differences among the turbulence intensities for U=1, 2, and 3 m/s are ignorable in the case of d/D=1/10. Although, by increasing the d/D value, the differences among the turbulence intensities become significant, but, for all cases, at meeting point the turbulence intensities are not considerable. For instance, as demonstrated in figure 6, at meeting point the maximum turbulence intensities occurred in U=1 m/s are 0.27%, 0.77%, and 0.93% for d/D=1/10, 1/5, and 1/4, respectively. It seems with increasing the undisturbed wind velocity and decreasing the d/D value, the level of turbulence intensity attenuates.

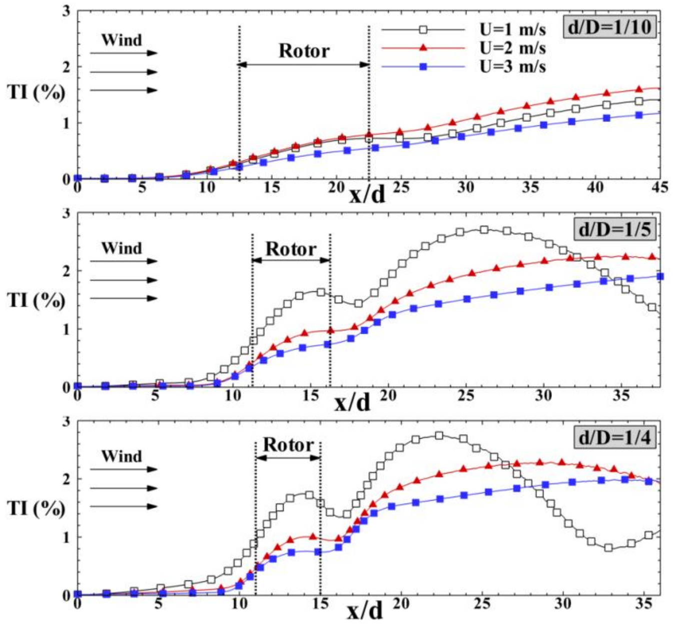

Figure6. *Distribution of the turbulence intensity along the axis passing from the center of the structure in stream wise direction for d/D=1/10, 1/5, and 1/4 in G/D=1.5 under three different undisturbed wind speed of U=1, 2, and 3 m/s*

Figure 7 illustrates the wind potential per swept area of the VAWT, P/A, obtained from eq. (4) along the d/D for G/D=1.5 and 2.0 at meeting point. For convenience, the wind potentials obtained using the external structures are compared with those of the conventional cases. As expected, the wind potential per turbine swept area enhances using the external structure. The rate of this enhancement increases by increasing the d/D value. On the other hand, the higher G/D, leads to a gradual reduction in the wind potential for a specific wind speed and d/D value.

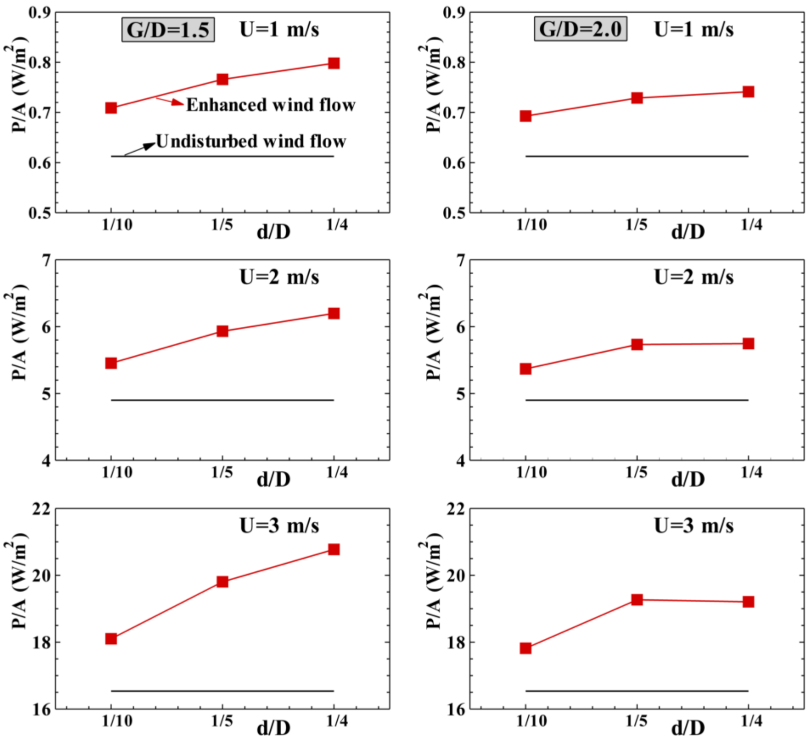

Figure7. *Variation of wind potential per turbine swept area with d/D in G/D=1.5 and 2.0 at meeting point under three different undisturbed wind speed of U=1, 2, and 3 m/s*

Figure 8 presents the sensitivity of the virtual VAWT to wind speed along the d/D for G/D=1.5 and 2.0 at the meeting point. For undisturbed wind speed of U=1 m/s, maximum enhancements in wind power comparing to the case without the structure are occurred in d/D=1/4 which are 27.6% and

19.68% for G/D=1.5 and 2.0, respectively. In U=2 m/s, these enhancements are 24.4% and 16.3% and in the case of U=3 m/s, they reduce to 23.6% and 15.3% for G/D=1.5 and 2.0, respectively.

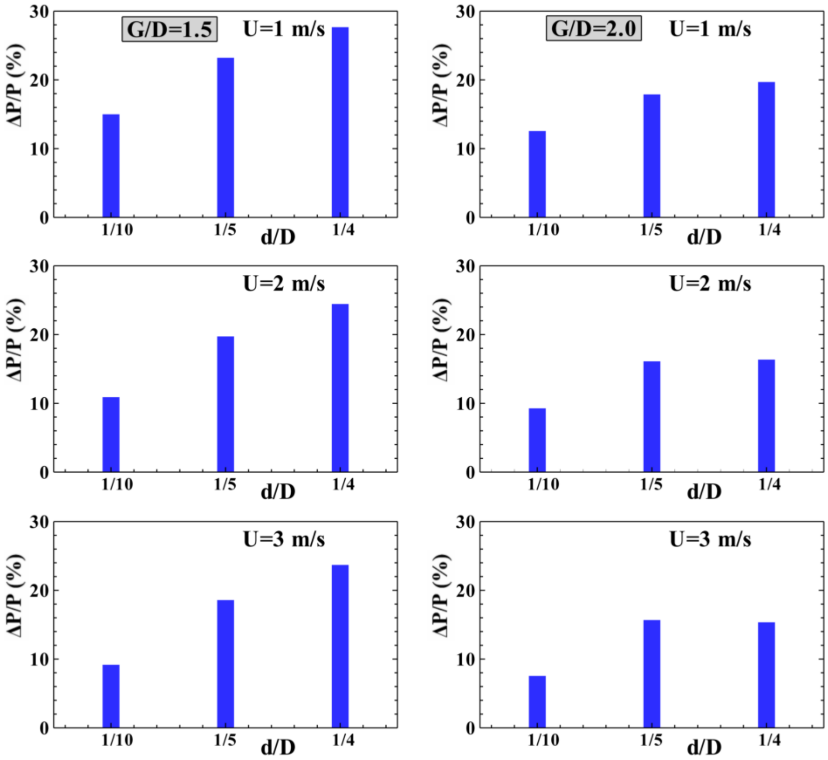

Figure8. *Sensitivity of the VAWT to wind speed along the d/D for G/D=1.5 and 2.0 at meeting point under three different undisturbed wind speed of U=1, 2, and 3 m/s*

4. Conclusion

An innovative external structure constructed by four circular cylinders is introduced to improve the VAWT performance at low wind potential regions. Computations are performed using computational fluid dynamics tool for different non-dimensional parameters of d/D and G/D under several low undisturbed wind speeds in the range of 1 m/s≤U≤3 m/s. For enhanced visualization, several results are presented in this study. First of all, it was demonstrated that the introduced innovative structure constructed by four circular cylinders in a square configuration develops higher wind speed at the virtual VAWT meeting point compared with conventional case. This increased wind speed at the meeting point enhances the wind potential around the VAWT rotor and hence, the net output of the VAWT will be increased. Finally, it was revealed that compared with conventional case, such simple external structure around a virtual VAWT develops maximum 27.6%, 24.4%, and 23.6% more wind power potential for U= 1, 2, and 3 m/s, respectively. It was hoped the obtained results in this study arouse interest among the VAWT users, particularly at low wind potential regions.

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