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Three-dimensional Numerical Study of the Performance of a Small Combined Savonius-Darrieus Vertical Wind Turbine

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P A P E R I N F O

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A B S T R A C T

Energy crisis and global warming have encouraged the use of renewable energy resources such as wind power. Among different types of wind turbines, vertical axis wind turbines can be easily installed in residential areas. In this study, a computational fluid dynamics analysis was performed to predict the performance characteristics of three configurations of small vertical axis wind turbines. For this purpose, an shear stress transport k-omega turbulent model and a rotating frame of reference were employed. Initially, a Savonius and a Darrieus wind turbine were simulated; the low power coefficient of the Savonius wind turbine and the poor performance of the Darrieus wind turbine in low tip speed ratios were the main disadvantages of these systems. Finally, a combined Savonius-Darrieus wind turbine was proposed to deal with these drawbacks. The power coefficient of this combined wind turbines was nearly as high as the Darrieus wind turbine (0.3), while the Savonius blades recover the low torque obtained at low tip speed ratios and help produce more consistent torque, making it suitable for residential applications.

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INTRODUCTION

Due to the increasing demand for renewable energy to replace fossil fuels, wind energy has become more appealing because of its high reliability and low environmental impact. Small wind turbines can be used easily at or near the residential areas, houses, and farms. Vertical axis wind turbines (VAWTs) are getting more attention to small scale wind turbines [1]. However VAWTs have lower efficiency compared to HAWTs (Horizontal axis wind turbines) [2], they can operate using wind in all directions and more importantly, they do not require any yaw mechanisms. Furthermore, they are low-cost, quiet, and self-starting at low speed, and can be packed closer to each other in wind farms. Also, they impose lower forces on the support structure and can function in turbulent and gusty winds.

VAWTs are mainly classified into two types; Savonius and Darrieus. Savonius is the most basic type of VAWT, which was introduced by a Finnish engineer named Savonius in the 1920s [3]. This type of turbine is made by cutting a cylindrical surface into halves along its central axis that the cross-section resembles an “S”. These turbines are driven by the drag forces that are exerted to blades by wind. On the other hand, Darrieus turbines are driven by lift forces. They were invented by a French engineer named Darrieus who submitted a patent in 1931 [4]. It consists of two or three thin blades which their cross-section is like an airfoil. These blades are attached to a rotating vertical shaft.

Many researchers have investigated the performance of Savonius and Darrieus wind turbines both numerically and experimentally. Jiang and Yan [5] found that a conventional Savonius turbine has a very low power coefficient of about 0.15 with respect to 0.35 for the Darrieus turbines and 0.45 for HAWTs. Two-bladed Savonius turbine is more efficient but the three-bladed one has a higher starting torque [6]. Overlap ratio, which is defined as the ratio of the overlap distance between turbine blades by the blade chord length, plays a key role in optimizing Savonius turbines and a ratio of 0.15-0.25 was suggested by several experts [7, 8]. Using endplates, which cover the top and the bottom of buckets, seems to have enhanced the performance of these turbines. The diameter of these plates is recommended to be 1.1 times the diameter of the turbine [8, 9]. Moreover, adding extra stages, which are angled the blades of the first stage, can reduce the fluctuation of torque without significant loss of the performance [10]. Similar to multi-stage Savonius wind turbines, using helical blades can produce more uniform torque [11, 12]. In the case of Darrieus turbines, the shape of airfoils has a significant impact on the overall performance and the self-starting characteristics of the turbine. Extensive

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studies have been conducted to examine the effects of the shape of airfoils [13, 14]. Three-bladed Darrius wind turbines are more desirable than two-bladed ones [15]. Other researchers measured the key design parameters of Darrieus turbines such as aspect ratio, swept area, chord-radius ratio, and twisted blades [16-18].

Both Savonius and Darrieus wind turbines have some advantages and disadvantages. Savonius turbines give a high value of starting torque, while most of the Darrieus turbines are not self-starting at all. On the other hand, Darrieus turbines are far more efficient than Savonius turbines [19]. Combined Savonius-Darrieus VAWTs were used to resolve the self-starting problem of Darrieus turbines and low-efficiency of Savonius turbines. Several configurations have been investigated both numerically and experimentally. Wakui et al. [20] studied two combined configurations with a two-stage two-bucket Savonius rotor and a two-bladed Darrieus rotor in a wind tunnel. They have found the maximum power coefficient of 0.18. Feng et al. [21] combined a Savonius rotor with a four-bladed Darrieus one and reported that it is self-started at low tip speed ratio. Kavade and Ghanegaonkar [22] tested a small combined configuration for household applications in a wind tunnel and reported a 0.23 power coefficient. Wakui et al. [23] analyzed two types of Savonius-Darrieus combined VAWTs and concluded that power extraction for these turbines depends on the wind condition and the system scale.

Most of the numerical studies in this area are two-dimensional, and there are a few research done in three-dimensional models, taking into account the effect of depth and aspect ratio. The limited three-dimensional studies have only investigated the more common combined wind turbines of Eggbeater (or Curved-bladed) type [24, 25] and there are not enough straight-bladed combined VAWTs models. In this study, three configurations for Savonius, Darrieus, and combined Savonius-Darrieus VAWTs (straight-bladed) are presented. A steady-state three-dimensional CFD simulation using Ansys package (CFX and ICEM CFD) is performed and the performance parameters of the turbines are calculated. In order to measure the impact of the incident angle, the simulation was repeated several times in different angles to cover a full rotation. This study aims to propose a VAWT configuration to be low-cost and easy to construct while maintaining a high value of power coefficient. In this regard, two initial configurations of Savonius and Darrieus VAWTs are presented and numerically tested. Then, a final modification of a combined Savonius-Darrieus VAWT is investigated considering the previous configurations. The final configuration is relatively efficient, self-starting, easy to build, and low-in-cost and can be used in household applications.

GOVERNING EQUATIONS

In order to get the required data, four equations were used that govern the wind turbines: a continuity equation and three momentum equations in three directions which are known as Navier-Stokes equations. The continuity equation states that the mass of a system remains constant over time. Similar derivations could be obtained using the conservation of momentum in each of the three axes.

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

$$\rho(V.\nabla)V = -\nabla P + \rho g + \nabla . \tau \tag{2}$$

where V is the velocity vector, ρ is the density, P is the static pressure, g is the gravity of Earth, and τ is the stress tensor which is stated as follows:

$$\tau = \mu(\nabla V + (\nabla V)^T - \frac{2}{3}\delta \, \nabla . V) \tag{3}$$

where μ is the viscosity and δ is the unit tensor. Using the averaged and fluctuated components, as it is shown for velocity in Equations (1) to (3), can be rewritten in the form of Reynolds Averaged Navier Stokes (RANS) equations:

$$U_i = \overline{U}_i + u_i \ , \ \overline{U}_i = \frac{1}{\Delta t}\int_t^{t+\Delta t} U_i dt \tag{4}$$

$$\frac{\partial U_j}{\partial x_j} = 0 \tag{5}$$

$$\rho \frac{\partial}{\partial x_j}\left(U_i U_j\right) = -\frac{\partial \mathrm{P}}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} - \rho\overline{u_i u_j}) \tag{6}$$

where U is a velocity component, $\overline{U}$ and u are the time-averaged and fluctuating components, Δt is a time scale that is large relative to the turbulent fluctuations.

In Equations (5) and (6), the bar, indicating the average values, is dropped except for parameters of fluctuating quantities. $\rho\overline{u_i u_j}$ is known as Reynolds stress which comes from the convective term of the conservation equation of momentum. In order to solve the equations, the Reynolds stress should be modeled using new equations. In this study, Shear Stress Transport (SST) turbulence model is used which is a two-equation model that combines the conventional k-omega and k-epsilon turbulence models [26].

The power coefficient of a wind turbine is defined as the ratio of generated power to the energy available in the wind (Equation (7)). It is used to determine how efficient the wind turbine is. It can be calculated as follows:

$$C_p = \frac{Generated\ power}{Wind\ power} = \frac{P_{out}}{P_{in}} \tag{7}$$

$$P_{in} = 0.5.\rho.v^3 \tag{8}$$

$$P_{out} = T.\omega \tag{9}$$

$$C_p = \frac{T.\omega}{0.5.\rho.v^3 DH} \tag{10}$$

$$C_p = \frac{T.\omega}{0.5.\rho.v^3 DH} \tag{10}$$

where C_p is the power coefficient, P_{out} and P_{in} are output and input powers, v is the speed of the wind, ω is the angular speed of the wind turbine, D and H are the turbine's diameter and height, and T is the torque value on blades. Similarly, the torque coefficient, which is a measure of torque exerted on the blades of a wind turbine, can be calculated via Equation (11). These parameters are usually calculated as a function of tip speed ratio which is the ratio of the tangential speed of the tip of a blade to the speed of the wind (Equation (12)).

$$C_t = \frac{4T}{\rho . v^2 . D^2 H} \quad (11)$$

$$T.S.R = \frac{\omega . D}{2v} \quad (12)$$

where C_t is the torque coefficient and *T.S.R* is the tip speed ratio of the wind turbine.

PHYSICAL MODEL AND COMPUTATIONAL DOMAIN

In this study three vertical wind turbines have been investigated: a Savonius turbine, a Darrieus turbine, and a combined Savonius-Darrieus turbine. Analyses are carried out using computational fluid dynamic ANSYS 17.1 software, where CFX was the solver and ICEM CFD was the mesh generator. The Savonius turbine has two buckets at two stages which have an angle difference of 90 degrees to obtain the best performance with a relatively uniform torque generation. Endplates were used at both ends of the buckets with radios of 1.1 times the turbine's radios, and the overlap ratio, which is the ratio of the overlap distance between the buckets to the diameter of each of them, was 0.15. Each stage has an aspect ratio (ratio of the height of the turbine to its diameter) of 1, and the profile of the buckets was semicircular. On the other hand, in the Darrieus turbine, three straight blades were used with the profiles of NACA 0015 airfoil, and the overall aspect ratio was 1.25.

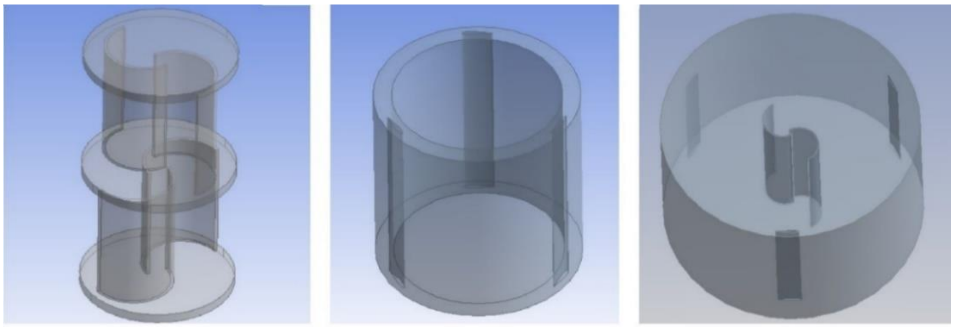
In order to take advantage of both the Darrieus and the Savonius turbines, the last proposed turbine was a combined Savonius-Darrieus turbine. In this turbine, three airfoils of NACA 0015 were used to form the outer part of the turbine as a Darrieus rotor. Two smaller semicircular buckets were placed in the internal space between Darrieus blades to increase the self-starting ability of the turbine. This configuration considered to be more efficient than other forms of combined wind turbines [27]. The blades and buckets were similar to previous Savonius and Darrieus turbines. More information about these configurations presented in Table 1 and Figure 1.

The computational domain was divided into two parts; the inner part that contains the blades and the buckets rotated relative to the incoming fluid stream, and the other part is stationary. A rotating frame of reference was implemented for the inner part to simulate the rotation of the turbine in steady-state. For each state, the inner domain was rotated at most 15 degrees, and the run was repeated until a complete turn was covered. Finally, the obtained data were averaged in all directions, and overall parameters were calculated. Furthermore, the dimensions of the computational domain were large enough to exclude the effects of their walls.

To obtain high-quality special discretization, the two domains were separately meshed and connected using a general grid interface (GGI) connection. The inner (rotating) domain requires more attention, because most of the important flow effects take place there. To do this, a high quality unstructured tetrahedral mesh was employed on both domains, as illustrated in Figure 2. The number of elements and nodes varied depending on the configuration. The number was 277,805 elements in the outer domain and 978,180 elements in the inner domain of the combined rotor.

The boundary conditions consist of an inlet, an outlet, and four symmetric faces. The turbine's blades were considered as no-slip walls, and there was an interface between the rotating and stationary domains that can be observed in Figure 3.

The strategy to solve the governing equations was using a guessed pressure in order to, first, solve the momentum equations, and an equation for a pressure correction was obtained. Typically, many iterations were required, and an implicit approach was used at any step. The discrete systems of linearized equations were solved using an Incomplete Lower Upper (ILU) factorization technique [28] as an iterative solver.

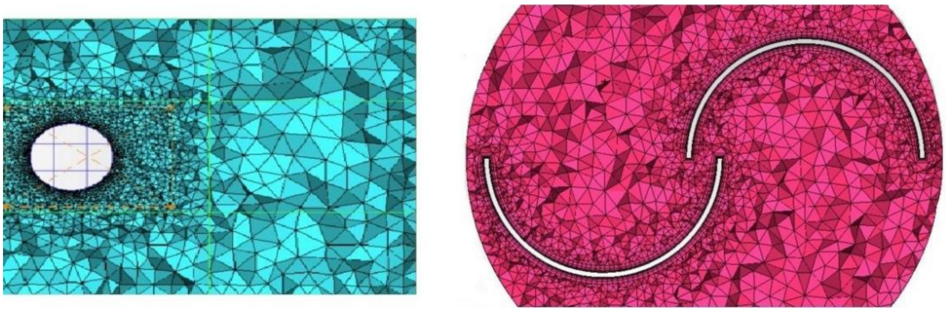


(a) (b) (c)

Figure 1. Geometry of (a) Savonius, (b) Darrieus, and (c) Combined Savonius-Darrieus turbines

TABLE 1. Parameters of the three wind turbines

Turbine type	Savonius	Darrieus	Combined
Number of blades (buckets)	2 buckets	3 blades	2 buckets – 3 blades
Blade (bucket) shape	Semicircular	NACA 0015	Semicircular - NACA 0015
Turbine diameter [m]	1.85	1.67	2.6
Turbine height [m]	3.9	2	1.3



(a) (b)

Figure 2. Mesh structure for (a) outer domain, and (b) inner domain

The numerical solution was validated through reproducing the results of two experimental studies using the same geometry and characteristics. The first study was an experiment done by Kamoji et al. [29] in a wind tunnel to examine the effect of geometrical parameters on the performance of the Savonius rotors, and the second one was a wind tunnel testing conducted to determine the performance behavior of the 3.5 kW Darrieus by Bravo et al. [30]. A great similarity was seen between the results of the numerical model and these studies as illustrated in Figure 4.

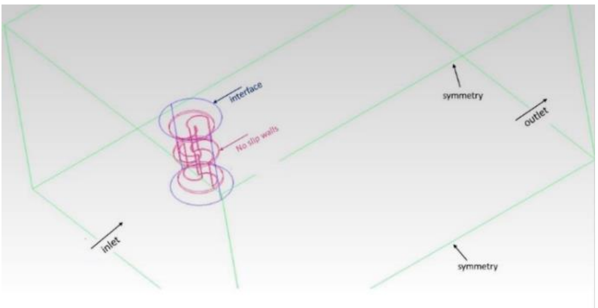


Figure 3. Boundary conditions

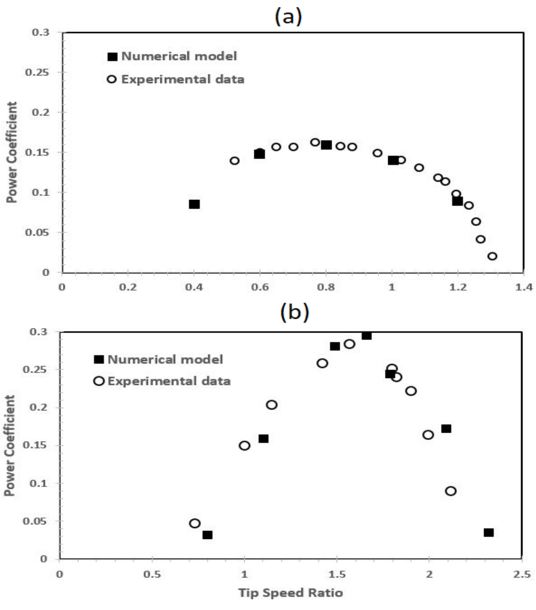


Figure 4. Power coefficient of (a) experimental data from Kamoji et al. [29] and its computational model (b) experimental data from Bravo et al. [30] and its computational model

RESULTS AND DISCUSSION

The power coefficient of the two-stage Savonius turbine used in this study is plotted in Figure 5 (a) as a function of tip speed ratio. The maximum amount of the power coefficient is 0.15 which is obtained at the tip-speed ratio of 0.8. It shows that the Savonius wind turbines are not as efficient as other types of wind turbines. The relatively small tip speed ratio determines that the turbine rotates slowly with respect to Darrieus wind turbines, making it suitable for urban use due to its less noise and vibration. In Figure 5 (b), the torque coefficient is plotted versus the rotor angle, where a moderate fluctuation can be seen in the amount of torque coefficient. However this fluctuation is reduced as a result of adding a new stage compared to conventional Savonius wind turbines [10].

The same results are presented in Figure 6 for the Darrieus wind turbine. The maximum power coefficient has increased to 0.3 at a tip speed ratio of 1.6. Although the efficiency is higher than the Savonius turbine, it is obtained at high tip speed ratios meaning that this turbine spins faster than other

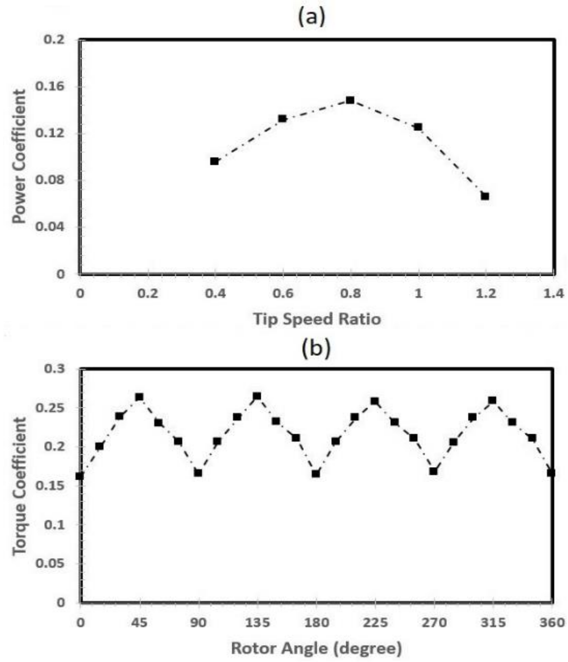


Figure 5. (a) Power coefficient as a function of tip speed ratio, (b) Torque coefficient as a function of rotor angle, for the Savonius wind turbine

types of wind turbines. Torque coefficient values are less than the Savonius turbine, and the fluctuations have increased, too. Since the turbine performs well only at high tip speed ratio, and the torque, obtained in this case, is relatively small; there would be some problems in its self-starting characteristics, and it may not be suitable to be used in low wind-speed areas and spaces with highly turbulent wind flows.

Figure 7 shows the performance of the combined Savonius-Darrieus wind turbine. Although the maximum power coefficient of this turbine is almost as efficient as the Darrieus one, it is obtained at a lower tip speed ratio of 1.1, which indicates that its optimum rotation is faster than the Savonius turbine and slower than the Darrieus turbine. Figure 7 (b) indicates that the torque coefficient is mostly generated by Darrieus blades, especially at higher tip speed ratios, but Savonius blades help recover the low torque at low tip speed ratios. They can produce most of the turbine's torque at tip-speed ratios of lower than 0.5. In fact, the less the tip speed ratio, the more Savonius blades contribute to maintaining a high torque coefficient. Torque coefficient is also plotted versus the rotor angle as shown in Figure 7 (c); the torque generated solely by Darrieus blades shows a great fluctuation, and at some specific angles, the torque coefficient reaches zero, which is highly adverse. Although the torque produced by the Savonius blades is smaller than the Darrieus blades, it plays an important role in increasing the amount of torque at angles that Darrieus blades perform poorly, producing more favorable overall torque.

Figure 8 shows the pressure contours associated with the single Darrieus turbine (a, b, and c) and the combined Savonius-Darrius turbines (d, e, and f). The counters are plotted for three different incident angles between the rotors and the inflow in order to assess the flow behavior with respect to this phase angle. The contours are shown for tip speed ratios at which both systems operate at their maximum efficiencies. According to this figure, for the single Darrieus rotor, the region of high and low pressures is mostly associated with the blades' positions. These regions move as the blades rotate. However, in the case of the combined system, there are localized regions with high and low pressures. These regions are associated with simultaneous interaction between the Darrieus and Savonius rotors. In order to qualitatively evaluate the flow behavior resulting from the

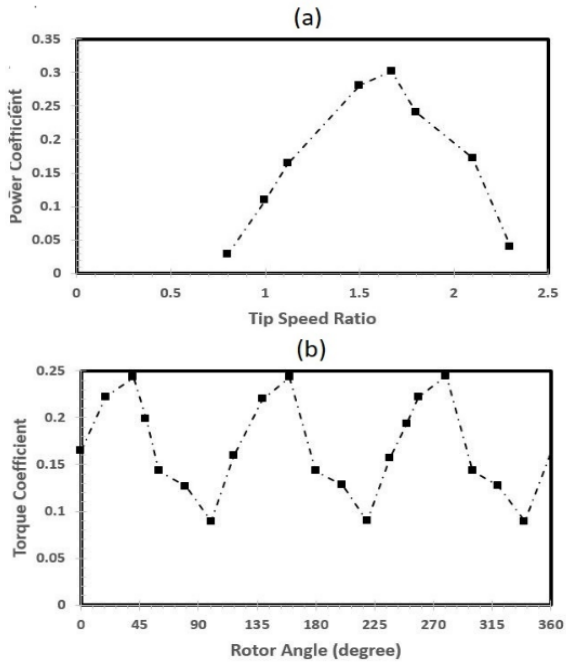


Figure 6. (a) Power coefficient as a function of tip speed ratio, (b) Torque coefficient as a function of rotor angle, for the Darrieus wind turbine

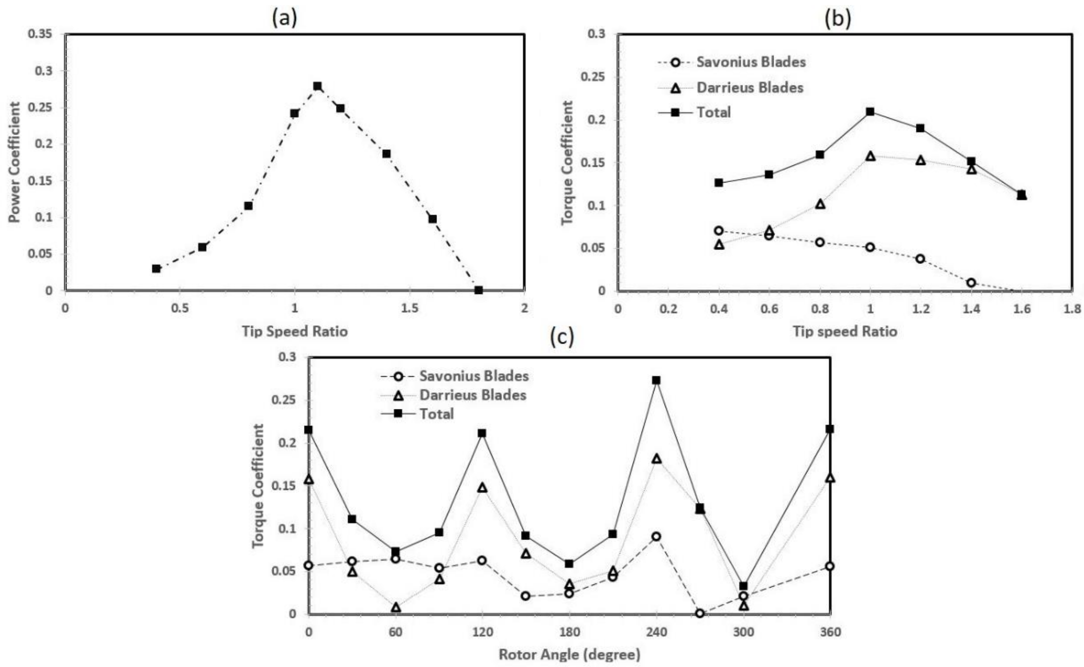


Figure 7. (a) Power coefficient as a function of tip speed ratio, (b) Torque coefficient as a function of tip speed ratio, and (c) Torque coefficient as a function of rotor angle, for the combined Savonius-Darrieus wind turbine

corresponding interaction, vector maps of the combined system are plotted for different incident angles (Figure 9). The vector maps are also compared with those obtained for the single Darrieus rotor. It can be seen that unlike the single rotor, within the upwind half of the combined rotor, a vortical flow structure is formed. The location of this vortex is almost fixed as the turbine rotates. This vortex forces the air to accelerate in one direction and decelerate in the other direction and therefore it results in the formation of the corresponding pressure regions. The reason for the fixed position of the vortex location can be attributed to this fact that in the simulation, the Darrieus and Savonius rotors move at the same rotational speeds. This is in agreement with the real physical situation at which the rotors are connected to a single axial shaft. Hence, one can infer why the maximum power coefficient occurs at a lower tip speed ratio for the combined turbine compared to the single Darrieus turbine [31]. In other words, for a constant inflow wind speed, as the rotational speed of the combined rotor increases, the area of the pressure regions expands and this will negatively affect the rotor's performance.

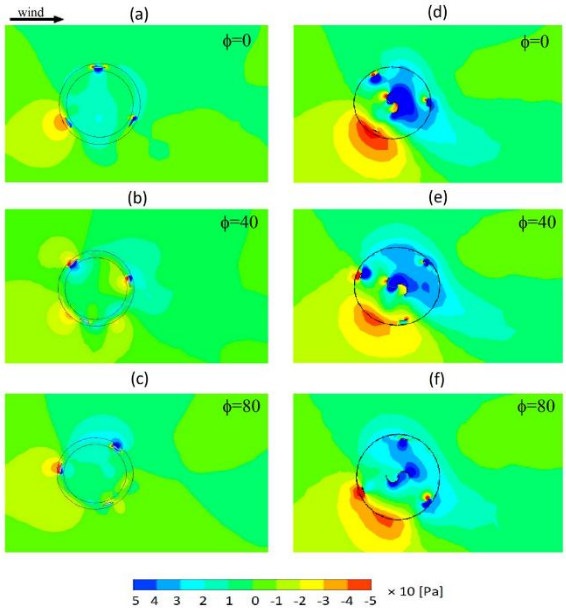


Figure 8. (a) Power coefficient as a function of tip speed ratio, (b) Torque coefficient as a function of tip speed ratio, and (c) Torque coefficient as a function of rotor angle, for the combined Savonius-Darrieus wind turbine

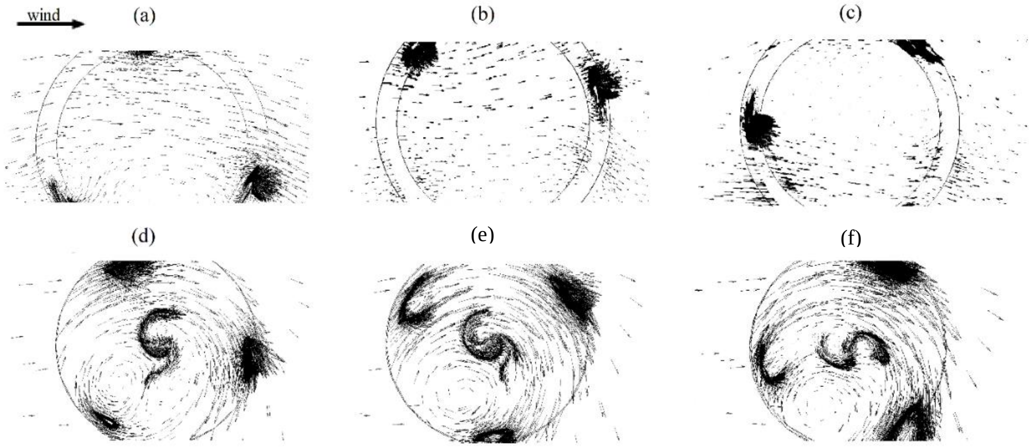


Figure 9. Vector maps for the single system (a, b and c) and the combined system (d, e and f) for different incident angles (ϕ) of the rotors

CONCLUSIONS

In the present paper, a numerical approach was used to simulate the performance of three vertical wind turbines, suitable for residential use. An SST k-omega turbulence model was employed and the rotation of the turbine was modeled by defining a rotating frame reference inside the main domain in steady-state. The turbines were simulated at all angles with respect to wind flow.

The Savonius wind turbine, with two semicircular buckets and end plates, generated a large amount of torque coefficient, rotating in relatively low rotation speed. Adding an extra stage significantly improved the consistency of the torque generation at different angles, but its power coefficient was poor and not satisfying (0.15 at TSR of 0.8). On the other hand, the Darrieus wind turbine performed better and the power coefficient increased to 0.3 at TSR of 1.6, although the generated torque was quite low and fluctuating, making it unsuitable for low speed or turbulent wind flow blowing in residential areas.

Finally, a combined Savonius-Darrieus wind turbine was introduced taking advantage of the merits of both the Savonius and the Darrieus turbines. It was almost as efficient as the Darrieus wind turbine, and the torque generated by Savonius blades helped it to provide less fluctuating torque. Furthermore, it could perform well in relatively low tip speed ratios (power coefficient of 0.3 at TSR of 1.1) with respect to the Darrieus turbine. It can be an excellent choice for residential areas since high-speed wind flow is not always available, and its cost is fairly low due to its simple structure.

REFERENCES

1. Bahaj, A.S., Myers, L. and James, P.A.B., 2007. Urban energy generation: Influence of micro-wind turbine output on electricity consumption in buildings. Energy and Buildings, 39(2): 154-165.
2. Antheaume, S., Maître, T. and Achard, J.L., 2008. Hydraulic Darrieus turbines efficiency for free fluid flow conditions versus power farms conditions. Renewable Energy, 33(10): 2186-2198.
3. Savonius, S.J., 1931. The S-rotor and its applications. Mechanical Engineering, 53(5): 333-338.
4. Marie, D.G.J., 1931. Turbine having its rotating shaft transverse to the flow of the current., U.S. Patent 1,835,018.
5. Jiang, C. and Yan, Q., 2007. Study on the comparison between the horizontal axis and vertical axis wind turbine. Shang Hai Electricity, 2: 163-165.
6. Sheldahl, R.E., Blackwell, B.F. and Feltz, L.V., 1978. Wind tunnel performance data for two-and three-bucket Savonius rotors. Journal of Energy, 2(3): 160-164.
7. Roy, S. and Saha, U.K., 2013. Review on the numerical investigations into the design and development of Savonius wind rotors. Renewable and Sustainable Energy Reviews, 24: 73-83.
8. Roy, S. and Saha, U.K., 2013. Review of experimental investigations into the design, performance and optimization of the Savonius rotor. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 227(4): 528-542.
9. Plourde, B.D., Abraham, J.P., Mowry, G.S. and Minkowycz, W.J., 2012. Simulations of three-dimensional vertical-axis turbines for communications applications. Wind Engineering, 36(4): 443-453.
10. Hayashi, T., Li, Y. and Hara, Y., 2005. Wind tunnel tests on a different phase three-stage Savonius rotor. JSME International Journal Series B Fluids and Thermal Engineering, 48(1): 9-16.
11. Kamoji, M.A., Kedare, S.B. and Prabhu, S.V., 2009. Performance tests on helical Savonius rotors. Renewable Energy, 34(3): 521-529.
12. Kang, C., Yang, X. and Wang, Y., 2013. Turbulent flow characteristics and dynamics response of a vertical-axis spiral rotor. Energies, 6(6): 2741-2758.
13. Chinchilla, R., Guccione, S. and Tillman, M.J., 2011. Wind power technologies: a need for research and development in improving VAWT's airfoil characteristics. Journal of Industrial Technology, 27(1): 1-6.
14. Mohamed, M., 2012. Performance investigation of H-rotor Darrieus turbine with new airfoil shapes. Energy, 47(1): 522-530.
15. Islam, M., Fartaj, A. and Carriveau, R., 2008. Analysis of the design parameters related to a fixed-pitch straight-bladed vertical axis wind turbine. Wind Engineering, 32(5): 491-507.
16. Migliore, P.G., Wolfe, W.P. and Fanucci, J.B., 1980. Flow curvature effects on Darrieus turbine blade aerodynamics. Journal of Energy, 4(2): 49-55.
17. Kirke, B.K., 1998. Evaluation of self-starting vertical axis wind turbines for stand-alone applications. Griffith University, Australia.
18. Gupta, R. and Biswas, A., 2010. Computational fluid dynamics analysis of a twisted three-bladed H-Darrieus rotor. Journal of Renewable and Sustainable Energy, 2(4): 043111-(1-15).
19. Debnath, B.K., Biswas, A. and Gupta, R., 2009. Computational fluid dynamics analysis of a combined three-bucket Savonius and three-bladed Darrieus rotor at various overlap conditions. Journal of Renewable and Sustainable energy, 1(3): 033110-(1-13).
20. Wakui, T., Tanzawa, Y., Hashizume, T. and Nagao, T., 2005. Hybrid configuration of Darrieus and Savonius rotors for stand-alone wind turbine-generator systems. Electrical Engineering in Japan, 150(4): 13-22.
21. Feng, F., Li, S., Li, Y. and Xu, D., 2012. Torque characteristics simulation on small scale combined type vertical axis wind turbine. Physics Procedia, 24: 781-786.
22. Kavade, R.K. and Ghanegaonkar, P.M., 2017. Design and Analysis of Vertical Axis Wind Turbine for Household Application. Journal of Clean Energy Technologies, 5(5): 353-358.
23. Wakui, T., Tanzawa, Y., Hashizume, T., Outa, E. and Usui, A., 2000. Optimum method of operating the wind turbine-generator systems matching the wind condition and wind turbine type. In World Renewable Energy Congress VI. Pergamon, pp. 2348-2351.
24. Ghosh, A., Biswas, A., Sharma, K.K. and Gupta, R., 2015. Computational analysis of flow physics of a combined three bladed Darrieus Savonius wind rotor. Journal of the Energy Institute, 88(4): 425-437.
25. Yanuarsyah, I., Djanali, V.S. and Dwiyantoro, B.A., 2018. Numerical study on a Darrieus-Savonius wind turbine with Darrieus rotor placement variation (Vol. 1983, No. 1). AIP Conference Proceedings. AIP Publishing. https://doi.org/10.1063/1.5046228
26. Menter, F.R., 1994. Two-equation eddy-viscosity turbulence models for engineering applications. AIAA Journal, 32(8): 1598-1605.
27. Siddiqui, A.S., Mian, S.N., Alam, M., ul Haq, M.S., Memon, A.H. and Energy, M.S.J., 2018. Experimental Study to Assess the Performance of Combined Savonius Darrieus Vertical Axis Wind Turbine at Different Arrangements. 2018 IEEE 21st International Multi-Topic Conference (INMIC). 2018. IEEE, pp.1-8.
28. Meijerink, J.A. and Van Der Vorst, H.A., 1977. An iterative solution method for linear systems of which the coefficient matrix is a symmetric Mathematics of Computation, 31(137): 148-162.
29. Kamoji, M.A., Kedare, S.B. and Prabhu, S.V., 2009. Experimental investigations on single stage modified Savonius rotor. Applied Energy, 86(7-8): 1064-1073.
30. Bravo, R., Tullis, S. and Ziada, S., 2007. Performance testing of a small vertical-axis wind turbine. In: Proceedings of the 21st Canadian Congress of Applied Mechanics (CANCAM07), Toronto, Canada, June. pp.3-7.
31. Sahim, K., Santoso, D. and Puspitasari, D., 2018. Investigations on the Effect of Radius Rotor in Combined Darrieus-Savonius Wind Turbine. International Journal of Rotating Machinery, 2018:1-7.

Persian Abstract

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چکیده

در سال‌های اخیر، بحران انرژی و گرمایش جهانی موجب توجه روزافزون به انرژی‌های نو مانند انرژی باد شده است. در بین انواع مختلف توربین‌های بادی، استفاده از توربین‌های بادی عمود محور برای تامین انرژی مناطق مسکونی بسیار مورد توجه قرار گرفته است. در این پژوهش، از یک شبیه سازی عددی سه بعدی برای پیش‌بینی عملکرد سه نوع توربین بادی کوچک عمود محور استفاده شده است. جهت این کار از یک چارچوب مرجع چرخان و مدل توربولانسی SST-K-omega بهره برده شده است. ابتدا توربین‌های نوع ساوونیوس و داریوس شبیه‌سازی شد که بازده پایین توربین ساوونیوس و عملکرد نامناسب نوع داریوس به علت سرعت نوک پره پایین به عنوان مشکلات اصلی این توربین‌ها شناسایی شدند. در نهایت، یک طرح پیشنهادی به صورت توربین ترکیبی از نوع ساوونیوس-داریوس ارائه گردید که علاوه بر بازده نزدیک به نوع داریوس (۰/۳)، پره‌های ساوونیوس آن میزان گشتاور تولید شده را در سرعت‌های نوک پره پایین افزایش می‌دهد تا با تولید یک گشتاور یکنواخت در سرعت‌های باد پایین و مناطق مسکونی قابل استفاده باشد.