Parametric Study of Hybrid Savonius-Darrieus Turbine

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Abstract—**The current work presents the study to predict the pressure and velocity field distributions for a hybrid two-bucket Savonius rotor and three blade egg-beater type Darrieus rotor vertical axis wind turbine using Fluent in ANSYS 15.0. Two cases of overlap conditions for the Savonius rotor i.e. 10.7% and 20.5% have been considered in this study. The Savonius rotor height is assumed approximately equivalent to rotor diameter and NACA 0012 airfoil cross-section has been considered for Darrieus rotor. Contours of relative velocity and static pressure have been obtained from simulation study and it has been observed that the high performance of the hybrid rotor can be attributed to the high relative speed observed in proximity of Darrieus rotor.**

Keywords— Vertical axis wind turbine; Savonius–Darrieus rotor; NACA 0012

I. Introduction

Vertical axis wind turbines have an attractive feature that they accept wind from any horizontal direction and do not need the complicated head mechanisms of conventional horizontal axis wind turbines. Moreover, they are simple in construction, self-starting and inexpensive. The resulting mechanical simplification is sufficient to warrant interest in any new vertical axis concept that arises. A hybrid Savonius–Darrieus vertical axis wind turbine has got better efficiency than a Savonius turbine alone and also has higher starting torque than a Darrieus turbine. But works on the combination of Savonius and Darrieus wind turbines are very scarce as very limited information related to them is available in literature. In view of this, a hybrid two bucket Savonius three blade Darrieus wind turbine has been designed. Such hybrid rotors can also be suitable for low wind speed applications as it provides high starting torque.R. Gupta et al. [1] have compared two blade Savonius and combined two blade Savonius three blade Darrieus experimentally in subsonic wind tunnel. The overlap variation was made in the Savonius rotor only. The authors reported an improvement in the power coefficient for Savonius-Darrieus machine compared to Savonius machine alone under the same operating conditions. R. Gupta et al. [2] in 2008 undertook a similar study with a three-bucket Savonius rotor system with provisions for overlap variations and a combination of three-bucket Savonius rotor placed ontop of the three-bladed Darrieus rotor. They tested them in a subsonic wind tunnel and observed 51% power coefficient at no overlap and recorded an improvement in the power coefficient for Savonius-Darrieus machine as compared to Savonius turbine alone under the same working conditions. R. Gupta et al. [3] carried out a CFD analysis to predict the power coefficient (Cp) and tip speed ratio (TSR) of a two-bucket Savonius turbine without any overlap and with 16.2%, 20%, 25%, 30% and 35% overlap conditions and then compared these values of Cp with experimental results. R. Howell et al. [4] presented an experimental as well as computational study for the aerodynamic performance of a small scale vertical axis wind turbine (VAWT). It has been observed that the performance coefficient reported from the two dimensional computational model was significantly higher than that of the experimental and the three-dimensional CFD model. The authors concluded the presence of the over tip vortices in the 3D simulations to be responsible for the large difference in efficiencies of 3D and 2D CFD models. M. Samanoudy [5] have designed, manufactured and tested a Giromill wind turbine to study the effect of pitch angle, number of blades, airfoil cross-section and its chord length, radius of turbine rotor on the performance of the wind turbine. It has been observed by the author that for effect of pitch angle, the obtained maximum power coefficient was decreasing and similar behavior was observed when decreasing the number of blades from four to two blades. Dobrev and F. Massouh [6] have made use of CFD to study the behaviour of a Savonius wind turbine to determine its performance under different flow field conditions. From the results obtained it has been analysed that maximum useful blade torque was produced at 27° angular position of the blade and that the blade convex side contributed nearly 80% to the total useful torque produced. M.R. Castelli et al. [7] have proposed a new performance prediction model for a straight bladed Darrieus wind turbine. The CFD model was used to determine the energy performance and aerodynamic forces acting on the blades of the vertical-axis Darrieus wind turbine. P. Sabaeifardet al. [8] have described theeffect of number of blades, airfoil type and turbine solidity on the performance of small scale straight-bladed Darrieus vertical axis wind turbine.From the results obtained it has been observed by the authors that the turbine with 35% solidity has the best self-

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starting ability and efficiency among all geometries. F. Feng et al. [9] have analysed a 50W rated power combined straight blade vertical axis wind turbine (CSB-VAWT) for starting torque, dynamic torque and power performance. R. Gupta and K. Sharma [10] has undertook a study of flow physics around a combination of three-bladed Darrieus and three-bucket Savonius wind turbine with overlap conditions ranging from 10.87% to25.87% for the Savonius part of the combined rotor using Fluent 6.0 CFD software. W. Widodo et al. [11] have presented Computational Fluid Dynamics (CFD) analysis to determine the pressure difference between convex and concave sides of the 5KW Savonius blade.

R. Gupta et al. [12] have analysed the power coefficients (Cp) for a Savonius wind turbine with helical rotor having its shaft at 45^0 twist angle. The authors have studied the turbine at different tip speed ratios and changing the rotor angle from 0° to 180°. It has been observed that the 45°, 90°, 225° and 270° rotor angles contributed maximum to the total power production. K. Morshed et al. [13] have performed different wind tunnel experiments on a three-bladed Savonius wind turbine scale models without overlap and with different overlap ratios to obtain pressure around the convex and concave surfaces of each blade and also to determine the static torque for the rotor. From the results of the study it has been observed that for higher Reynolds number, better performance coefficients were reported for the turbine model without overlap and at lower Reynolds number, the turbine model with moderate overlap conditions gave better results. M. Hameed and S. Afaq [14] has presented a new concept for the design of a small scale Darrieus wind turbine having straight and symmetrical blades using beam theories for the analytical modeling and ANSYS 11.0 for numerical modeling. P. Deshpande and X. Li [15] has performed a numerical study of three-bladed fixed pitch giromill-type VAWT for its aerodynamic at two different solidities (0.2 and 0.4) with symmetrical and unsymmetrical airfoils at wind velocities of 3m/s and 5 m/s. It has been observed that the maximum efficiency of themodeled airfoils was at a tip speed ratio of 3 and the highest power coefficient was observed to be 0.4 at 5 m/s. A. Biadgoet al. [16] have conducted numerical and analytical investigation on straight blade fixed pitch vertical axis wind turbine using airfoil NACA0012 as a blade profile to assess its performance. From the results obtained, the authors concluded that minimum performance at lower tip speed ratios for the modeled turbine could be attributed to the inability of NACA0012 to self-start. M. Ali [17] has conducted experimental investigations to compare the performance of two-blade and three-blade Savonius wind turbines. The author tested both the models in a subsonic wind tunnel and observed that under the same operating conditions, the two blade Savonius wind turbine performed more efficiently having higher power coefficient than three blade Savonius wind turbine. R. Lanzafame et al. [18] have prepared 2D CFD model for two different types of H-Darrieus turbines and validated the model by comparing the numerical results with experimental data available in scientific literature. The results demonstrated good capabilities of the Transition SST turbulence model over the classical fully turbulent models. G. Thanigaivel [19] has designed a 50W hybrid turbine to make Darrieus completely self-starting for the cut in speed and rated speed of 3m/s and 7m/s.

It has been observed from the literature available that work related to hybrid configuration of Savonius and Darrieus is very limited and also authors find it difficult to find a paper reporting the CFD based study of the combination under study. Keeping these in perspective, present paper aims at the parametric study has been conducted for a hybrid three-bladed Darrieus two-bucket Savonius vertical axis wind turbine using Fluent CFD software and the pressure and velocity contours obtained from the study have been presented here.

II. COMPUTATIONAL PROCEDURE

Based on the literature survey, a hybrid Savonius-Darrieus turbine with three blade Darrieus system and two bucket Savonius system has been designed and modeled for CFD simulations.

A. Physical Model

The Darrieus rotor is a three-bladed system and the Savonius rotor is a two-bucket system. In the hybrid configuration of Darrieus-Savonius rotor, the buckets of the Savonius rotor are 57.5mm diameter each, 3mm in thickness and 200mm in height [6]. The Darrieus rotor in the hybrid configuration has NACA 0012 airfoil cross–section with 40 mm chord and 200mm rotor diameter. Since the Savonius rotor has been placed inside the Darrieus rotor, therefore, height of the combined rotors is equivalent to height of Darrieus rotor. Thus the ratio of rotor diameter to rotor height is close to 1. Overlap is defined as the distance of theinner edge of the bucket from the axis of rotation assuming the arc is carried to the full semi-circle. Two different overlap conditions: 10.7% and 20.5% have been investigated in this paper. The central shaft of the rotors is 8mm in diameter. The endplate for Savonius rotor is 5mm thick and provides support to Savonius rotor. The CAD model of the hybrid turbine is shown in Fig. 1.

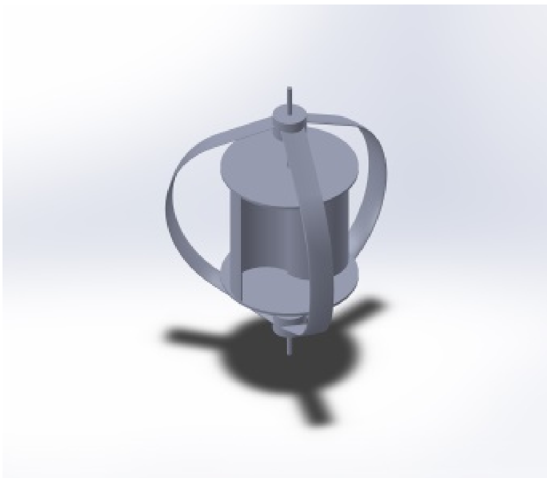

Fig. 1. CAD Model of the hybrid three-blade Darrieus and two-blade Savonius turbine.

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B. Computational Grid

The computational grid (mesh) has been generated in ANSYS Fluent. Fig. 2 shows the computational domain that has been used for the hybrid turbine. Velocity inlet and pressure outlet boundary conditions have been taken on the right and left boundaries respectively. The computational domain is 2.45m x 0.65m x 0.65m long, wide and high respectively. The length of the computational domain is such that inlet and outlet faces are five times the blade diameter distance away from the central axis of the hybrid turbine. Fig. 3 shows the mesh generated for the computational domain. The density of mesh has been kept high near the blade peripheries to get more accurate results as shown in Fig. 4.

C. Boundary Conditions and Turbulence Model

For CFD simulations, steady state incompressible flow has been considered. The moving reference frame method has been adopted as it takes less simulation time to study the condition in which an observer is moving with the rotating reference frame whereas the rotor is fixed with respect to the observer. The turbine has been analysed for a Tip Speed Ratio(TSR) of 0.3. A single reference frame has been used in this study.

The finite difference forms of continuity equations, Navier-Stokes and turbulence equations for an incompressible flow of constant viscosity have been solved by the in-built functions of the fluent CFD solver. The numerical simulation has been carried out by considering steady stateincompressible flow and solving the equations for conservation of mass, momentum and turbulence.

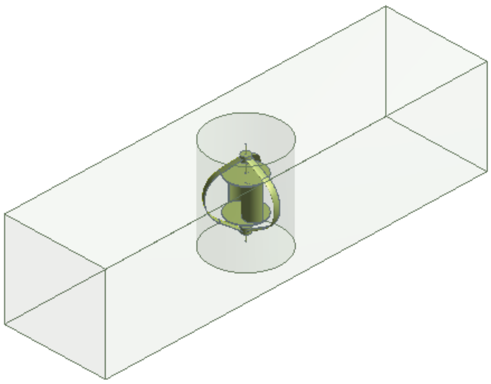

Fig. 2. Computational domain for hybrid Savonius-Darrieus turbine.

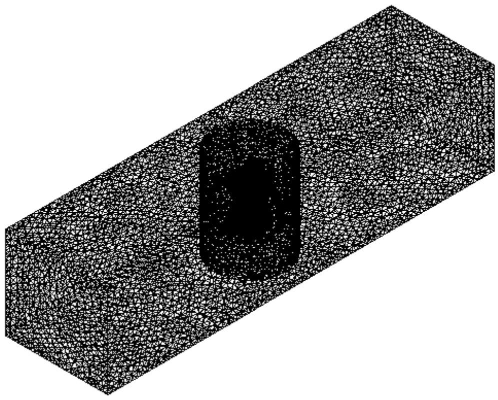

Fig. 3. Mesh generated for the computational domain

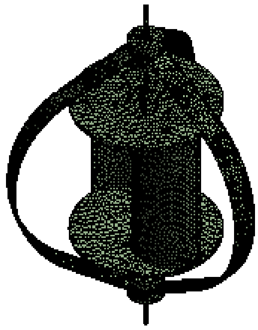

Fig. 4. Computational grid (mesh) for hybrid Savonius-Darrieus turbine.

The conservation of mass equation can be written in vector form as [10]:

$$\nabla.(\rho\overrightarrow{V}) = \vec{S}_m \quad (1)$$

Where the value of $\vec{S}_m$ is zero for steady state flow. The momentum equation in terms of relativevelocity, $\vec{V}_r$ in the vector form can be written as [10]:

$$\frac{\partial}{\partial t}\left(\rho\overrightarrow{V_r}\right) + \nabla.\left(\rho\overrightarrow{V_r}\overrightarrow{V_r}\right) + \rho\left(2\vec{\omega}\overrightarrow{V_r} + \vec{\omega}\vec{\omega}r\right) = -\nabla P + \nabla.(\bar{\bar{\tau}}) \quad (2)$$

From the eddy viscosity concept in Stokes' hypothesis for Newtonian fluids, the Reynolds stress tensor$\bar{\bar{\tau}}$ can be expressed as [10]:

$$\bar{\bar{\tau}} = \mu \quad (3)$$

The realizable k-ε turbulence model with standard wall functions has been used for CFD simulations. The modeled transport equations for *k* and ε are [10]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon - Y_m \quad (4)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (5)$$

Where k is turbulence kinetic energy, ε is rate of dissipation of turbulence kinetic energy,G_k represents the generation of turbulence kinetic energy due to mean velocity gradients, Y_m represents the contribution of dilatation in compressible turbulence to overall dissipation rate, $C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = S\frac{k}{\varepsilon}$, rest are model constants.

Table I shows the various boundary conditions that have been used in this study.

TABLE I: SOLUTION SPECIFICATION

Specification	Details
Solver	Steady, realizable (*k*- Є) model with standard wall function
Material	Air (Density (ρ) = 1.225 Kg/m^3, Viscosity(μ) = 1.7894e-05 Kg/m-s). Aluminium (Turbine) (ρ = 2719 Kg/m^3)
Operating Pressure	Atmospheric pressure (1.01325 x 10^5 Pa).
Boundary conditions	
Inlet	Velocity Inlet (4.5m/s)
Outlet	Pressure Outlet(Gauge pressure=0 Pa)
Solution Methods	
Pressure Velocity Coupling	SIMPLE(The sequential algorithm, Semi-Implicit Method for Pressure-Linked Equation)
Spatial Discretization	Pressure (Second Order) Momentum (Second Order Upwind)
Solution Controls	
Under-Relaxation Factors	Pressure(0.3) Momentum(0.7)
Residual Monitors	0.001 (continuity, x-velocity, y-velocity, *k*, Є).
Force Monitors	Drag Monitor, Lift Monitor and Moment Monitor.
Solution Initialization	
Initialization Method	Standard Initialization
Initialization	Inlet

III. RESULTS AND DISCUSSIONS

In this section the results obtained from the CFD study have been presented.

- The developed CFD model in present study has been validated by comparing the results with those of available in scientific literature [6]. Figs. 5 (a, b) shows the comparison of results available in literature and the results obtained. It has been observed from these figures that the profiles of velocity fields are almost of same nature.

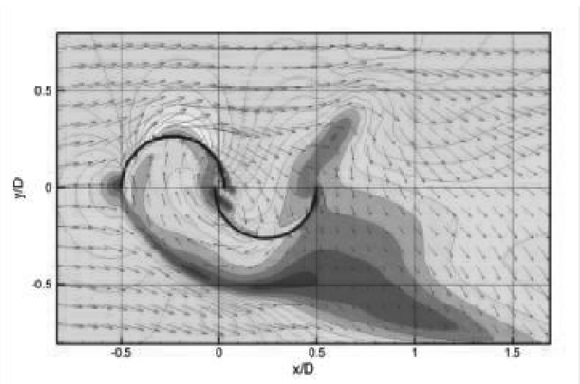

Fig. 5(a). Velocity fields as reported by I. Dobrev and F. Massouh [6]

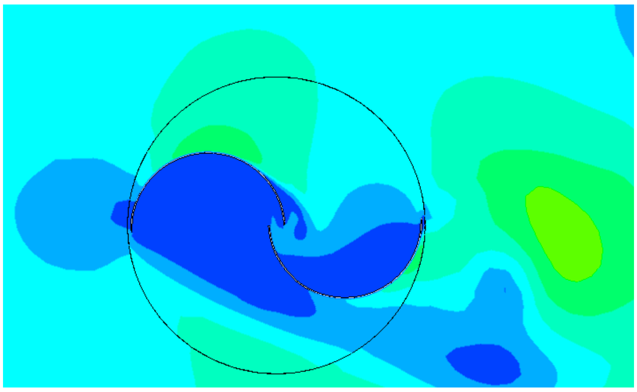

Fig. 5(b). Velocity fields obtained from the CFD model under same test operating conditions.

- The relative velocity contour and pressure contour for 10.7% overlap condition is shown in Figs. 6 (a) and 6 (b) respectively. It has been observed that the maximum value of relative velocity is 8.52m/s for inlet velocity of 4.5m/s near the Darrieus rotor and the maximum reported pressure is 25.21Pa in proximity of Savonius rotor.

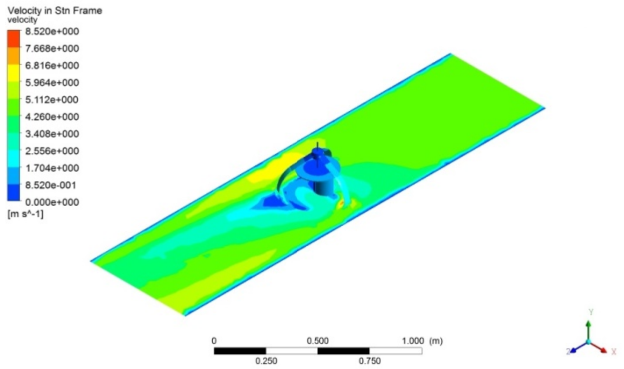

Fig. 6(a).Relative Velocity Contour for the hybrid turbine with Savonius rotor at 10.7% overlap.

- The relative velocity contour and pressure contour for 20.5% overlap condition is shown in Figs. 7 (a) and 7 (b) respectively. It can been analysed that the maximum value of relative velocity is 8.29m/s for inlet velocity of4.5m/s near the Darrieus rotor and the maximum reported pressure is 23.76Pa in proximity of Savonius rotor.

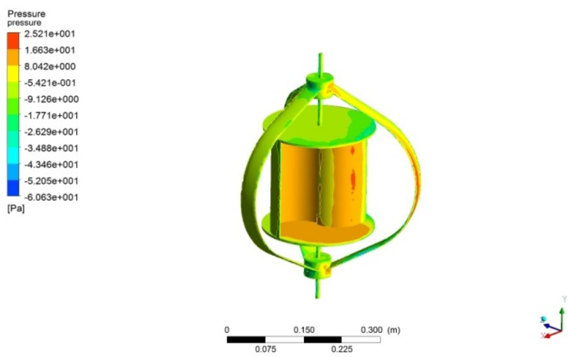

Fig. 6(b). Pressure Contour for the hybrid turbine with Savonius rotor at 10.7% overlap.

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- On comparing the pressure and relative velocity contours for the two overlap conditions it has been observed that on increasing the overlap from 10.7% to 20.5%,the value of relative velocity reduced from 8.52m/s to 8.29m/s whereas the value of maximum pressure reduced from 25.21Pa to 23.76Pa.

IV. Conclusions

The hybrid model of Savonius and Darrieus has been developed. The parametric study of the same clearly shows the effect of overlap variation on the performance of the rotor. During the study, it has been observed that the wind speed relative to the hybrid rotor is high in the proximity of the blades of the Darrieus rotor. On decreasing the overlap ratio from 20.5% to 10.7%, it has been observed that there has been an increase of2.77% in relative wind velocity and 6.1% in maximum value of pressure. Therefore good aerodynamic performance of the hybrid rotor and high power coefficient due to increased wind speed near the Darrieus blades are the benefits of the proposed hybrid configuration.

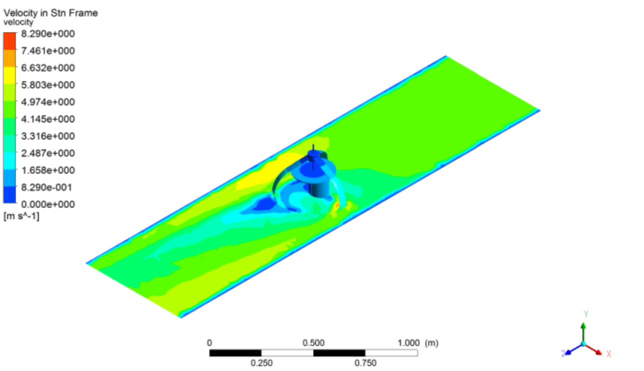

Fig. 7(a). Relative Velocity Contour for the hybrid turbine with Savonius rotor at 20.5% overlap.

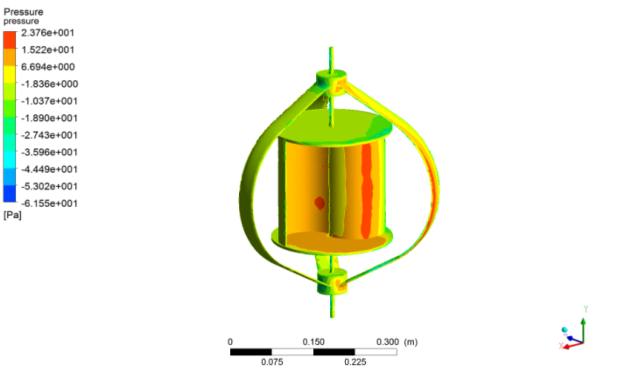

Fig. 7(b). Pressure Contour for the hybrid turbine with Savonius rotor at 20.5% overlap.

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