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Conference paper

Numerical investigation of turbulent flow over a small-scale vertical axis wind turbine

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ABSTRACT

The present paper aims to analyse the aerodynamics of turbulent fluid flow over a vertical axis wind turbine (VAWT). A 2D study is carried out for a two-bladed SAVONIUS wind turbine, where the rotor diameter is D=20cm. The governing equations (Unsteady Reynolds Averaged Navier Stokes URANS) are solved numerically using a CFD (computational fluid dynamics) open-source code based on the finite volume method; the SST k-ω turbulence model is applied for the system closure. An arbitrary mesh interface (AMI) technique is applied at the sliding interface boundary, which is a circular surface separating between the rotating zone and the fixed zone where the mesh remains stationary. The numerical results allow predicting the vorticity and pressure distributions over a rotating wind turbine for different tip speed ratios in order to characterize the generated wake. The velocity deficit is calculated for different positions behind the rotor to characterize the disturbance rate of the flow.

1. INTRODUCTION

According to a report by the International Energy Agency (IEA), wind energy is one of the fastest-growing sources of electricity globally, with installed wind capacity increasing by 15% in 2020 despite the disruptions caused by the COVID-19 pandemic (IEA, 2020). This growth is driven by various factors, including technological advancements for both onshore and offshore (la Tour, 2023), favourable government policies, and declining costs. Another report by the National Renewable Energy Laboratory (NREL) examined the benefits of integrating wind energy into the electricity grid, including improved grid reliability and resilience, reduced emissions, and lower energy costs (NREL, 2021).

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Vertical axis wind turbines (VAWT) are useful in small facilities for low power capacity, the most important advantage compared to horizontal axis wind turbines (HAWT) is the independency of the orientation system. One of the most used is the SAVONIUS, a VAWT based on the conversion of the kinetic energy of wind to mechanical energy, where the drag is the acting aerodynamic force. After the invention of the SAVONIUS wind turbine (la Tour, 2023), many studies have been carrying out to improve and characterize the SAVONIUS aerodynamics:

The performances of a tiny Savonius were investigated experimentally and numerically by Dobrev & Massouh, 2021. The outcomes demonstrate how well the 3D Detached Eddy Simulation (DES) matches the experimental findings. Wenehenubun, Saputra & Sutanto, 2015 compared the efficiency of two, three, and four-bladed Savonius rotors in order to investigate the effect of the number of blades on a Savonius. They found that the three-bladed rotors are more efficient in higher λ, while the four-bladed rotors perform well with lower tip speed ratios.

Hesami & Nikseresht, 2021 and Hesami, Nikseresht & Mohamed, 2022 investigated the viability of a single and twin Savonius rotor with wind-lens using high-fidelity numerical simulations. The outcomes demonstrate a notable increase in power provided by the newly constructed system.

In the present research study, the aerodynamics of a small-scale vertical-axis wind turbine is examined and analysed using computational fluid dynamics simulations; the downstream flow structure is analysed, in term of velocity and pressure distribution, for different tip speed ratio values.

2. MATHEMATICAL MODELLING AND NUMERICAL APPROACH

The unsteady Navier Stokes equations for a turbulent incompressible flow are solved numerically using the finite volume method.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_i}\left(u_i u_j - \tau_{ij}\right) = -\frac{\partial p}{\partial x_j} \tag{2}$$

Turbulence is modelled by the two-equation SST k-ω turbulence model, involving the turbulent kinetic energy k and the specific dissipation rate ω (Menter, 1994):

$$k = \frac{3}{2}(\bar{U} I)^2 \tag{3}$$

$$\omega = \frac{k}{C_\mu \epsilon} \tag{4}$$

Where $\bar{U}$ is the mean velocity value, I is the turbulence intensity, C_μ is a constant and ε represents the turbulent energy dissipation.

In order to simulate the fluid flow around a rotating wind turbine of a diameter D, a hybrid mesh is generated in a rectangular domain, where the VAWT axis is located at 10 D from the fluid inlet and the top and bottom sides. The distance between the outlet and the VAWT axis is 40 D, however, the free stream flow conditions are reached at the domain boundaries (figure 1), where zero gradient condition is obtained at the top and bottom boundaries, and no incoming flow at the outlet boundary.

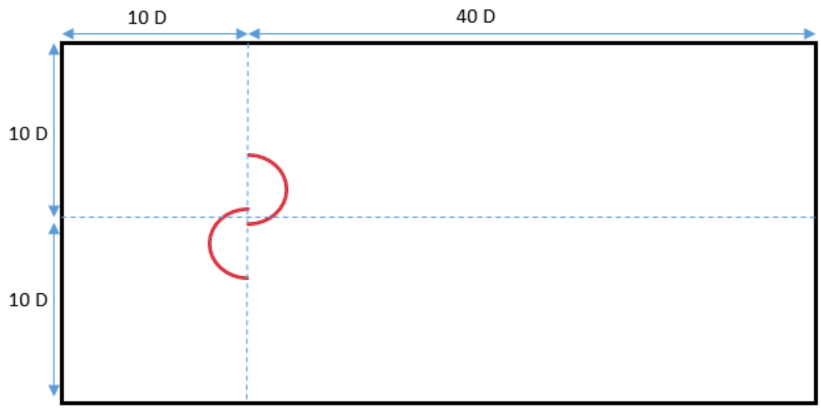


Fig 1. Computational domain

The CFD open-source code used (openfoam) is based on the finite volume method; a hybrid mesh is generated for the prescribed computational domain composed of 95000 cells. Inlet condition is given to the left side of the domain; however, the velocity is initiated as follows:

$$U_\infty = \begin{pmatrix} 9 \\ 0 \\ 0 \end{pmatrix} m/s \tag{5}$$

In order to reduce the computations time, a wall function is applied to the wall boundaries (blades and hub). For this purpose, the dimensionless first layer thickness of the mesh (y^+) is fixed between 50 and 80 due to the dynamic behaviour of the VAWT.

$$y^+ = \frac{\Delta y \, u_\tau}{\nu} \tag{6}$$

Where: Δy is the first grid cell high, u_τ is the friction velocity and ν is the kinematic viscosity

An implicit scheme is applied for the temporal discretisation and the PIMPLE algorithm is used for the pressure-velocity coupling (Greenshields, 2023). An adjustable time-step Δt configuration is used for the computations to ensure the Courant-Friedrichs-Lewy condition CFL<1.

3. RESULTS AND DISCUSSION

A two-bladed SAVONIUS wind turbine is considered for the present research. The unsteady Reynolds Averaged Navier Stokes equations are solved numerically where computations are performed for a time T corresponding to 10 rotational periods (Dobrev & Massouh, 2021) in order to reach the revolutions stability.

The moment, lift and drag coefficients evolution are depicted in figure 2. Since the SAVONIUS wind turbine is based on the drag force, the drag coefficient is higher than the lift coefficient where it has a positive value for most positions taken by the blade except when the blade is near the -90º position.

The pressure distribution is shown in figure 3 for the horizontal and the vertical positions. The high pressure applied on the concave surface of the blade conducts to drag the blade in the flow direction and then provokes a rotational motion.

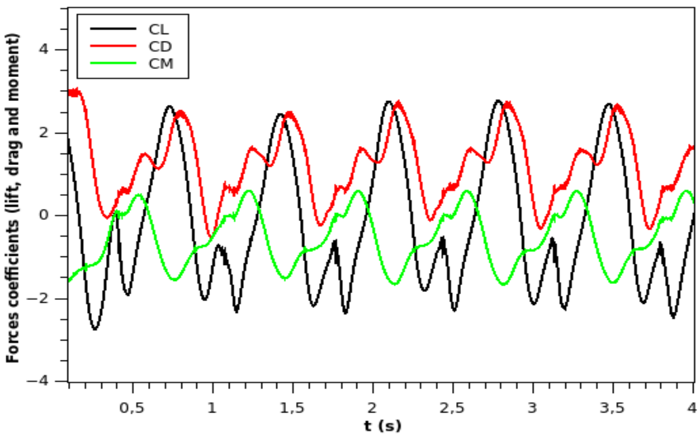


Fig 2. C_L, C_D and C_M variation

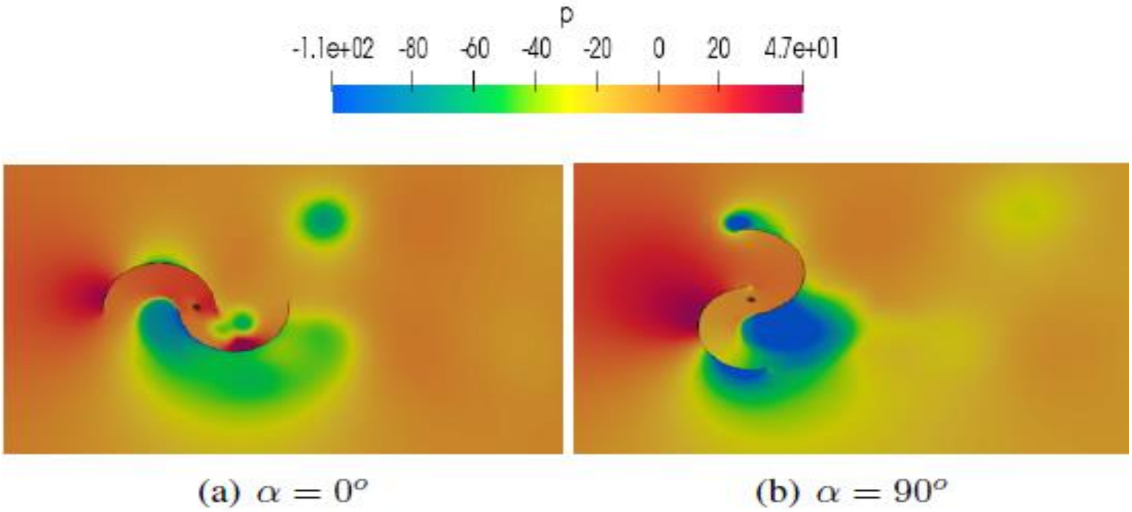


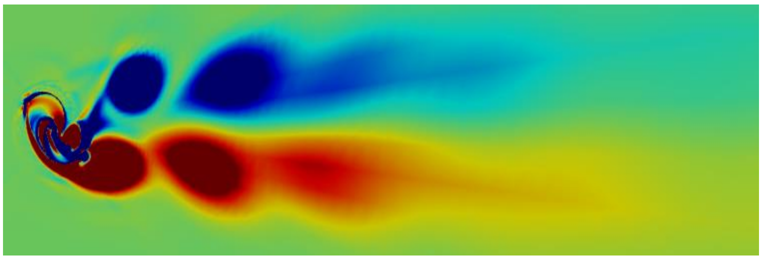
Fig 3. Pressure distribution

Figure 4 shows the vorticity distribution downstream the rotor for different λ.

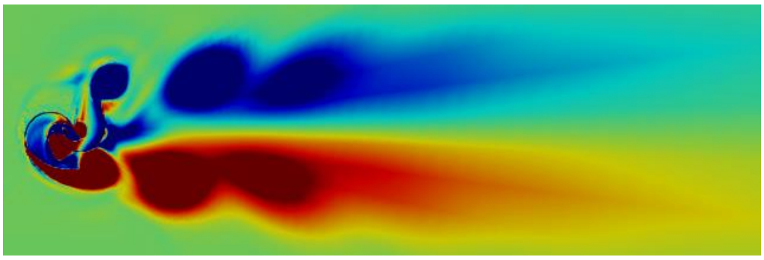
At the lower tip speed ratio of λ = 0.7 (a), we observe two distinct vortex structures downstream of the rotor. These vortices are counter-rotating, indicating the presence of strong shear layers and regions of high vorticity. The vortices are relatively intense and concentrated, suggesting significant energy extraction from the wind by the rotor at this tip speed ratio.

As the tip speed ratio increases to λ = 0.9 (b), the vortex structures appear to be more diffused and less intense compared to the lower tip speed ratio case. The counter-rotating behavior is still present, but the vortices are weaker and more spread out in the wake region downstream of the rotor.

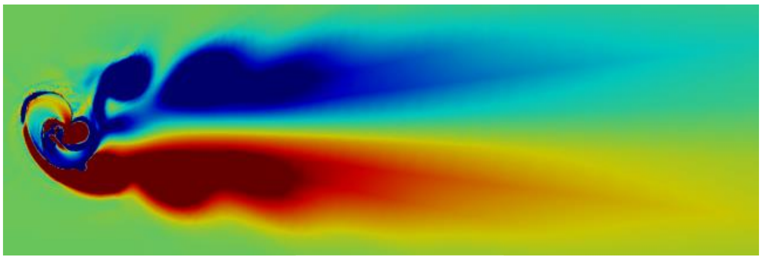
At the higher tip speed ratio of λ = 1.1 (c), the vorticity distribution becomes more evenly distributed, and the distinct counter-rotating vortex structures are less prominent. The wake region downstream of the rotor appears to be more uniform, with lower vorticity levels compared to the previous cases.



a) λ=0.7



b) λ=0.9



c) λ=1.1

Fig 4. Vorticity magnitude

The downstream flow disturbance is shown in figure 5, the velocity deficit is most pronounced at the closest downstream positions (nearwake region), with a deep, narrow profile. This indicates a significant reduction in wind speed immediately behind the rotor due to the energy extraction by the rotor blades.

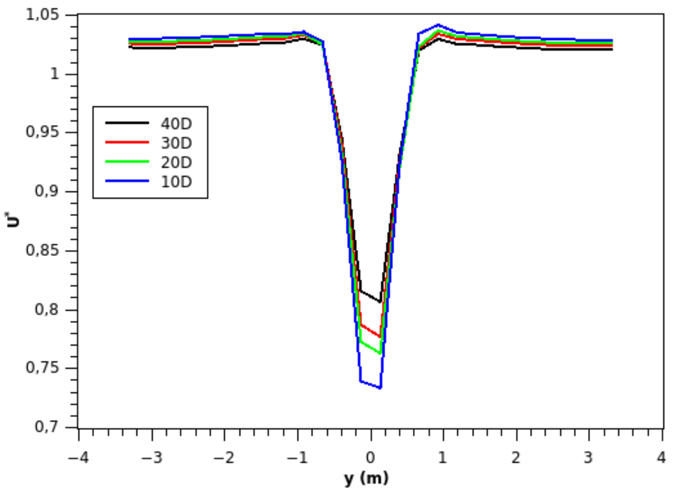


Fig 5. Velocity deficit for different downstream positions

4. CONCLUSION

Wind power production is strongly related to the suitable design of the rotor, for this purpose, the aerodynamic study of flow around the blades is an important step to be carried out. The present research study allows the prediction of the aerodynamic forces on a SAVONIUS rotor undergoing a turbulent flow, the pressure distribution is shown for different times as well. The vorticity distribution downstream is influenced by the tip speed ratio, where specific vorticity patterns appear forming downstream wake.

In order to enhance the aerodynamic efficiency of the Savonius rotor, it is proposed for further studies to provide the turbine with deflectors, where the flow is focused on the blades; the aim is to design a configuration of wind lenses that leads to decrease the negative torque.

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