

# Aerodynamic design and optimization of a Darrieus H-Rotor wind turbine: Structural analysis and performance optimization

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**Abstract:** As a contribution to the energy transition and the search for new sustainable solutions for decentralized electricity generation, this paper aims to design and optimization of a new type of Darrieus H-Rotor VAWT, specially tailored to the conditions of an urban and industrial environments. It is intended to be a robust and efficient wind turbine that can deliver a nominal power of 2 kW at low and moderate wind speeds. The methodology used is based on the analysis of wind resources (Mean Wind Speed, Weibull distribution), aerodynamic modeling using QBlade. Structural analysis using CATIA revealed that the Configuration of the second case (with 4 mm blade thickness and 4 vertical supports of 2 mm) offered an excellent compromise, achieving a reduced mass (13 kg) and a controlled maximum stress (85.4 MPa), well below the elastic limit of aluminum. From an aerodynamic perspective, CFD simulations using ANSYS Fluent (k- $\omega$  SST turbulence model in transient regime) enabled the visualization of the Cl/Cd ratio and pressure distribution at various angles of attack, thereby validating the effectiveness of the selected configuration. In this study, an optimized wind turbine blade design has been developed that is not only structurally robust and aerodynamically efficient, but also well-suited for deployment in urban environments.

**Keywords:** Darrieus H-Rotor wind turbine, Vertical axis wind turbine, Aerodynamic optimization, CFD simulation, Structural analysis, Urban wind energy.

## 1. Introduction

Wind energy stands out among the renewable energy sources with huge potential in the generation of electricity, following the growth in popularity since the beginning of the 2000s. Wind turbines are commonly classified based on the axis around which they rotate into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). While HAWTs are widely used in medium- and large-scale power production applications across the world, their effectiveness is highly compromised in urban locations where the wind velocity is low, turbulent, and highly variable, making it hard for horizontal axis machines to perform optimally in such settings [1]. In this regard, VAWTs are seen as a more viable choice for urban settings owing to their effectiveness in harnessing wind energy in weak and varying conditions, reduced noise and safety risks, and visual appeal compared to HAWTs [1,2].

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The Darrieus H-Rotor type of VAWTs has received considerable research interest over time due to its unique aerodynamic properties, design simplicity, and possible improvement in efficiency.

In the last ten years, research in the field of Darrieus-type vertical axis wind turbines (VAWTs) has made significant progress, particularly due to computational fluid dynamics simulations, leading to a much deeper understanding of the complex aerodynamics involved. Optimization of blade shapes, efficiency, stability, and self-starting features have been among the main areas explored through research activities. In a recent work, Fertahi et al. [3] presented a thorough review of developments in designing and analyzing Darrieus VAWTs within the period 2014-2024, discussing the aspects of optimization as well as the aerodynamics of the turbine. Ahmad et al. [4] concluded that a solidity of 0.625 can help in achieving a  $C_p$  value of 0.37 at a TSR of 2.5, while increasing solidity widens the operational range, and multi-rotor turbines with a blockage ratio of 0.893 increased the power extraction capability by 37.3%. The study done by Satrio et al. [5] analyzed the positioning of the upstream cylindrical obstacle, where a perfect position ( $x/D = 0.0$ ;  $ds/D = 0.5$ ) was found to increase the value of  $C_p$  by 28.4%. The work by Ansaf et al. [6] used metamodeling techniques (Kriging, experimental designs), together with Nelder-Mead optimization, to orient the vanes with maximum efficiency of 177%.

The area of self-starter performance was also considered, with Celik et al. [7] working with J-shaped blades and reporting remarkable improvement in their dynamic startup performance, especially where the opening is outwards and the pitch angle is positive, while the thick NACA 0018 section was found to perform better than cambered profiles. In another study by Iddou et al. [8], various turbulence models were evaluated for VAWTs through ANSYS Fluent, including Spalart–Allmaras, SST  $k-\omega$ , TSST, and realizable  $k-\epsilon$ .

In addition to the aerodynamic studies, studies concerning the structural behavior of VAWT blades have also gained significance, especially focusing on the impact of materials used on the efficiency and safety of the blades. In a study by Hameed et al. [9], the structural behavior of straight-bladed H-Darrieus VAWT blades with Glass-Epoxy Composite material having SHELL99 elements was analyzed using ANSYS software. By substituting Aluminium with Glass-Epoxy, which has lesser density, greater strength, and improved strength-to-weight ratio, the centrifugal force was considerably decreased. The optimum stacking order of plies, ( $[45^\circ/90^\circ/0^\circ/-45^\circ]$  S), yielded maximum bending stress of 74.9 MPa to 54.6 MPa, and maximum deflection from 4.86 mm to 4.493 mm.

The area of urban applications has been greatly aided by CFD research in recent years as well. Abhinav et al. [10] performed a thorough study of H-type Darrieus wind turbine aerodynamics in urban settings, considering how blade geometry, TSR, and environmental factors affect performance. Jang et al. [11] analyzed the performance of H-Darrieus small vertical axis wind turbines, stressing the need to combine CFD analysis with experiments to get correct predictions. In addition, Salvador-Gutiérrez et al. [12] performed a bibliometric and technological assessment of vertical-axis wind turbines, revealing global trends in research, current technological deficiencies, and increasing importance of VAWTs in urban and decentralized energy systems. Díaz et al. [13] performed a systematic assessment of tropical regions with VAWTs and identified 48 papers, with 49% being site measurements, 22% CFD simulation, and 17% climate forecasting. At the same time, there was no focus on VAWT performance during extreme weather conditions. Lastly, Peng et al. [14] offered some general recommendations on modeling VAWT using CFD

analysis, such as choosing an appropriate turbulence model, proper discretization scheme, computational domain, and accounting for aerodynamic noise.

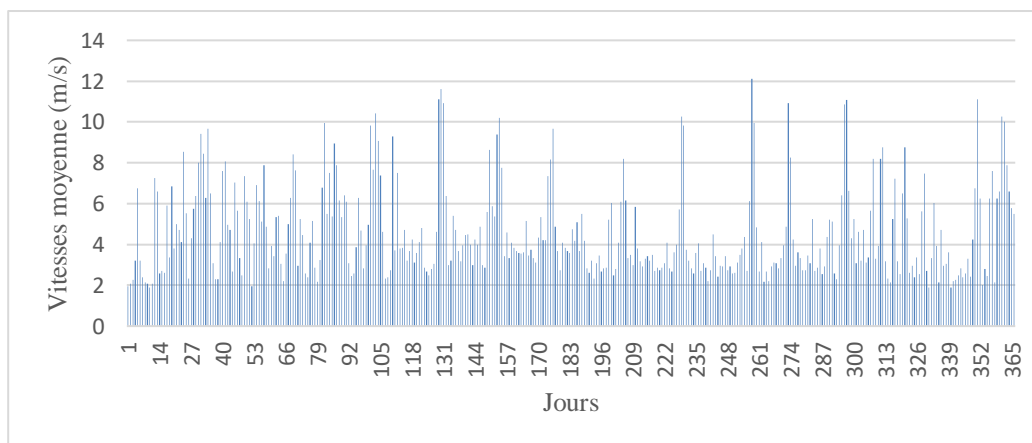
Based on the conclusions reached through the above-mentioned studies in terms of aerodynamic optimization, mechanical strength, and adaptability to site conditions, as well as recognizing the relatively limited amount of research on small-scale urban VAWTs tailored to the conditions of Morocco's urban climate, this paper attempts to provide an integrated approach for the design of Darrieus H-Rotor VAWTs, with the focus on three main approaches, namely aerodynamic design and optimization with QBlade software, structural design and assessment with CATIA software, and CFD numerical simulation with ANSYS Fluent software, in order to achieve a highly efficient, light-weighted, and robust wind turbine generator.

## 2. Methodology

### 2.1. Wind Resource Assessment

Figure 1 presents the changes of the daily average wind speed throughout a year. As seen from this graph, the wind resource exhibits considerable fluctuation on the daily timescale. There are several instances where the daily wind speed exceeded 10 m/s, which means that there were days when very strong winds occurred, which would result in substantial energy output. Nevertheless, there are also many instances when the wind speed was relatively low, even lower than 2 m/s, especially during day 180-260, i.e., the summer period.

Such variations stress the necessity of analyzing the wind source carefully to determine how the wind turbine will perform on a daily basis and guarantee that it will be reliable. They also emphasize the necessity of designing a mechanism that can sustain high variations in wind velocity and still maintain energy production stability.



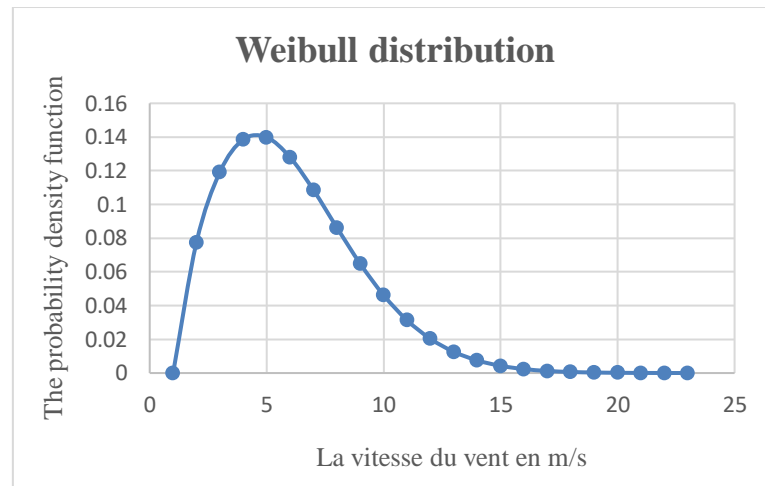
*Figure 1 : Average wind speed variation over one year*

Because wind velocity varies temporally and spatially, its behavior can be modeled using statistics. One model that is widely used for this purpose, particularly in intertropical areas, is the Weibull function. It can capture the wind velocity variability and provide an estimation of the likelihood of wind velocities. This analysis provides valuable insights into the wind velocity situation and evaluates wind turbine performance [15].

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \times e^{-\left(\frac{v}{c}\right)^k} \quad \text{Avec : } \begin{cases} c = 1.125V_m / (1 - B) \\ k = 1 + 0.482 (V_m - 2)^{0.51} \\ B = 1 - 0.81 (V_m - 1)^{0.089} \end{cases} \quad (1)$$

The wind analysis results indicate an average wind speed  $V_m$  of 4.65 m/s, with the Weibull distribution parameters defined by  $B = 0.092886$ , a scale parameter  $c=5.666462$ , and a shape parameter  $k=1.779878$ .

Figure 2 shows the probability density function of wind speeds at the site, with the most frequent speed around 5 m/s.



**Figure 2 : Weibull Distribution**

## 2.2. Aerodynamic Design

The earlier research findings revealed the superior aerodynamic performance of NACA 0015 at specific circumstances, whereas NACA 0018 is better with higher lift, but slightly more drag [16]. NACA 0018 works best with low Reynolds number and is both structurally strong and aerodynamically efficient, making it ideal for small VAWTs. Testing the performance of NACA 0018 airfoil with low Reynolds numbers ranging from 50,000 to 200,000 under various turbulence levels showed the ability of NACA 0018 to perform well because of its good trade-off between aerodynamics and structure [17].

Simulation results from QBlade for NACA 0018 airfoil based on Tangier's medium but gusty wind condition proved that it is indeed the most appropriate one. With its thick design, it offers stability in terms of stall as well as high L/D ratio of  $\sim 50$  at  $\alpha \approx 7^\circ$  with a minimum of 30 L/D at  $\alpha \leq 12^\circ$  where stall occurs at around  $\alpha \approx 8^\circ$ . In contrast, simulation results from QBlade revealed that NACA 0015 has better aerodynamic properties when operating at smaller angles of attacks but has less stability in stall and lower maximum lift values.

Turbine sizing is done by running simulations with different setups with maximum wind velocity of 11 m/s, TSR of 2.5, and chord length of 0.37 m. Simulation results reveal that the higher the height and the larger the diameter of the turbine setup, the better the power generated. The most optimized setup was found to be at  $H = 3$  m and  $R = 1.2$  m giving  $C_p$  of 0.4.

Considering Formula 2, several values of solidity ( $\sigma$ ) were chosen to calculate the chord length that corresponds to each one. All these data were employed to calculate the Reynolds number for

each configuration to assess the aerodynamic performance using QBlade. In particular, the maximum value of  $C_p$  (power coefficient) was evaluated. The results are presented in Table 1 and show that there is a reverse dependence between solidity and  $C_p$ . As the former parameter grows, the latter parameter reduces. In particular, the most effective aerodynamic configuration corresponds to  $\sigma = 0.15$ . As a result, the chord length equals 0.37 m.

$$\sigma = \frac{B \times c}{2\pi \times R} \rightarrow c = \frac{\sigma \times 2\pi \times R}{B} \quad (2)$$

*Table 1 : Chord length as a function of solidity*

Solidity	c (m)	Re	Cp (max)	Pmax (W)
0.15	0.3768	291356.4	0.42	2400
0.20	0.5024	388475.2	0.38	2200
0.25	0.628	485594.1	0.36	2100

### 2.3. Structural Design

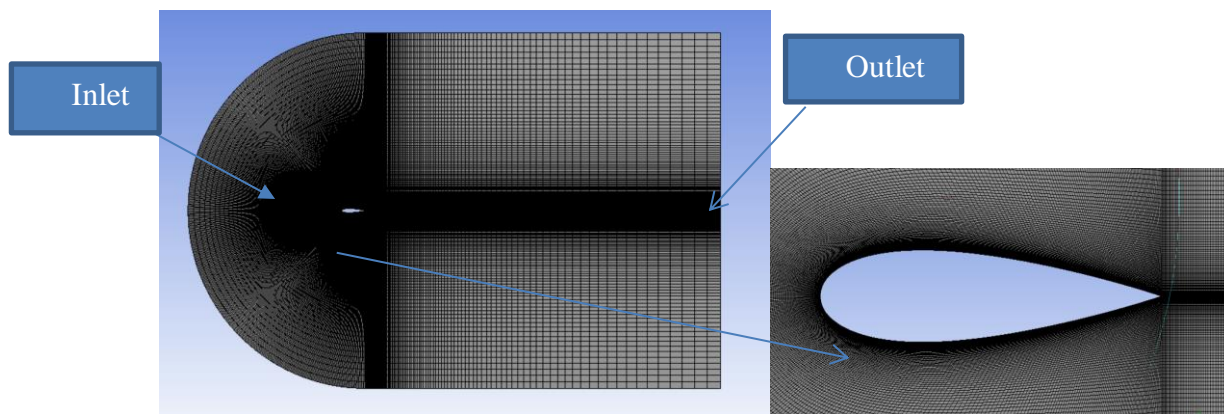
Two different geometries have been considered in order to ensure reinforcement of the blade and keeping in view its mass, as listed in Table 2. The simulation of these geometries in CATIA software will help in determining their stress levels according to Von Mises and mass.

*Table 2 : Description of the different configurations*

Case	Configuration	Thickness	Internal Supports	Mass (kg)
1	Blade 4 mm + 4 vertical supports	4 mm	4 × (2 mm × [58, 64, 58, 42] mm × 3 m)	13
2	Blade 4 mm + 4 NACA0018 supports	4 mm	4 × (2 mm × 370 mm × 66 mm)	12.5

### 2.4. CFD Simulations

Figure 3 illustrates the meshing process that was performed around the NACA airfoil for the 2D CFD analysis using ANSYS software. A structured mesh was used, where there was an even spacing of elements, particularly within the vital parts around the airfoil. High-density meshes were employed near the leading edge and trailing edge of the airfoil to precisely simulate boundary layer interactions and significant pressure variations. It is important to note that mesh refinement was performed gradually close to the airfoil, while coarse meshing was done further away to minimize computational costs.



*Figure 3 : Meshing of the NACA airfoil in ANSYS Fluent*

The boundary conditions were defined as follows: a velocity inlet with a constant speed of 5 m/s and a pressure outlet set to 0 Pa. For each angle of attack, the flow direction was adjusted using the X and Y velocity components calculated from the corresponding formulas.

- X component :  $V_x = V \cdot \cos(\alpha)$
- Y component :  $V_y = V \cdot \sin(\alpha)$

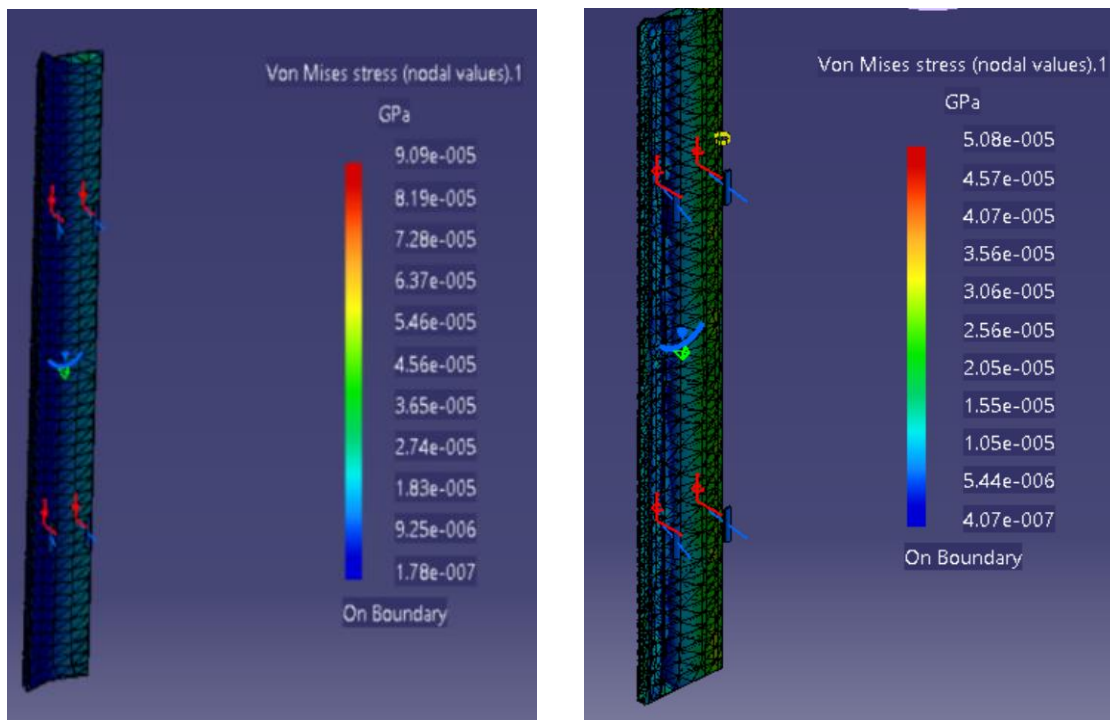
### 3. Results and discussion

#### 3.1. Structural analysis of the blades

For this study, FEA was carried out using CATIA software for Von Mises Stress analysis of two blade designs that lack support, as shown in Figure 5 below. The Octree Tetrahedral Mesh was used for more accurate prediction of stresses at a minimal computational expense. The use of this mesh helps analyze the mechanical behavior of the structures when subjected to rotating forces by computing the equivalent stresses, thus identifying areas that might experience failure.

In Figure 5a, the first configuration, with a weight of 12 kg, achieves its highest level of stress at 90.9 MPa. On the other hand, in Figure 5b, the second configuration, which has a marginally higher weight of 13 kg, has a lower peak value of stress at 85.4 MPa, as well as a more even stress distribution along the blade. While both designs stay comfortably under the limit of the aluminum yield strength (240 MPa), the second design has a superior mechanical behavior.

Accordingly, the second case was chosen as the best approach due to the most appropriate compromise of its structural resistance and mass, considering a maximal stress value equal to 85.4 MPa and a safety factor amounting to approximately 2.8. Thus, safe functioning is assured at specified loads, whereas the likelihood of deformation can be excluded. Consequently, such a blade model is considered to be applicable to H-rotor wind turbines..



5a

5b

Figure 4 : Von Mises stress distribution (in GPa) of the six configurations

### 3.2. Results of 2D CFD simulations

It can be seen from the first set of results, displayed in figure 6 below, that there is an increase in the lift to drag ratio ( $C_l/C_d$ ) with an increase in angle up to  $4^\circ$ . There is then a maximum at about 8.8 at  $10^\circ$  and the ratio drops off after that point due to partial stall, confirming that  $10^\circ$  is optimum.

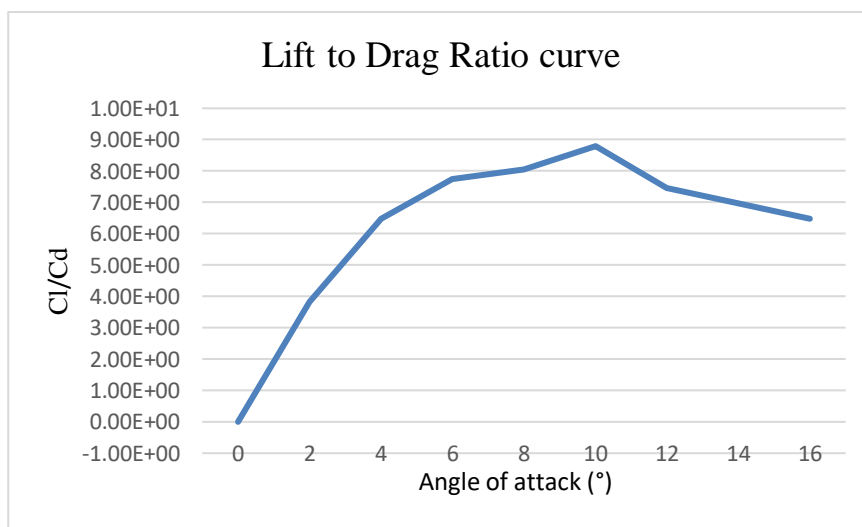
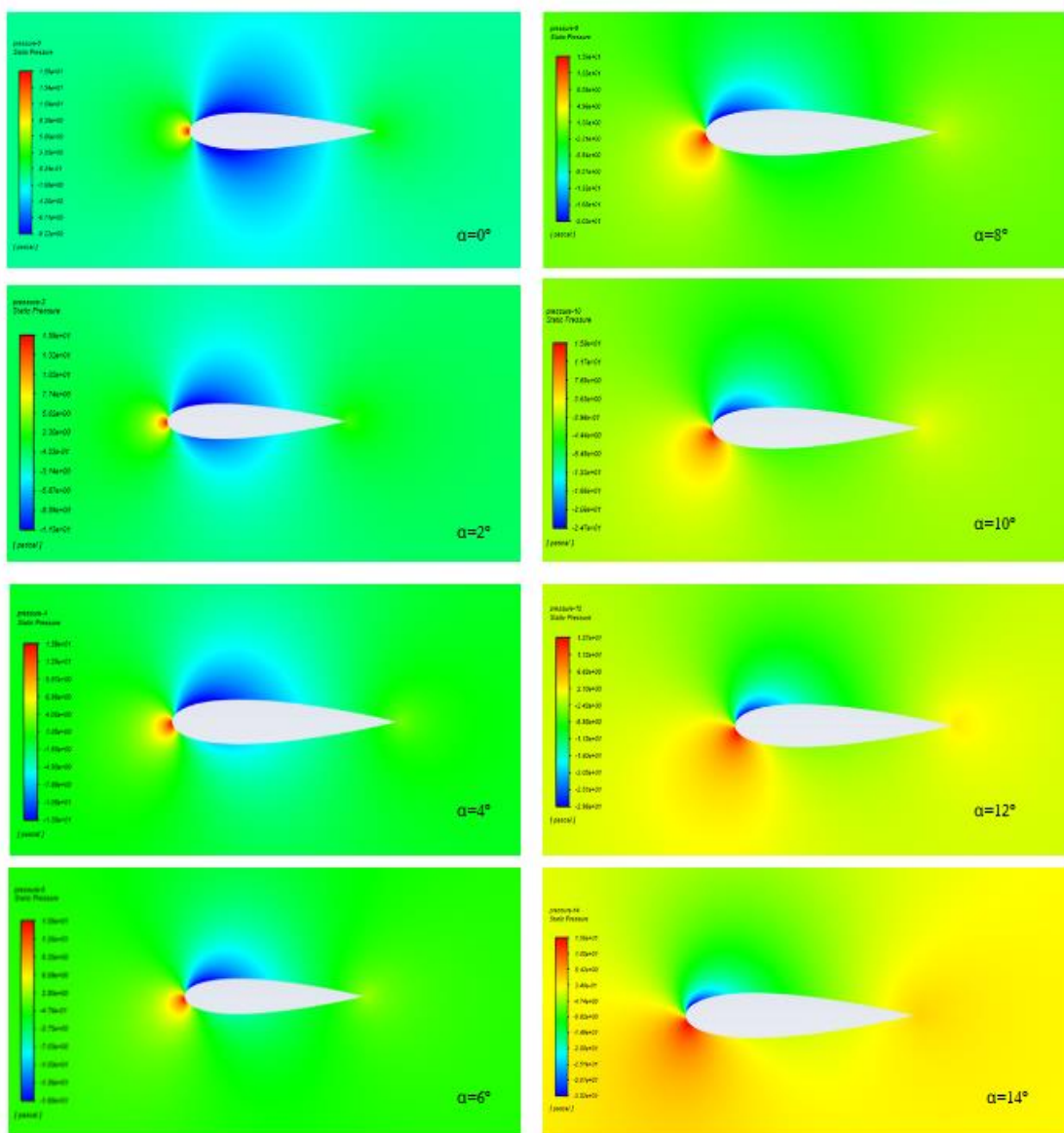


Figure 5 : Variation of the lift-to-drag ratio ( $C_l/C_d$  dimensionless) with respect to the angle of attack

The second series of results that were generated using CFD is primarily focused on the distribution of pressure around the NACA airfoil at varying angles of attack. This will provide an insight into the variation of the flow field with respect to the angles of attack.

For NACA 0018 Airfoil with Angles from  $0^\circ$  to  $14^\circ$ , it becomes possible to determine the most appropriate designs to produce maximum lift and stability of the flow pattern. For instance, when the angle is  $10^\circ$ , there is a pronounced low-pressure zone along the top surface while the bottom surface maintains high pressure, thus producing maximum lift. However, when the angle is lower ( $2^\circ - 6^\circ$ ), there is moderate lift; while at higher angles ( $12^\circ - 14^\circ$ ), there is flow separation close to the trailing edge. Therefore,  $10^\circ$  angle becomes the most appropriate for this study..



*Figure 6 : Pressure distribution around the NACA airfoil for different angles of attack*

#### 4. Conclusion and perspectives

As a result of this study, the design of a vertical-axis wind turbine of 2 kW H-rotor type was carried out based on a joint theoretical, numerical, and urban constraints method. From the aerodynamic analysis, the critical components determining the performance were determined by the local wind resource assessment, which proves site feasibility. Based on the QBlade software simulations, the best configuration was determined as follows: Three-bladed turbine having NACA 0018 airfoil, rotor height of 3 meters, diameter of 2.4 meters, and chord length of 0.37 meters. CATIA-based structural analysis proved that a blade structure made of aluminum of 4 mm thickness and four 2 mm supports having total weight of 13 kg is optimal as far as the strength and lightness are concerned since its stress level does not exceed the elasticity limits. Stress level did not exceed the yield strength, thus providing a safe operation with a safety factor of around 2.8. 2D CFD simulation in ANSYS Fluent indicated the optimal angle of attack of 10°, which provided the maximum lift-to-drag ratio. For future research, there is a need to conduct a proof-of-concept validation using the prototype in an urban environment and its acoustic effect analysis. Overall, the findings support the reliability of the chosen method and lay the groundwork for developing efficient urban wind turbines appropriate for today's energy needs.

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