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*Original scientific paper*

# EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE POSSIBILITY FOR INCREASING WIND TURBINE EFFICIENCY BY NEW ROTOR HUB DESIGN

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Abstract: The aerodynamic performance of a wind turbine heavily depends on the blade airfoil designs, therefore the initial strategy for enhancing efficiency involves using multiple airfoils with varied geometries in blade construction. Building on this, a more innovative approach introduces new geometries for turbine hubs, allowing designers to retain the primary blade shape and dimensions during the design process. This process leverages theoretical aerodynamic principles, mathematical models and data from turbine operation under wind flow conditions. The numerical model, originally developed with various airfoils, is validated by comparison with experimental results, confirming its reliability. The unsteady airflow model reveals changes in wind turbine efficiency and aerodynamic coefficients at varying angles of attack of the blades. The next phase includes experimental testing of a wind turbine scaled physical model with a newly designed hub with a hemispherical shape. The 3D-printed model allows for testing at different angles of attack, enabling comparability between numerical and experimental outcomes. Adjusting the position of the hemispherical hub in relation to the blade root provides insights into its effect on wind capture. This method highlights the differences between a conventional turbine hub and an unconventional hemispherical hub, utilizing the same blade configuration. The first approach is implemented in software for airfoil design and analysis, while the second method is employed in software for designing structural elements of the whole turbine.

**Key words:** wind turbine; blade design; airfoils; hub design

## ЕКСПЕРИМЕНТАЛНО И НУМЕРИЧКО ИСТРАЖУВАЊЕ НА МОЖНОСТА ЗА ЗГОЛЕМУВАЊЕ НА ЕФИКАСНОСТА НА ВЕТЕРНА ТУРБИНА ПРЕКУ НОВ ДИЗАЈН НА НОСОТ НА РОТОРОТ

Апстракт: Аеродинамичките перформанси на ветерна турбина во голема мера зависат од дизајнот на аеропрофилот на лопатките. Оттаму почетната стратегија за подобрување на ефикасноста вклучува користење повеќе аеропрофили со различни геометрии при нивната конструкција. Последователно, поиновативниот пристап воведува нови геометрии за носот (центарот) на работното коло, дозволувајќи им на дизајнерите да ја задржат примарната форма и димензии на лопатките при процесот на дизајнирање. Во овој процес се користат теоретски аеродинамички принципи, математички модели и податоци за работата на турбините во услови на струење на ветер. Нумеричкиот модел, првично развиен со различни аеропрофили, е валидиран преку споредба со експериментални резултати, потврдувајќи ја неговата веродостојност. Моделот на нестационарно струење на воздух ги открива промените во ефикасноста и аеродинамичките коефициенти при различни нападни агли на лопатките на ветерната турбина. Следната фаза вклучува експериментално испитување на скалиран физички модел на ветерната турбина со нов дизајн на носот во облик на хемисфера. Моделот отпечатен со 3Д техника овозможува тестирање при различни нападни агли, овозможувајќи споредливост помеѓу нумеричките и експерименталните резултати. Приспособувањето на положбата на хемисферичниот центар во однос на коренот на лопатката дава увид во влијанието врз зафаќањето на ветерот. Овој метод ги истакнува разликите помеѓу конвенционален центар и неконвенционален хемисферичен центар, користејќи ја истата конфигурација на лопатката. Првиот пристап е имплементиран во софтвер за дизајнирање и анализа на аеропрофили, додека вториот метод е применет во софтвер за проектирање на конструктивните елементи на целата турбина.

**Клучни зборови:** ветерна турбина; дизајн на лопатка; аеропрофили; дизајн на центар на ротор

## 1. INTRODUCTION

The global strategy to gradually move from fossil fuels to renewable energy sources has become increasingly urgent in recent years. This initiative is driven by the pressing need to confront climate change by reducing greenhouse gas emissions and securing a sustainable energy future. Given the inherent variability in electricity demand on a daily basis, a new challenge arises to integrate various renewable energy resources, thereby ensuring a reliable and stable electricity network capable of meeting fluctuating demand patterns. The idea for combining renewable energy resources has embraced the act for taking new innovative steps in the attempt of increasing their power generation efficiency and reliability. In addition to hydropower, which is widely recognized as the largest and most cost-effective renewable energy source globally, with a notable capacity for balancing the ratio of energy demand and energy production, wind energy has appeared as a standout resource with a great potential regarding power generation flexibility. It is acclaimed for its scalability, environmental benefits, and continuous technological advancements [1].

Understanding the impact of wind flow on the turbine's rotor construction is of great importance due to the nature of the turbulent flow, which appears regardless of the rotor aerodynamics, and significantly reduces the wind turbine power generation efficiency. The fundamental of this understanding are the blades, composed of various airfoils in order to form an entity which will optimize and enhance the aerodynamics of the rotor, concerning lift and drag force. A common strategy to enhance wind turbine power generation efficiency focuses on improvements of the blade design for efficiently capturing and transferring the potential wind energy to the shaft, and ultimately the electrical generator. Blade efficiency, in terms of the ability to capture the wind flow, peaks at their upper portions and declines towards the turbine hub due to the turbulence from the hub's interaction with wind flow and the shape of the blades at that region. Increasing the surface area of the blades allows for greater wind energy capture, leading to increased energy production and improved efficiency. However, this approach is constrained by the costs associated with blade production and transportation [2, 3].

Other techniques for improving the performance of a horizontal axis wind turbine (HAWT) are constantly being carried out. The number of blades is one of the factors that impact how well wind turbines perform [4]. Wang and Chen [5] used CFD to numerically examine the impact of blade numbers 2, 4, 6, and 8, on a small-scale ducted wind turbine's performance at an inflow speed of 12 m/s. The k-e turbulence model was used for the numerical calculations. It was observed that adding more blades results in a higher starting torque and a slower cut-in speed. However, more blades result in more obstruction and slower blade entrance velocity, which reduces the power coefficient of the rotor. On the other hand, Shintake [6] notes that the performance of a HAWT increased with an increase of the blade number from 1 to 3 and decreased with an increase of the blade number from 3 to 5. The effect of blade number on the aerodynamic performance of a small-scale HAWT was investigated experimentally and numerically by Eltayesh [7]. The study was conducted by installing an experimental setup of wind turbine rotors with three-, five-, and six-bladed wind turbines at a constant pitch angle, different velocities and tip speed ratios. The study also used ANSYS Fluent for conducting numerical calculation using the SST k-w turbulence to monitor the effect of blade number on the power and thrust coefficient. The results showed that compared to the five-bladed and six-bladed wind turbines, the performance of a three-bladed wind turbine increased by 2% and 4%, respectively, while keeping a good agreement between the calculated and measured values.

The X-Rotor concept [10], a wind turbine rotor design developed to face the challenges of offshore spaces, combines horizontal-axis and vertical-axis wind turbine technologies to optimize efficiency and reduce costs. The innovative rotor comprises a primary rotor in a double-V configuration and secondary rotors attached to the primary blades' tips. These secondary rotors (HAWT), consequently to their reduced size, can reach significantly higher rotor speed, therefore provide enough power take-off, eliminating the need for gearbox or bespoke generators, and reducing maintenance costs.

Joining the trend of producing new innovative designs for enhancing wind turbine efficiency, Hui Hu and colleagues at Iowa State University [11] introduced the Dual-Rotor Wind Turbine (DRWT) concept. Their research focused on mitigating root losses near the hub and reducing aerodynamic inefficiencies caused by wake interactions in wind farms. The DRWT system bring into service a secondary, smaller, co-axial rotor designed to capture energy in regions typically underutilized by conventional HAWT. Through experimental and numerical studies, the team demonstrated that the secondary rotor not only improved energy capture but also enhanced wake mixing, leading to greater overall efficiency.

Similliar to the DRWT, Sandip A Kale and S.N. Sapali analyzed various innovative multi rotor wind turbine designs. By utilizing multiple smaller rotors [12], these systems can increase the swept area without the need for excessively large rotors. Multi-rotor configurations, such as co-planer, co-axial, and counter-rotating designs, amount to the potential for higher energy capture while addressing challenges like structural weight and complexity. These systems have been evaluated for their technological advantages, feasibility, and cost-effectiveness, demonstrating benefits in both power output and structural efficiency compared to traditional single-rotor system

In the pursuit of achieving optimal techno-economic solutions for enhancing the efficiency of conventional HAWTs, this study addresses the less-explored role of turbine hubs in maximizing wind energy utilization. The focus is on the implementation of an unconventional novel hemispherical hub design, aiming to optimize airflow interaction at the root of the blades - a region associated with energy losses - while maintaining the number of blades, and blade configuration, including shape, and length.

This paper presents a comparative analysis of the wind energy harnessing ability between a conventional HAWT, and a HAWT with a hemispherical hub. The comparison is conducted by obtaining key performance metrics, including the power coefficient (Cp), revolutions per minute (RPM), and cut-in wind speed, as functions of wind velocity. The results were acquired by performing experimental measurements under varying wind flow for both designs, validated by a numerical model.

## 2. THEORETICAL BACKGROUND

As airflow interacts with a wind turbine, it induces a boundary layer near the turbine's surface due to fluid disturbances forcing blades to move. This boundary layer, influenced by fluid viscosity, plays a pivotal role in understanding the dynamics of velocity at the fluid-solid interface. Variations in fluid pressure, governed by the Bernoulli principle, contribute to the development of lift and drag forces [10].

To optimize turbine efficiency, specific airfoil shapes are strategically chosen to generate a turbulent boundary layer, thereby delaying separation [10]. Figure 1 illustrates the intricate airflow patterns around turbine blades. The lift coefficient and drag coefficient, detailed in subsequent formulas, quantitatively assess the boundary layer's impact on lift and drag forces, respectively.

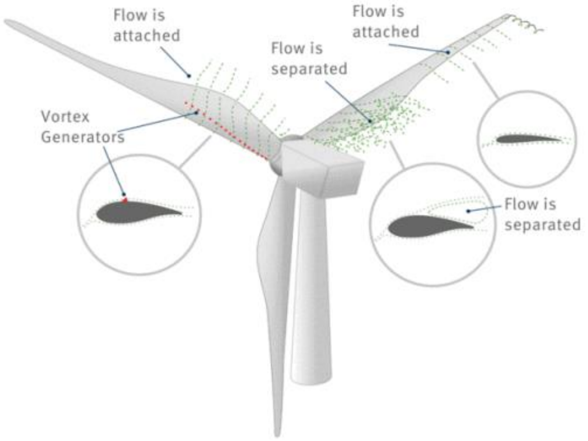

**Fig. 1.** Airflow behavior around turbine blades

The conveyance of mechanical forces between a solid body and a fluid occurs across the body's entire surface through fluid pressure. In wind turbines, the combined effect of natural wind and rotor-induced flow generates an aerodynamic force on the rotating blades [10].

Figure 2 illustrates the resultant force represented as $F$, decomposed into perpendicular (lift) $L$ and parallel (drag) $D$ components relative to the wind velocity $W$. Lift counteracts gravity and both forces are influenced by the angle of attack, which is the angle between the blade chord line and the wind direction.

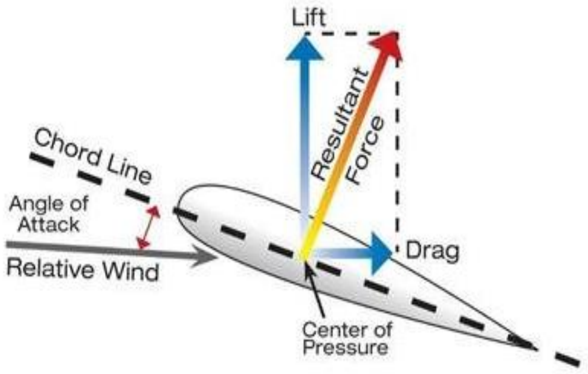

**Fig. 2.** Forces acting over an airfoil

The forces are given by the following expressions:

$$L = \frac{1}{2} C_L \rho A W^2 \tag{1}$$

$$D = \frac{1}{2} C_D \rho A W^2 \qquad (2)$$

where $\rho$ is the density of air, $C_L$ and $C_D$ are the lift and drag coefficients, respectively, $A$ is the aifoil planform area.

## 3. NUMERICAL MODEL

Airflow over a wind turbine is modeled and simulated using the XFOIL software tool, part of the Qblade software suite. The wind turbine rotor blades are composed of multiple asymmetrical NACA4412 airfoils. Initial boundary conditions used for the modeling setup were Reynolds number of $1 \cdot 10^6$ indicating a turbulent flow, $N_{\text{crit}}$ of 9 indicating the critical value of detachment of the air current from the airfoil, angle of attack in the range from –15 to +20° and constant air density of 1,225 kg/m$^3$.

Figure 3 and Figure 4 illustrate the simulated optimal angle of attack which is determined for optimal airflow over the blades and boundary layer. The value of that angle is 6°.

The wind turbine rotor with 44 cm in diameter, is designed consisting of three blades, each blade comprised of ten segments. The first two segments of every blade are designed from circular airfoils for the purpose of easy installation in the turbine hub, while the remaining eight segments are designed using the NACA4412 airfoil, as shown in Figure 5.

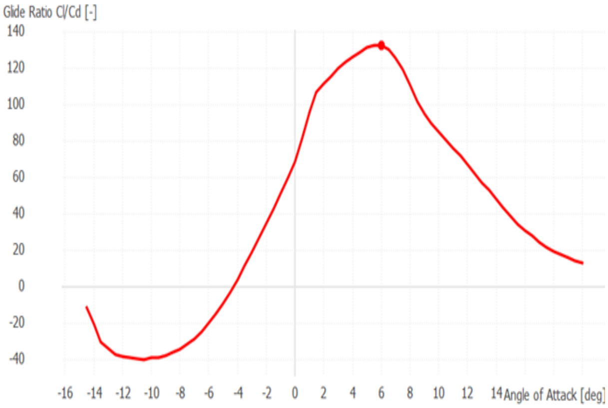

**Fig. 3.** Glide-ratio to angle of attack ratio (Optimal angle of attack)

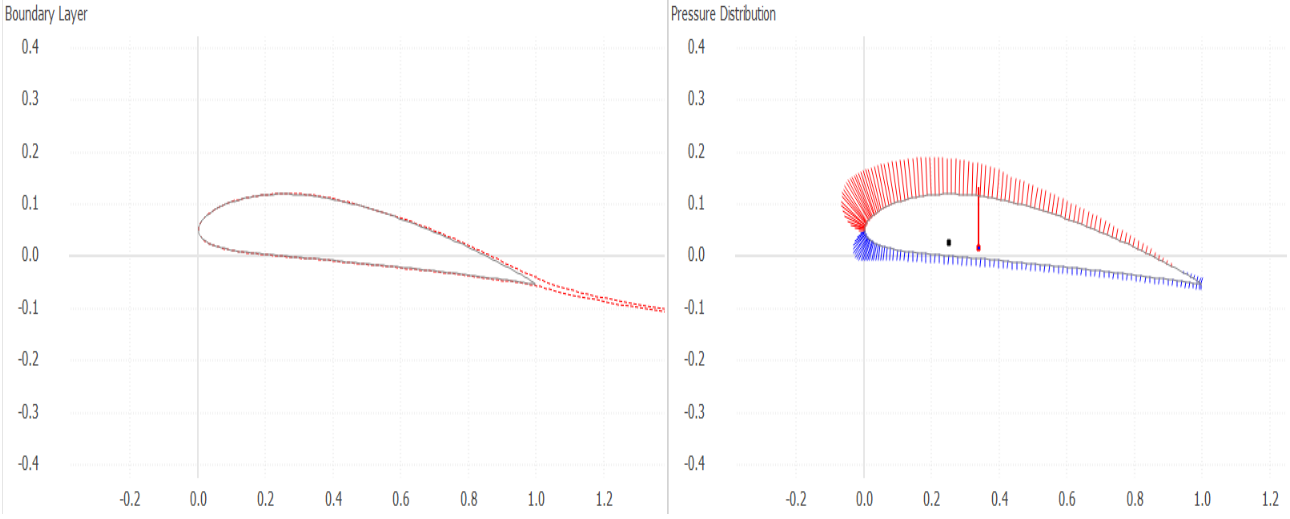

**Fig. 4.** Boundary layer and pressure distribution at optimal angle of attack

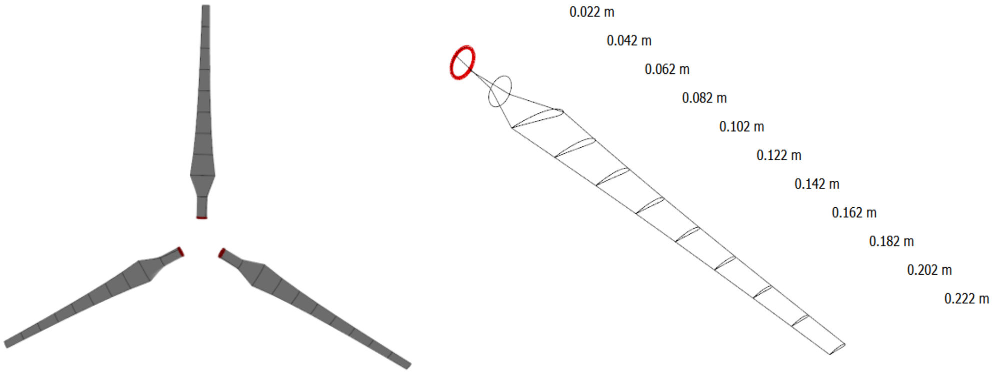

**Fig. 5.** Wind turbine blade design

The standard chord line optimization, twist optimization and Tip Speed Ratio (TSR) $\lambda$ are used for the optimization of the blade geometries. The TSR is determined iteratively using the following equation:

$$C_p = C_1(C_2 - C_3\beta^2 - C_4)e^{C_5}, \qquad (3)$$

where: $C_1$ = 0.5, $C_2 = \frac{R}{\lambda}$, $C_3$ = 0.022, $C_4$ = 5.6, $C_5 = -\frac{0.17R}{\lambda}$, and $\beta$ = 1°. Optimal $C_p$ is achieved at TSR of 5.2.

The standard Betz model is applied to optimize the chord line for maximum efficiency. This model is an indicator of the best efficiency that can be achieved for a wind turbine under ideal conditions – utilizing the wind power excluding the occurrence of power losses. The Stall method is used for optimizing the blades twisting for a predetermined optimal TSR value, enabling automatic regulation of turbine operation.

Rotor operation is simulated using the Blade Element Momentum (BEM) model – a 2D model which performs discretization of the blades and calculates loads based on local fluid flow, incorporating mass and momentum conservation. Correction methods such as Prandtl Type factor and 3D correction factor are utilized for accurate simulation, accounting for rotor three-dimensionality.

## 4. EXPERIMENTAL SETUP

Experimental measurements of the number of rotations of the turbine rotor are performed at the laboratory of fuid mechanics and hydraulics at the Faculty of Mechanical Engineering in Skopje. Three blades are designed in SolidWorks using coordinates from the wind turbine rotor's numerical model in Qblade, ensuring identical geometry between the experimental and numerical models.

A standard hub and a modified hemispherical hub are created for the conventional and unconventional rotor assemblies, respectively, as shown on Figure 6.

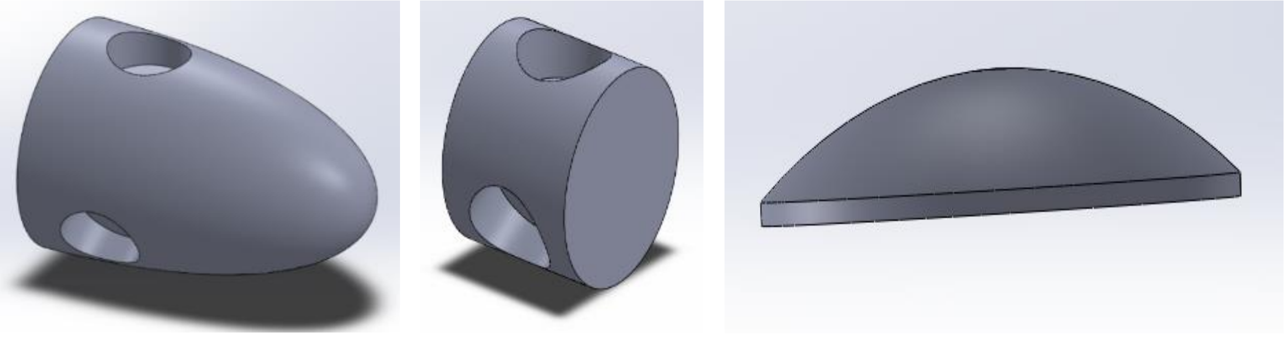

**Fig. 6.** Design of two turbine hubs

The rotor geometries are produced using a 3D printer and assembled into a single unit, mounted on a 36 cm metal stand. Balancing of the metal pole is achieved using two metal ropes to reduce vibrations from airflow during testing. The wind turbine is positioned at the air tunnel exit, measuring 275×275 mm in area. The fluid stream inlet speed, generated by a fan at the tunnel entrance, is controlled using a frequency regulator. A net is installed in the air tunnel to disrupt vortex effects caused by the fan's positioning.

Measurements are conducted at seven different speeds for both rotor configurations. In addition, two additional tests were performed on the modified hub rotor, adjusting the distance of the hemisphere from the blade center. Airspeed is measured using a digital anemometer, and the number of rotations of the rotor with a digital tachometer. The experimental system consisting of a balanced wind turbine, wind tunnel, and accompanying measuring devices is shown in Figure 7.

The experiment is used in order to validate the numerical model for the wind turbine operation in the wind tunnel, and to use it in an attempt to increase the utilization of the air flow, increase the number of revolutions of the rotor and eventually increase its efficiency, by implementing the new turbine hub.

**Fig. 7.** Experimental system

## 5. NUMERICAL MODEL VALIDATION

Validation of the numerical model was done by comparing the experimentally measured values and numerically obtained results for the number of revolutions per minute of the turbine rotor as an essential factor in power generation. This was facilitated by the rotor adaptable design, allowing for blade rotation and precise angle adjustments. Figures 8 and 9 show the comparison between the experimental and numerical data for angle of attack 3° and 6°, respectively. It can be seen that the results are in good agreement. The differences that exist can be assigned to the measurement errors, errors of the numerical model and the influence of surrounding airflow conditions.

After the numerical model is being validated, it can be used for simulations of operation for other wind turbines with different airfoils, blade design and rotor configuration, furthermore they can serve as a basis for further adjustments to the experimental model and subsequent validation through the numerical analysis.

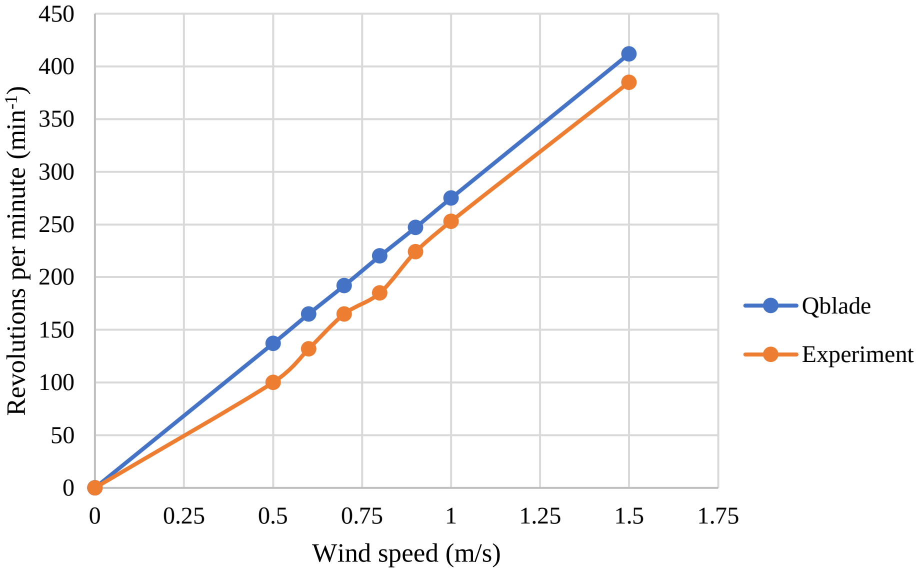

**Fig. 8.** Collective pitch 3°

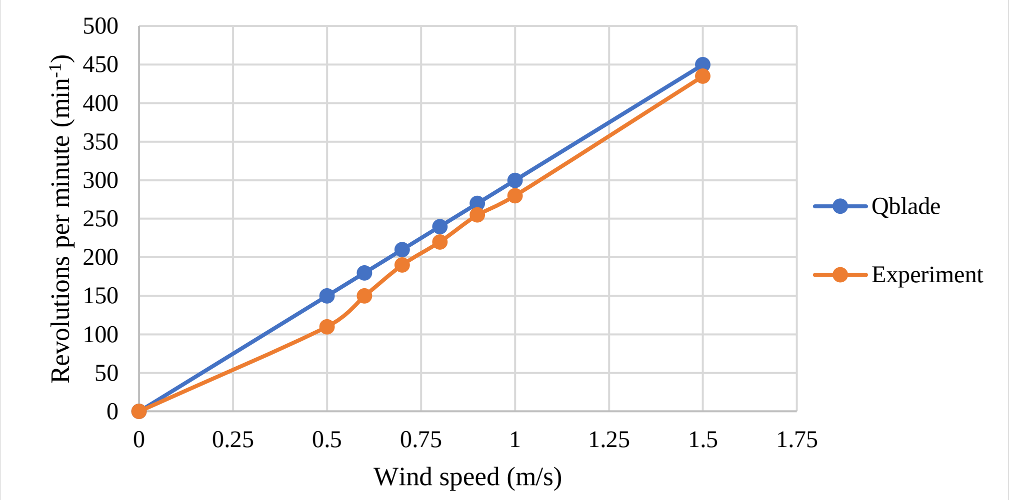

**Fig. 9.** Collective pitch 6º

## 6. RESULTS AND DISCUSSION

The wind turbine performance was observed with a modified configuration using the hemispherical hub. The number of rotations was measured under identical installation conditions as the standard turbine, which had been validated through both numerical and experimental models. With the optimal 6º angle of attack determined from simulations and verified experimentally, measurements were taken of the rotor rotations at speed of 0.5, 0.6, 0.7, 0.8, 0.9, 1, and 1.5 m/s.

Furthermore, these measurements are expanded to include another variable – the distance of the hemispherical hub from the center of blade placement. This alteration affects the timing and duration of contact with the fluid current, consequently impacting the blade efficiency in capturing the fluid flow. The distances for this measurement were 5, 10, and 15 mm, respectively. Figure 10 shows the influence of the distance of the hub from the blade placement center on the number of revolutions.

In the case of the wind turbine with the hemispherical hub distanced 15 mm from the center of the blades, which is determined by the intersection of the blade's axis, a significant increase in revolutions per minute is observed. A portion of the wind flow is directed to the upper parts of the blades, resulting in enhanced utilization of wind power, therefore in increased rotational speed. The same portion of wind flow in the case of wind turbine with standard hub design is flowing by the hub and the lower parts of the blades, resulting in wake effect and increased losses, hence the lower value of the rotational speed.

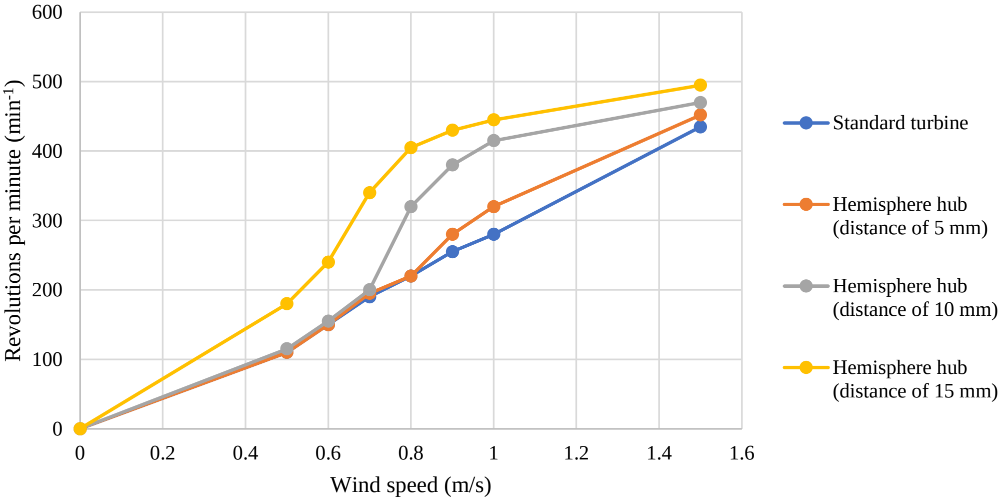

**Fig. 10.** RPM at wind speed from 0 to 1.5 m/s for different rotor configurations

While comparing the obtained experimental results, it must be noted that the discrepancy between the rotational speed of the standard wind turbine rotor and the one with the hemispherical hub distanced 5 mm from the center of the blades is relatively small. This indicates the limited benefit of implementing the hemispherical hub, which visibly depends on the distance between the center of the blades and the hemispherical hub itself

For these particular models, a simulation for determining the variation of the power coefficient as a function of the wind speed was conducted (Figure 11). Comparing Figures 10 and 11, we can clearly note that the examined turbine models are experiencing their full potential between wind speed of 1.3 and 1.35 m/s. This indicates an increase in vorticies and losses for higher wind speeds and higher rotational speed of the rotor, due to the stall effect.

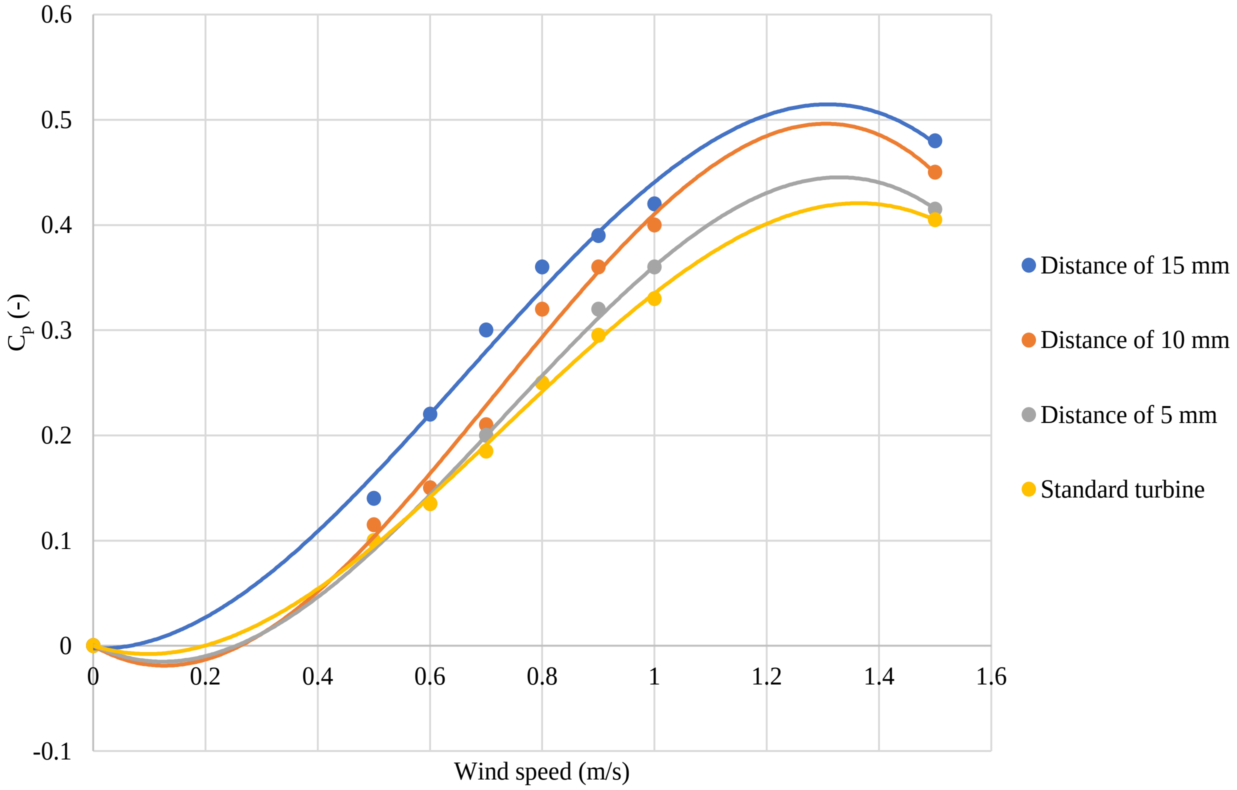

**Fig. 11.** $C_p$ variation as a function of different wind speed

For the wind turbine rotor with a hemispherical hub distanced 15 mm from the blade center, at the optimal wind speed of 1.3 m/s, the value of the $C_p$ is approximately 21.5% higher than the power coefficient of the standard wind turbine rotor configuration. For the rotor configuration with the hemispherical hub distanced 10 mm from the rotor center, at the optimal wind speed, the $C_p$ percentage difference is reduced, yet still amounts to a significant approximate of 19 %.

Additionally, it is notable that the right positioning of the hemisphere results in a better cut-in speed. Distancing the hemisphere 15 mm from the original hub center for this particular design, allows for better wind flow mitigation to the tip of the blades, enabling the rotor to start rotating and generating power earlier, and at lower wind velocities than the rest of the rotor configurations.

The experimentally obtained values of rotor revolutions cannot be directly compared to those of full-scale wind turbines due to its significantly smaller size. Scaling this experiment also means taking into consideration the rotor aerodynamic influence in a wind farm.

Regarding the aerodynamic similarity, the Reynolds number for a full-scale turbine would be significantly higher than the experimtal setup. The difference could impact boundary layer behaviour and the aerodynamic forces acting on the blades.

Although the loads on the wind turbine structure caused by the various rotor configurations were not subject in this paper, we must note that the hemispherical hub design may introduce different static and dynamic loads at full scale. Larger structures of this kind might require adjustments to ensure material strength and stability, particularly under high wind speeds or turbulent conditions.

The implementation of new geometries for this kind of structure will involve cost and practical feasibility, relating to manufacturing, installation, and maintenance.

The introduction of the hemispherical hub has shown a positive impact on increasing the rotor revolutions and power coefficient under identical operating conditions. This is attributed to its geometry, which directs the wind current towards the upper part of the blades, preventing losses from flow disruption between the blades.

The hemispherical hub could be a great efficiency solution for the multi-rotor wind turbines which use multiple smaller rotors instead of a single larger one, to increase the swept area, without the structural challenges of larger blades. Smaller rotors mean smaller hemispherical geometries, reducing the manufacturing cost and structural challenges, while enhancing every rotor efficiency.

Upwind rotors avoid tower shadowing but require complex yaw mechanisms to align with the wind. In contrast, downwind rotors simplify the design by aligning passively, but face efficiency losses due to tower interference. In both cases, the focus is on the blades, which in the optimization phase will eventually reach their full potential. Implementing the hemispherical hub could only strengthen the wind turbine’s ability to harness wind power.

Morphing blades, inspired by natural structures, are dynamically adjustable blades to changing wind conditions in order to improve aerodynamic performance. Implementing these blades to the multi-rotor wind turbine design, and utilizing the hemispherical hub design, could provide a novel hybrid approach to enhancing turbine efficiency.

Of course, this type of additional geometry, after examination of the multiple considerations regarding the scaling process, can be used not only for designing new wind turbines, but also for enhancing the efficiency of existing ones.

## 7. CONCLUSION

In this paper an experimental analysis on the number of rotations of two wind turbine rotor assemblies was conducted. Additionally, a numerical analysis on a standardly designed wind turbine rotor was performed for various angles of attack and different flow velocities, using NACA4412 airfoil-based blades. For the optimization of the rotor, the standard chord line optimization, twist optimization and TSR were used. This analysis was conducted using the Qblade software in order to produce a numerical model that can be experimentally validated. For this particular model, the optimal angle of attack was achieved at 6°, which gives the best glide ratio for the model, hence the instructions regarding the blade placement.

Changing the standard configuration of the wind turbine hub assembly by adding an unconventional geometry on the experimental setup, while maintaining the same geometry of the blades, for different angles of attack, different air flow speed, identical to the numerical model, an increase in the number of revolutions per minute of the rotor is achieved. The result notes an increased utilization of the potential wind energy, therefore an increase of the turbine efficiency.

These numerical and experimental models can be used for further analysis regarding the placement of the hemisphere, improving its aerodynamic geometry and its influence on the statics and loads on the whole construction of the turbine. Finally, these models can be used for further analysis regarding the influence of this geometry on the air flow at a wind farm.

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