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COMPARATIVE NUMERICAL ANALYSIS OF FLAT AND ROUND TIPS ON AERODYNAMIC EFFICIENCY AND PERFORMANCE IN IEA 10MW WIND TURBINE BLADES

J Ramarajan, Neeraj Paul Manelil, Johannes Nicolaas Theron, Leo Höning and Bernhard Stoevesandt.

Fraunhofer Institute for Wind Energy Systems
Department Aerodynamics and numerical Energy Meteorology
Küpkersweg 70, 26129 Oldenburg, Germany.
e-mail: ramarajanjmech@gmail.com,

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Summary. Wind turbines efficiently convert wind energy into electricity, and the design of the blades plays a crucial role in their performance. Specifically, the blade tip design significantly impacts turbine efficiency. Currently, most turbines numerically studied feature flat tips. Not many high fidelity CFD studies are reported for the inclusion of winglets in the numerical simulations. Winglets are actually helping in good wake recovery and noise reduction. The present study examines the IEA 10MW turbine blade for tip modifications. Initially a flat tip is numerically studied using OpenFOAM v2306 with two different turbulence models such as Spallart Allmaras (SA) and SST k-ω, the results are compared with BEM results. Later, a comparison is made between flat-tip and winglets tip. The rounded tips designed as winglet-like shapes introduced in both upstream and downstream directions at two different heights of 1 % R and 2 % R. The findings reveal that the downstream winglet with 2 % R height tip improved turbine performance by 0.2 % compared to flat tip.

1 INTRODUCTION

Wind energy resources are expanding day by day, driven by the growing demand for energy resulting from modernization and the reduction of fossil resource usage. Along technological advancements, increasing turbine power output is achieved by a growing size of the turbine rotors. Research on wind turbines and wind farms is actively focused on enhancing turbine performance. The blades of the modern turbines are carefully designed in order to extract maximum possible energy from the flowing wind.

The tip design of the blade plays a key role on the performance of the turbine. The tip of the blade can be modified in order to maximize the turbine performance. Flat tips are conventionally used in the HAWT's cfd simulations. Including the winglet tips in the CFD simulation sometimes bring the divergence in simulations due to poor mesh quality at the sharp winglet edges, but including the winglets in the simulations captures the actual complicated flow phenomenon near the winglet edges. The winglet shape tip modification that can be adopted in the turbines for the performance improvement. The winglets shapes are playing a vital role in directing the tip vortex away from the turbine blades thereby reducing the induced drag acting on the turbine blade. Hence, the performance is expected to improve. It also gives us the sleeve-like solution to fit in the existing blades. Imamura et al. [1] numerically evaluated the aerodynamic effectiveness of winglets on a horizontal axis wind turbine of NACA0012 profile. The winglets in this study are designed as inclined extensions of the rotor blades. For the numerical analysis, the vortex lattice method with a free wake model was utilized, chosen for its applicability to arbitrary blade shapes and independence from empirical wake geometry data. The study involved calculating the flow field of the rotor wake and overall rotor performance, comparing the results of rotors with and without winglets. To understand the effect on blade strength, the flapwise bending moment was also computed. The results reveal that winglets considerably enhance the power coefficient with only a minor increase in the flapwise bending moment, in contrast to blades with radially extended winglets.

The tip modification by Johansen and Sørensen [2] reported the numerical analysis on the investigation of wind turbine blades equipped with winglets with NACA 64-018 airfoil. They examined five different winglets with modification in twist and camber distributions. Among that, four winglet modifications were directed towards the pressure side (upstream), while the other was directed towards the suction side (downstream). In addition, a blade with the same planform area as of the winglet cases with original rectangular tip. They concluded that including the winglet shape in the downstream direction resulted in higher power production. An increase of 0.6 % to 1.4 % has been observed at a wind velocity of 6 m/s in the presence of a winglet. However, the effects of sweep and cant angles are not considered. In another study, Johansen and Sørensen[3] reported that the inclusion of winglets can increase power output. The findings indicate that reducing the curvature radius and increasing the height of the winglet lead to higher mechanical power and thrust. However, the study found that sweeping the winglet at a 30° angle and adjusting the twist angles have minimal impact on power enhancement. Gaunaa and Johansen [4] explored the theoretical and computational aspects of using winglets on wind turbines. The theoretical analysis reveals that the power increase from winglets stems from reducing tip effects, rather than the previously believed downwind vorticity shift caused by downwind winglets. Findings suggest that downwind winglets outperform upwind ones in optimizing C_p, although a simple radial extension of the wing provides a greater increase in power production. However, shorter downwind winglets ($> 2\%$) nearly match the C_p improvement achieved by radial extensions. The study also designs a rotor with a 2 % downwind winglet, using the Navier-Stokes solver EllipSys3D for further computation. Zahle et al. [5] investigated redesigning a wind turbine blade tip to increase energy production of the IEA 10MW turbine blade while keeping the load constraints. They parameterized the blade shape to allow adjustments in chord, twist, blade length extension, and three winglet-like parameters. Using EllipSys3D, they developed a surrogate model to optimize the tip shape numerically under geometric and load constraints. The study reveals that integrating a winglet into the blade extension enhances power output by 2.6 %, without raising the flapwise bending moment at 90 % radius. In contrast, a straight blade extension only yielded a 0.76 % increase in power production.

Mourad et al. [6] introduced winglets in HAWTs to enhance efficiency. They examined the effects of winglet height and toe angle on a three-bladed SD8000 airfoil with a 1m diameter. Among the four heights evaluated, a winglet height of 0.8 % R showed the best performance, improving efficiency by 6 % compared to no winglet. With this optimal height, the toe angle's effect in both directions was studied, revealing that a +20° toe angle in the upstream direction improved performance, while a toe angle in the downstream direction decreased performance.

Kulak et al. [7] investigated the impact of winglets on small wind turbine (SWT) rotors using experimental and computational fluid dynamics (CFD) methods. Experimental results show that pressure side (PS) winglets can enhance turbine power, whereas suction side (SS) winglets may alter performance. Flow structure analysis reveals that winglets reduce radial flow and complicate tip vortex structures but increase total drag and flapwise bending moments. Winglets offer a cost-effective improvement for SWTs, especially with rapid manufacturing technologies, by enhancing existing rotor geometries. Barlas et al. [8] stated, innovative aeroelastically optimized tip extensions can significantly enhance wind turbine performance and reduce costs. They introduced a new design optimization framework for wind turbine blade tip extensions using surrogate aeroelastic modeling. The optimization maximizes power within load constraints, resulting in a load-neutral gain of up to 6 % in annual energy production. Detailed performance evaluation shows good agreement between solvers at low turbulence, with increasing differences at higher turbulence levels. Madsen et al. [9] introduced a sophisticated shape optimization framework based on computational fluid dynamics, marking the first comprehensive exploration of curved tip shapes for wind turbine rotors using a high fidelity direct CFD approach, aimed at maximizing power using 12 design variables while adhering to geometric constraints and constraints on the bending moment at 90 % blade length. The optimized shape features approximately 1 % blade extension, 2 % flapwise displacement, and slightly below 2 % edgewise displacement, resulting in a notable 1.12 % increase in power output.

Zouboulis et al. [10] highlighted that curved blades (winglet like) are crucial for enhancing wind turbine efficiency by improving aerodynamic performance. Implementing these features on turbine blade tips reduces turbulence and loads while maintaining lift generation, leading to increased energy capture and lower operational costs. Optimizing these integrated blade tips maximizes their overall contribution to turbine performance. This study proposes a systematic workflow for optimizing a curved blade on wind turbine blades. The approach begins with shape optimization to enhance aerodynamics, followed by refining the internal structure to reduce mass while preserving airflow improvements. Computational validation through fluid dynamics and finite element analysis verifies performance enhancements. Additionally, the workflow integrates additive manufacturing for prototype production, leveraging digital fabrication's flexibility. The optimized curved blade model achieved a significant 30 % increase in torque generation while retaining 70 % of its original mass, resulting in a 0.81 % increase in total blade torque, demonstrating the efficacy of the proposed methodology. In addition the production is reported to reduce by 25 % [11] and an improved wake performance also reported [12].

In summary, the winglet tips are reported to improve the performance of the turbine. However, the previous studies are carried out mostly in small HAWT's. Some authors reported performance improvement for upstream side winglets, some others reported the performance improvement for the downstream winglets which needs a better clarification in terms of performance and flow characteristics. Very few studies are reported on including the winglets in IEA 10MW turbine blades. Among the few, to the authors knowledge none of them used OpenFOAM solvers for addressing the effect of tip modification. The aim of the present study is to carry out high fidelity CFD analysis using OpenFOAM v2306 to analyse the effect of tip modification by introducing winglet-like rounded tips in a large scale wind turbine blade like the IEA 10.0-198-RWT.

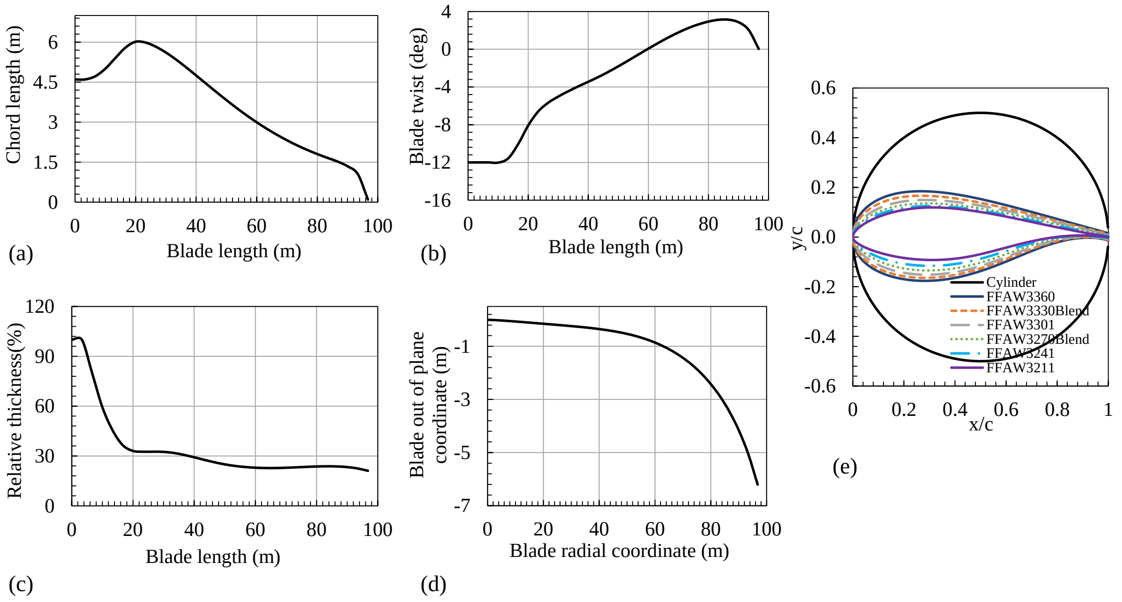


Figure 1: Planform data of IEA10.0-198-RWT (a) Chord length (b) Blade twist (c) Relative thickness (d) Blade out of plane coordinate (e) Base shapes

2 NUMERICAL METHODOLOGY

This section describes the complete details of the numerical methodology adopted for the present study. the details of governing equation, modelling of computational domain, meshing and solver details are discussed in the following sub sections. The data corresponding to the IEA10.0-198 Reference Wind Turbine is shown in Figure 1. The data is collected from the gitlab link. The variation in chord length, blade twist, relative thickness and blade out of plane coordinate with respect to running length of the blade, also the base airfoils are shown in Figure 1.

2.1 Governing equation

The continuity and momentum governing equations are fundamental in fluid dynamics, describing the conservation of mass and momentum within a fluid system. The continuity equation ensures that the mass entering a control volume equals the mass exiting, reflecting mass conservation. The momentum equation, accounts for the forces acting on the fluid, including pressure gradients, viscous forces, and external forces, ensuring the momentum balance. The continuity and momentum equations in the differential forms are given in Eqs 1 and 2 respectively.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_i u_j}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j} - \overline{\acute{u}_i \acute{u}_j}\right) \tag{2}$$

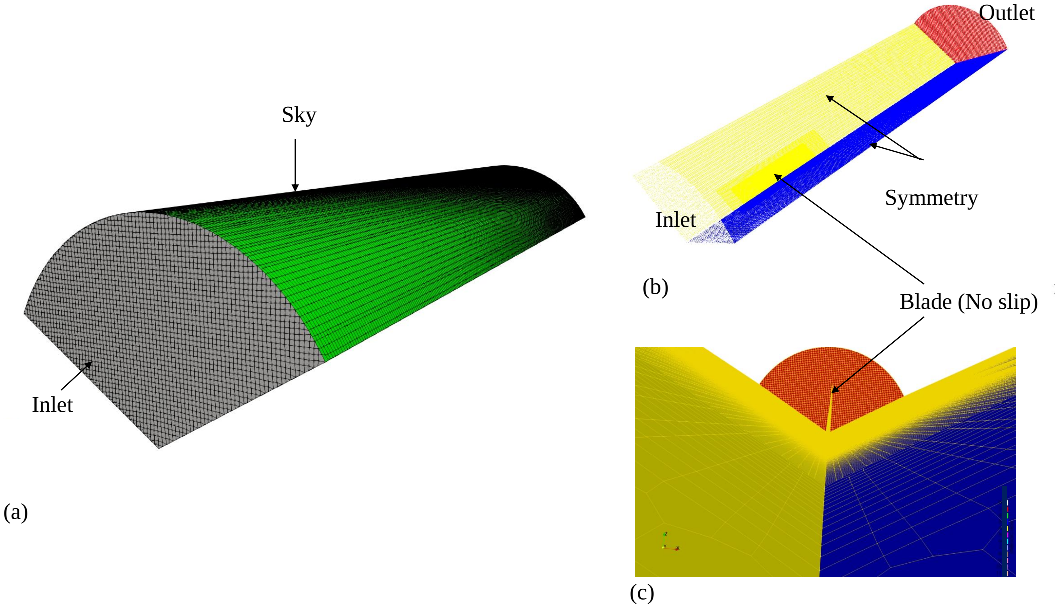


Figure 2: (a) Computational domain (b) Meshed domain with boundary condition (c) Blade view

2.2 Computational domain and boundary conditions

The computational modelling starts with generation of blade surface. The surface of the blade is generated using PGL (Parametric Geometry Library) from the planform and base airfoils data. The surface is generated with structured surface meshes. After the surface mesh generated, the output of PGL mesh is used in pyHyp[13] which uses hyperbolic volume mesh schemes to extrude the structured surfaces into volumes. The first layer thickness, number of layers and the distance of extrusion is specified for the volume mesh generation. Following this, the in-house meshing tool used at Fraunhofer IWES, called WindTurbineMesher, was used to generate the far-field mesh. A structured mesh provides the foundation for precise computational fluid dynamics simulations. The far-field domain was defined as one-third of a cylindrical sector with a radius of 840 meters and a length of 4800 meters, with the blade located 1200 meters from the inlet. The structured mesh was generated for this far-field region to maintain consistency and accuracy in the simulation environment. A uniform velocity of 9.92 m/s was applied at the inlet, and zero-gauge pressure was imposed at the outlet. A no-slip boundary condition ($u = v = 0$) was imposed on the turbine blade, a slip boundary was applied to the sky walls, and symmetry boundary conditions were imposed on the side walls. The Arbitrary Mesh Interface (AMI) was created between the rotor and blade surfaces. The rotor was imposed with angular velocity as per the tip speed ratio (TSR). The domain and boundary conditions are shown in Figure 2.

2.3 Mesh and grid independence study

To reduce computation time while maintaining acceptable accuracy, a grid independence test was carried out. To fit the linear velocity profile near the blade surface, the first layer thickness was maintained to fall within the viscous sublayer region by keeping it at 10^{-5} m. The dimensionless "y+" value was kept at approximately 1. The resulting meshes were subjected to quality checks, and any necessary refinements were made to improve mesh fidelity.

Table 1: Summary of grid independence study

Cases	Number of Surface elements (PGL)	Number of Volume Elements (pyHyp)	Torque (Nm)	Torque Deviation (%)	Thrust (N)	Thrust Deviation (%)
Case1	128x256	$2.32\text{x}10^6$	268960.8	–	30756.5	–
Case2	192x256	$3.35\text{x}10^6$	277223.0	2.95	30592.0	0.54
Case3	256x256	$2.32\text{x}10^6$	279026.5	0.6	30603.9	0.04

Power coefficient values were calculated at a tip speed ratio of 8.74. Table 1 summarizes the findings of the grid independence study. The number of vertices in the chordwise direction was set to 256, while the number of vertices in the spanwise direction was varied as 128, 192, and 256. Three mesh cases were considered to find the optimal case that offers the least computational time with reasonable accuracy. Case 2 was found to be better than Case 1 and Case 3. Case 2 had a 3% deviation in measured torque compared to Case 1, whereas further refinement in Case 3 resulted in only a 0.6% deviation. Hence, Case 2 was chosen as the optimum. Additionally, the thrust value was calculated, with no appreciable deviation found in all three cases.

2.4 Solution methodology

The governing equations such as continuity and momentum are solved with the help of opensource steady state solver simpleFOAM which is an OpenFOAM solver that was fast and accurate. The Spalart Allmaras turbulence model is used in this study which is reported as stable turbulence model for external aerodynamic flows. The SIMPLE scheme is used for the coupling of velocity and pressure. When it comes to k and ω, a second order upwind scheme is used, with convergence criteria for the residuals are set in the order of 10^{-5} The properties used for air are above sea level standard properties as given in Table 2.

Table 2: Air properties

Sl. no	Property	value
1	Density (ρ)	1.2254 kg/m^3
2	kinematic viscosity (ν)	1.460 x $10^{-5} m^2/s$

The operating conditions of the turbine in order to compare and validate our present simulation results with reference wind turbine, for the 0° pitch angle the parameters used for the reference turbine is used as given in Table 3.

Table 3: Operating Conditions

Sl. no	Wind Speed (m/s)	RPM	Angular Velocity (rad/s)	Pitch (°)	TSR
1	9.92	8.61	0.9016	0	8.74

3 RESULT AND DISCUSSIONS

The power available in the wind in motion is the change in rate of kinetic energy, called as Wind power (P_w). The wind with a velocity of V, and a density of ρ on the given cross section area A, can be calculated using Eq. 3.

$$P_w = \frac{1}{2}\rho A V^3 \tag{3}$$

The pressure coefficient (C_p) is non dimensional number as defined in Eq. 4

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V^2} \tag{4}$$

Tip speed ratio (TSR) is the ratio of angular velocity to the linear velocity as given in Eq. 5.

$$\lambda = \frac{R\omega}{V} \tag{5}$$

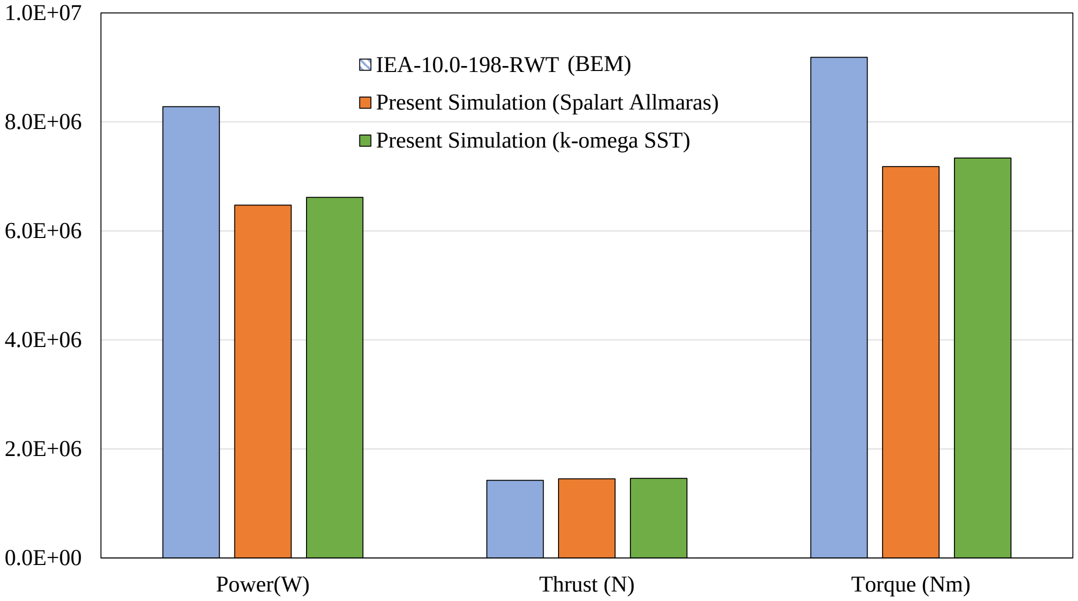


Figure 3: Validation

3.1 Validation of the present results

Initially, a numerical analysis of a flat-tip blade without pre-bend has been considered. From the simulation results, the values of thrust, torque, and power values has been calculated and compared with the reference wind turbine (IEA-10.0-198-RWT). The present CFD results underpredicted the values of torque and power. This could be possibly due to the exclusion of prebend, the flexibility of the blade, and transient effects. However, the thrust value matched the reference turbine with a deviation of less than 2 %.

Spalart-Allmaras turbulence model is initially used as a turbulence model, anyhow for validation, the two-equation SST k-ω turbulence model was also used in the simulation. The results showed a similar trend to those observed with the Spalart-Allmaras model. Nevertheless, the performance metric values were slightly higher for the k-ω model. The results are shown in Figure 3

3.2 Tip modification

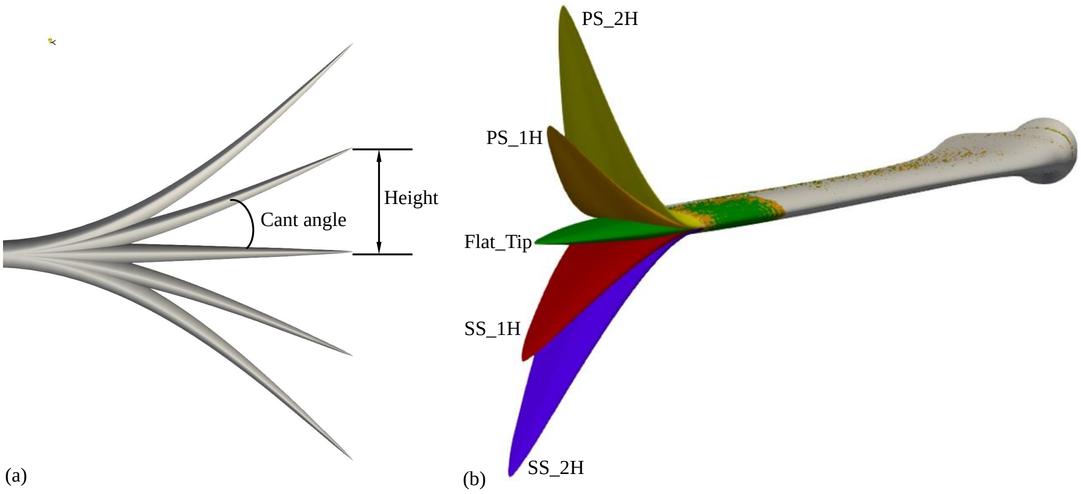


Figure 4: Modified tips

The same IEA 10MW blade, without prebend, was modified by introducing winglet-like shapes. At rated conditions the blade remains flat, hence the blade without prebend is considered in the present study. The last station of the airfoil is located at the height of 1 % and 2 % of the turbine's radius on both the suction and pressure sides of the blade. The modified blade with and without winglets is shown in Figure 4. Cant angle and height of the blade are the key parameters that define the winglet shape. In the present study, only the height of the winglets was varied, and its effect on the performance metrics of the turbine was studied. The cases considered for two heights are designated as PS_1H, PS_2H for the winglets at the pressure/upstream side of heights of 1 % R and 2 % R respectively, at the suction/downstream side it is designated as SS_1H, SS_2H respectively of the same heights. In summary, winglets are introduced with two different heights in both pressure and suction sides and the effect of them on the performance metrics are calculated from the simulation and the results are compared in Figure 5.

Among the cases considered, the difference in the performance metrics observed are shown in

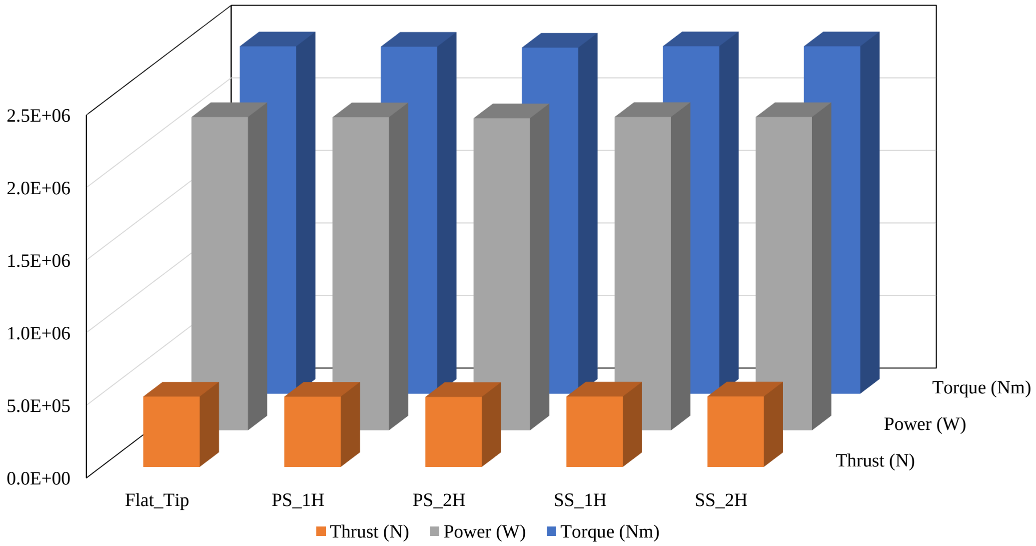


Figure 5: Effect of tip modification on thrust, power and torque

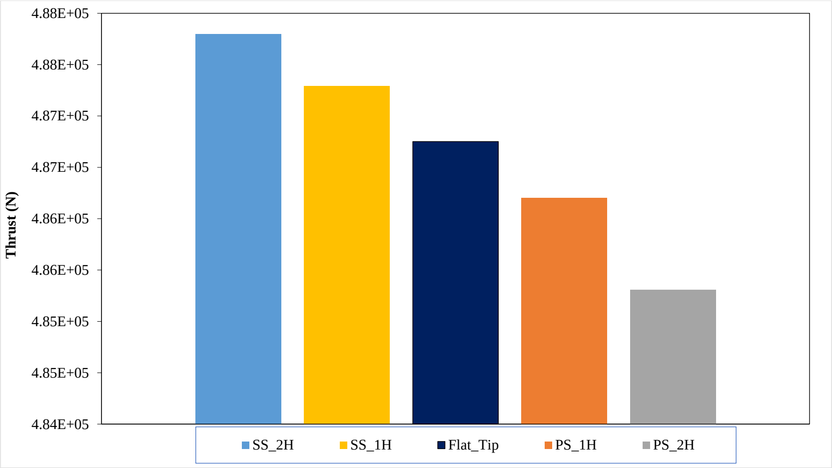


Figure 6: Effect of tip modification on thrust

the Figure 5. But the trend of torque, power and thrust had a similar trend. The introduction of winglet-like shapes in the downstream direction improved the performance of the turbine compared to the flat tip. Conversely, introducing the same shapes in the upstream direction reduced the performance of the turbine compared to the flat tip. The trend of thrust variation is shown in Figure 6, where the clear distinction in the effect of tip modification can be observed. The same trend is observed for other metrics such as torque and power. An improvement of about 0.2 % was observed for the winglet with a height of 2 % of the radius in the downstream direction. Similarly, the performance of the turbine reduced by about 0.5 % for the same height on the pressure side. For a winglet height of 1 % of the radius, there was an improvement of

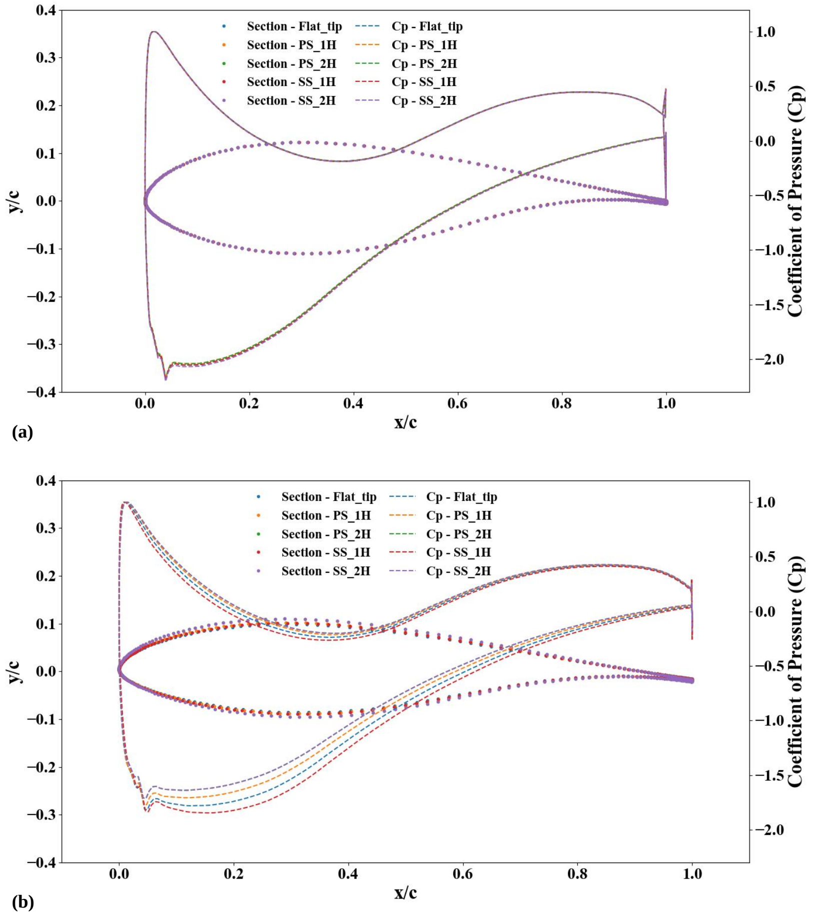
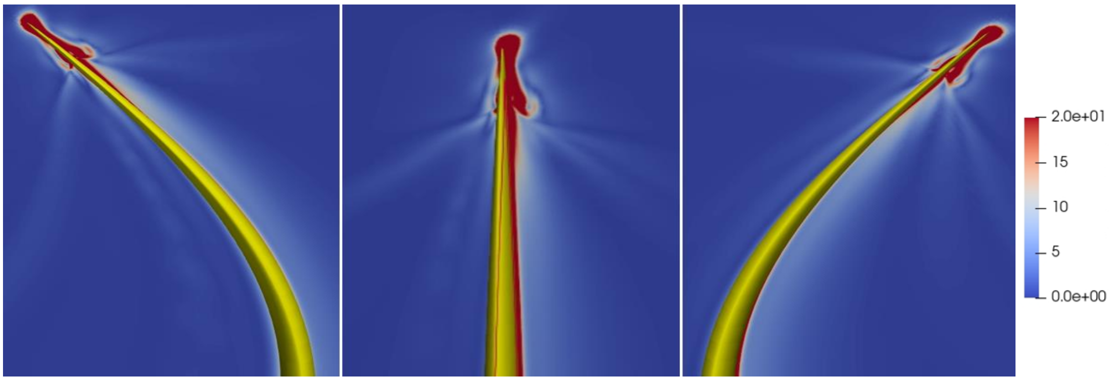


Figure 7: Effect of tip modification on pressure coefficient

(a) at r/R = 96.67 (b) at r/R = 98.5

0.1 % in the downstream direction, whereas a reduction of the same percentage was observed in the upstream direction.

The pressure coefficient values for all five cases are compared at two different locations of the blades. In Figure 7(a), at the distance of r/R = 96.67 the variation in pressure coefficient and the cross section of all the cases considered are shown. There is no variation in the cross section till this point, it can be seen in the figure the cross section of the all cases compared look the same. Also, the variation in pressure coefficient looks an identical curve for all the cases compared. But, in Figure 7(b) the pressure coefficient value and the cross section at a distance of r/R = 98.5 are compared for all the cases. The pressure coefficient is varying for all the cases, increased pressure coefficient on the pressure side, and reduced pressure coefficient on the suction side is observed for SS_2H case than the flat tip. The turbine with the winglet has a good influence on the pressure curve of the blade at the winglet region. In the present study, the effect of height of the winglet only considered, without taking the account of variation in other parameters of the winglet. A minimal variation in cross section between the airfoils also seen in the Figure 7(b) unlike Figure 7(a) is due to considering only the height of the winglet.



(a) PS_2H (b) Flat tip (c) SS_2H

Figure 8: Comparison of tip vortices

The tip vortices formation at the tip of the blade for three cases are shown in figure 8. The strengthened vortices relatively are observed for the flat tip than the winglet tips. comparatively the vortices strength is reduced with the winglet introduction which can be seen in the Figure. The winglet towards the downstream aligns to the incoming flow and also has better pressure curves makes it better than the flat tips for improved performance. Also, when the winglet aligned to the incoming flow, the noise produced will also be expected to reduce.

4 CONCLUSIONS

In the present study, high fidelity numerical analysis using OpenFOAM v2306 solver has been performed in order to study the effect of winglets in IEA 10MW turbine blade. Initially a base case without prebend and with flat tip is simulated and then the winglet shapes are introduced in the blade in both upstream and downstream directions with two different heights of 1 % and 2 % radius of the turbine. Two turbulence models are used in the present study, Spalart Allmaras and SST k-ω. From the analysis, SST k-ω model predicted the performance better than Spalart Allmaras. Inclusion of winglet shapes in the upstream direction (PS) reduces the performance of the turbine where as including the winglet in the downstream direction (SS) improved the turbine performance. From the present simulations and the cases considered, an improvement of 0.2 % power has been observed for the tip with winglet height of 2 % R. The formation of tip vortices showed how the strength of the tip vortices are reduced after introducing the winglets than the flat tip.

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