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Power Performance of Vertical Axis Wind Turbine in Martian Atmosphere Using CFD Simulation

Farshad Rezaei[1], Marius Paraschivoiu[2]
[1,2]Department of Mechanical, Industrial, and Aerospace Engineering, Concordia University, Montreal, Quebec, Canada
[1]farshad.rezaei@concordia.ca
[2]marius.paraschivoiu@concordia.ca

Abstract**—** When astronauts travel to Mars and potentially establish permanent habitats, a reliable energy source or multiple redundant energy sources are essential. Vertical Axis Wind Turbines (VAWTs) are well-suited for this purpose due to their efficiency and adaptability to the Martian environment. In this work, Computational Fluid Dynamics (CFD) was used to investigate the performance of VAWTs in the Martian atmosphere and their behavior when equipped with endplates. The findings indicate that the maximum power coefficient (C_P) achieved with an endplate is 0.18 These results highlight the potential of strategic design modifications to optimize VAWT performance in the low-density Martian atmosphere, a critical factor for sustainable energy generation in extraterrestrial habitats.

Keywords-CFD; VAWT; Mars; Endplate

I. Introduction

Humanity will likely settle on Mars because it offers a chance to explore new frontiers and ensure the survival of our species in case of disasters on Earth. Mars has resources like water ice and the potential for creating habitable environments through terraforming. Advances in technology and space travel make this ambitious dream increasingly achievable. For any future Mars settlement to be successful, it will be crucial to generate energy. It will be necessary to use a variety of energy sources in order to ensure reliability.

Martian dust storms absorb solar radiation in the upper atmosphere, leading to cooling at the planet's surface and warming in the higher atmospheric layers. This temperature imbalance intensifies wind speeds [1]. Therefore, while solar panels become less efficient during these storms, wind turbines can take advantage of the stronger winds. As a result, wind power can be a practical and complementary source of energy on Mars [2].

Renewable energy can be generated through both wind turbines and solar panels. Despite this, maintaining consistent energy production is difficult due to fluctuations in wind speeds and sunlight. Wind energy capture on Mars presents a unique combination of challenges and opportunities. Certain areas on Mars experience strong winds at regular intervals [3], and frequent dust storms can cover vast regions, significantly hindering solar power generation by obstructing sunlight. Wind has long been a sustainable energy source on Earth, used for centuries to pump water, mill grain, and generate electricity. Mars' atmosphere differs significantly from Earth's, necessitating the design of wind turbines tailored specifically to the unique characteristics of the Martian environment [4] [5] [6]. A study has also demonstrated that wind energy is a viable power source for Mars [2]. A Vertical Axis Wind Turbine (VAWT) is a viable option since it requires minimal maintenance, is durable, and can adapt to Martian conditions.

The substantial differences in air pressure and density between Mars and Earth impact properties such as kinematic viscosity, thermal conductivity, and specific heat capacity. As a result, Mars has a much thinner atmosphere, which might suggest that wind energy production would be inefficient according to very low-density value. However, according to Equation 1 (which describes power extraction from wind), power generation is strongly influenced by the cube of wind velocity and only depends linearly on air density. As a result, the high wind speeds on Mars could potentially compensate for its low atmospheric density, indicating that wind energy could still be effectively utilized.

$$P_{wind}=0.5\rho A_S U_\infty^3 \quad (1)$$

Where P is the power, C_P is the Power Coefficient, ρ is the wind density, V_∞ is the free stream velocity, and A_S is the swept area, which is defined as:

$$A_S=HD \quad (2)$$

Where H is the blade length and D is the turbine's diameter. The C_P is a non-dimensional parameter that indicates the proportion of the wind's available energy that is harnessed by the turbine, as follows:

$$C_P = P_{turbine}/P \quad (3)$$

Under these conditions, VAWTs are seen as ideal for Mars due to their simple design, which includes only one moving component—the rotor. VAWTs function regardless of wind direction thanks to this design, which eliminates the need for yaw mechanisms [7] [8]. Straight-bladed VAWTs have uniform, untwisted blades that are easier to transport and assemble than twisted and tapered blades for Horizontal Axis Wind Turbines (HAWTs) [9]. Furthermore, VAWTs are not subject to fatigue stresses caused by gravitational forces, making them more durable and reliable. Their capability to operate efficiently in turbulent wind conditions, a frequent occurrence on Mars, further strengthens the case for their use [10] [11]. Furthermore, in extraterrestrial applications where reliable performance and simple assembly are essential, VAWTs are a practical option, thanks to their ease of maintenance and scalability.

Since the atmospheric density on the surface of Mars is very low, the flow easily separates from the turbine blades. Therefore, certain geometrical features may be necessary to enhance the power performance of the VAWT. Additionally, researchers have shown that adding endplates to the VAWT can improve its power performance [12]. Installing endplates at the top and bottom of the turbine reduces flow spillage from the blade tips, thus enhancing aerodynamic efficiency and power output. The effects of endplates on VAWTs have been investigated both numerically and experimentally [13] [14] [15]. Ung et al. used numerical simulation to investigate the effects of endplate to study the flow features on the straight-bladed VAWT [16]. Their simulation demonstrated that endplates reduced the swirling vortex and enhanced pressure distribution along the blade span, particularly at the blade tip. Tan et al. investigated the effects of different circular endplate on the VAWT and found that the C_P increased 7.45% at the highest performance of the turbine [17]. Their findings indicated that endplates could prevent airflow from bypassing the blade tip, thus avoiding the formation of tip vortices. This improvement in aerodynamic efficiency near the blade tip leads to an overall enhancement in the C_P of a VAWT.

While Mars's lower atmospheric density poses challenges, the high wind speeds present on the planet offer a compelling opportunity for wind energy generation. This study goes beyond existing models by exploring how strategic design modifications, such as incorporating endplates, can optimize energy production in the Martian environment. This innovative approach provides new insights into maximizing efficiency under extreme atmospheric conditions, paving the way for more sustainable and resilient energy systems that could support a long-term human presence on Mars. Kumar et al. utilized Double-Multiple Streamtube model [18] and designed a 500 W Darrieus-type straight-bladed vertical-axis wind turbine (S-VAWT), considering the atmospheric conditions on Mars [19]. Their suggested geometry and operational conditions are used in the current research. However, this study advances the field by conducting a detailed Computational Fluid Dynamics (CFD) analysis, accounting for the effects of rapid flow separation and complex aerodynamic interactions. This research is unique and highly novel, as no similar studies exist that comprehensively address the power extraction of wind energy by a VAWT in the Martian atmosphere. By integrating these novel design elements, this research offers a significant leap toward practical renewable energy solutions in extraterrestrial environments.

II. Numerical Setup

A. *Numerical Modeling*

The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is commonly used in CFD simulations to address pressure-velocity coupling. It iteratively solves the governing equations for velocity and pressure in a segregated manner, ensuring mass and momentum conservation. The algorithm maintains mass conservation by solving a pressure correction equation [20]. Franchina et al. showed that the choice of turbulence model was essential for accurately predicting periodic blade separations and their effects on tip vortex development and boundary layer formation on the struts. Selecting an appropriate model helped minimize discrepancies between measured and predicted power coefficients [21]. In the Implicit Unsteady approach, multiple inner iterations are performed at each time step to achieve convergence, with at least ten iterations ensuring residuals remain below 1×10^{-5}. Smaller physical time steps result in less variation between steps, requiring fewer inner iterations. High-accuracy temporal discretization can be achieved using second-order time discretization. The STAR-CCM+ CFD toolbox has been used for the current research.

In this investigation, effects of different rotational velocities are considered for the VAWT, characterized by a non-dimensional parameter known as the Tip Speed Ratio (TSR). TSR is defined as the ratio of the blade's velocity to the wind's velocity and is represented as follows:

$$TSR = R\omega/U_\infty \quad (4)$$

Where R is the turbine's radius.

To change TSR values, the rotational velocity is adjusted, maintaining a constant rotational speed for each TSR value. Rezaei et al. show that at Mach numbers less than 0.2 for an airfoil under stall conditions, an incompressible flow solver provides highly accurate results [22]. In this case, the Mach number is 0.0833. Therefore, an incompressible solver is considered appropriate for this job. The K-ω SST turbulence model is employed in this study due to its proven success in predicting stall conditions, including static and dynamic stall [23] [11], and its effectiveness in predicting flow separation on airfoil surfaces. The Reynolds number based on the chord length for a VAWT on Earth with a blade chord length of 0.06 m and velocity of 9.3 m/s is equal to 3.82×10^{-4}, while for the current case in Martian atmosphere with the chord length of 0.71 m and velocity of 20 m/s, it is 2.57×10^{-4}. Since there is not significant difference in Reynolds number, the effectiveness of K-ω SST model in predicting flow separation still works for the Martian atmosphere. Posa used Large Eddy Simulation (LES) to study the wake recovery in downstream of a VAWT [24]. URANS simulations can effectively capture the overall features of dynamic stall, including the development of the dynamic stall vortex. However, they have difficulty accurately predicting details such as boundary layer evolution and momentum transfer after separation. [25] [26]. Although LES models offer greater accuracy, their high computational cost and extended run times make them less feasible for VAWT simulations, which involve multiple rotations and large-scale structures.

Kumar et al. studied and designed a 500 W Darrieus-type S-VAWT, taking into account Martian atmospheric conditions [19]. To accurately predict lift and drag coefficients for transitional flows, they used a transitional model compatible with the Spalart-Allmaras turbulence model. The wind turbine design and optimization involved iterative adjustments to rotor height, rotor diameter, chord length, and aerodynamic loads. The CARDAAV code, based on the "Double-Multiple Streamtube" model, was employed to evaluate and optimize the performance parameters of the S-VAWT [18]. Table 1 provides a summary of the design parameters for the fully optimized wind turbine as detailed by Kumar et al. [19]. In this research, the optimized turbine mentioned in the Table 1 will be used.

A. *Mesh Study*

To ensure the accuracy and reliability of the simulations, it is essential to perform a mesh independence study. For a VAWT with a similar geometry, a comprehensive mesh study has been done in [27], [28], and [27] by the same authors of this research. Table 2 presents the five different meshes used in this study. The results indicate that C_P is sensitive to both the prism thickness and the number of cells on the blade. From Mesh 3 to Mesh 5, the number of cells at the leading and trailing edges increases, leading to a slight increase in C_P. Mesh 5 demonstrates that, despite a significantly higher number of cells, C_P does not change significantly compared to Mesh 4. It shows that the solution has become independent of the mesh size. Therefore, to keep the computational cost low, Mesh 4 is selected for this research. The type of the mesh in the domain and around the airfoil are shown in Fig. 1. It is important to note that when using endplates, with the same characteristics as Mesh 4, the number of cells in the rotor section increases to 31,308,524 due to the additional endplates on the blades. To ensure high-quality meshes, T-shaped connections between components like struts and shafts are omitted in the CFD model. Rezaeiha et al. demonstrated that when the shaft-to-turbine diameter ratio is small, its impact on turbine performance is negligible [29].

III. Results and Discussion

Placing endplates at the top and bottom of the turbine helps minimize flow spillage from the blade tips, thereby improving aerodynamic efficiency. Endplates effectively contain the airflow within the rotor plane, resulting in enhanced aerodynamic performance and increased power output. Fig. 2 shows the endplate added to the VAWT's blade for this research. The profile of the endplate is the same as the profile of the blade, i.e., NACA 0018, with a doubled chord length and a thickness of 0.01 meters.

Fig. 3 shows the comparison of C_P values for the VAWT with endplate and without that in a uniform flow. Both curves follow a similar pattern, with C_P rising with TSR to a peak value before declining. The addition of endplates consistently produces higher C_P values compared to the baseline 3D simulation without them. The graph indicates that at small values of TSR, i.e. TSRs of 3 and 3.5, there are small changes in the power performance of the VAWT. It shows that tip vortices at small TSRs have small effects on the power performance of the VAW Nevertheless, at TSRs of 4 and 4.5, the graph demonstrates that there is a considerable increase in the power performance of the VAWT. The C_P values at TSRs of 4 and 4.5, are increased by 20% and 20.2% respectively, when the endplate added. This enhancement is especially significant at and near the peak TSR value. The endplates effectively confine the airflow within the rotor plane, reducing flow spillage from the blade tips and boosting overall aerodynamic performance.

TABLE I. The design parameters for the fully optimized wind turbine at Martian atmospheric conditions as detailed by Kumar et al. [19]

Optimized parameters for the 500 W VAWT [19]	
Number of blades	2
Radius (m)	4.475
Blade length (m)	5.4
Blade chord length (m)	0.71
Airfoil section	NACA 0018
Tip speed ratio	3.08
Free stream velocity (m/s)	20
ω (rad/s)	13.8

TABLE II. Different Mesh Characteristics

Mesh name	**Prism Thickness**	**First layer thickness**	**Number of cells the in rotor**	**C_P**
Mesh 1	0.0395	0.000348	9,074,286	0.0131
Mesh 2	0.041	0.000352	9,054,004	0.0333
Mesh 3	0.043	0.000379	16,879,501	0.044
Mesh 4	0.043	0.000379	27,802,869	0.047
Mesh 5	0.043	0.000379	100,295,473	0.049

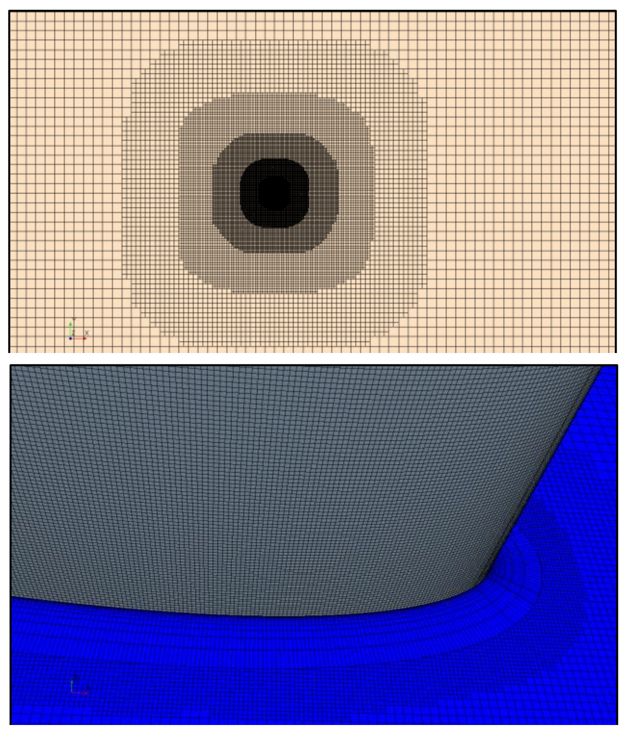

Figure 1. Type of the mesh in the domain of simulation (top); beside the blade (bottom)

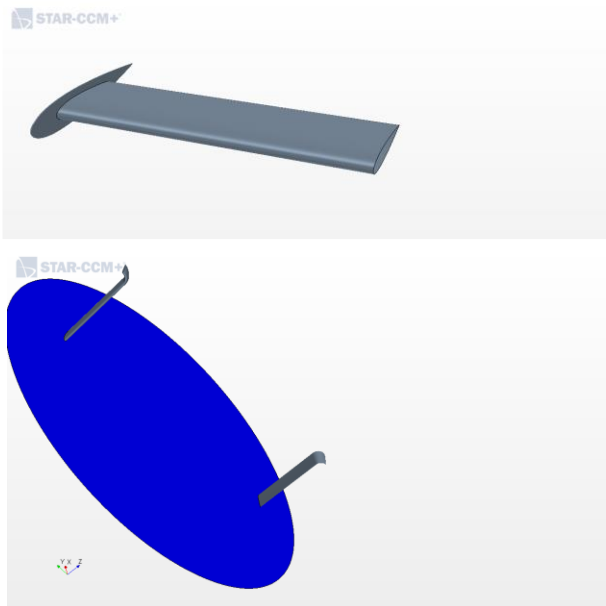

Figure 2. Adding endplate to the blade (top); Blades with endplate in the rotor (bottom)

This strategic modification is beneficial for optimizing VAWT performance in the Martian atmosphere, where efficiently harnessing wind energy is essential for supporting human habitats. The results in the Fig. 3 show that there is a reduction of the VAWT performance at TSR of 5, regardless of using endplate for the VAWT. This also happens for the VAWT when performing at Earth atmosphere condition [30].

The results show that the maximum C_P with an endplate is 0.18. This value is very close to the C_P of 0.2, which Kumar et al. [19] predicted for this geometry and operational conditions using the DMST method. The DMST method does not account for tip effects on the airfoil. The findings of this study indicate that when an endplate is added, the impact of tip vortices decreases. As a result, the simulation results align more closely with the value predicted by the DMST.

Fig. 4 illustrates the C_M values for the VAWT equipped with endplates in uniform flow at TSRs of 3 and 4. As expected, the effects of severe dynamic stall are evident at a TSR of 3. The dynamic stall causes the reduction of the power performance of the VAWT. However, at a TSR of 4, there are no signs of severe dynamic stall. Therefore, it is expected to have better performance of the VAWT. Additionally, as shown in Fig. 4, the maximum C_M values at a TSR of 4 are higher than those at a TSR of 3, resulting in better performance at the higher TSR, as depicted in Fig. 3. The stopping criterion is met when the change in C_P values between two consecutive rotations is less than 1%. Moreover, the C_M values for both TSRs suggest that the turbine has achieved stable operation. Fig. 4 shows the pressure contour over the blade and the winglet. It shows that high pressure zone happened in leading edges of the blade and the endplate, as expected.

Fig. 5 illustrates vorticity iso-surfaces, with high vorticity regions notably concentrated around the blade tips and in the wake behind the turbine. The addition of endplates aids in controlling the flow near the blade tips, thereby reducing the strength of tip vortices. By lessening the impact of these vortices, endplates help maintain higher pressure differences across the blade surface, which leads to improved lift and overall turbine performance. The iso-surfaces shown are likely smooth and more controlled, indicating enhanced flow behavior around the blades. This smoother flow suggests a reduction in turbulence intensity, which can lead to more stable aerodynamic performance and lower unsteady loading on the blades.

The figure also displays large, coherent vortex structures extending downstream, demonstrating how endplates affect wake development. Without endplates, these vortices would likely break down more chaotically, leading to increased energy dissipation and reduced aerodynamic efficiency. These endplates appear to create more organized and less dissipative vortex structures, potentially contributing to increased energy extraction. Furthermore, the presence of well-defined vortex structures suggests that the endplates help in extending the region of effective energy conversion, potentially allowing for better interaction with downstream turbines in a wind farm configuration.

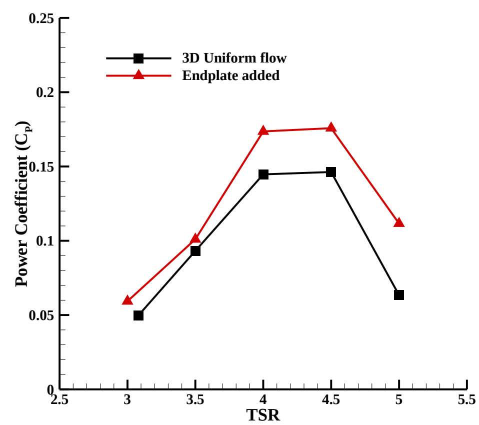

Figure 3. C_P values for the VAWT with and without endplate in a uniform flow at the Martian atmosphere

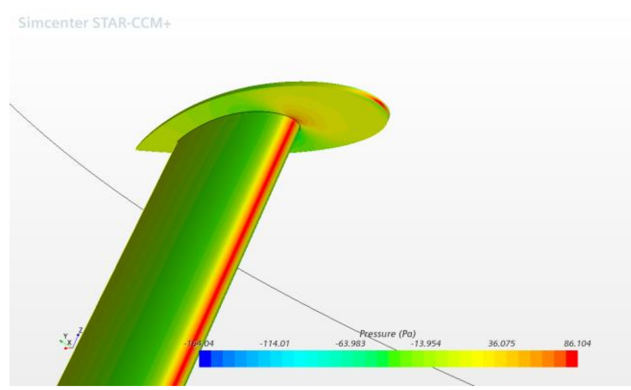

Figure 4. Pressure contours over the blade and the endplate

IV. CONCLUSION

The investigation demonstrates that incorporating endplates significantly improves the performance of VAWTs in the Martian atmosphere. Endplates enhance C_P by approximately 20% at higher TSRs, effectively confining airflow and reducing flow spillage from blade tips. The results show that the maximum C_P obtained with an endplate is 0.18, closely matching the 0.2 predicted by the DMST method. Since the DMST method does not consider tip effects on the airfoil, the findings of this study suggest that adding an endplate reduces the influence of tip vortices at Martian atmosphere. Consequently, the simulated results align more closely with the predictions made by the DMST. These results indicate that optimizing VAWT design through aerodynamic modifications can significantly enhance performance in the Martian atmosphere, contributing to efficient wind energy harnessing—an essential factor for supporting human habitats on Mars. Further research is necessary to explore the effects of different endplate geometries in a low-density atmosphere.

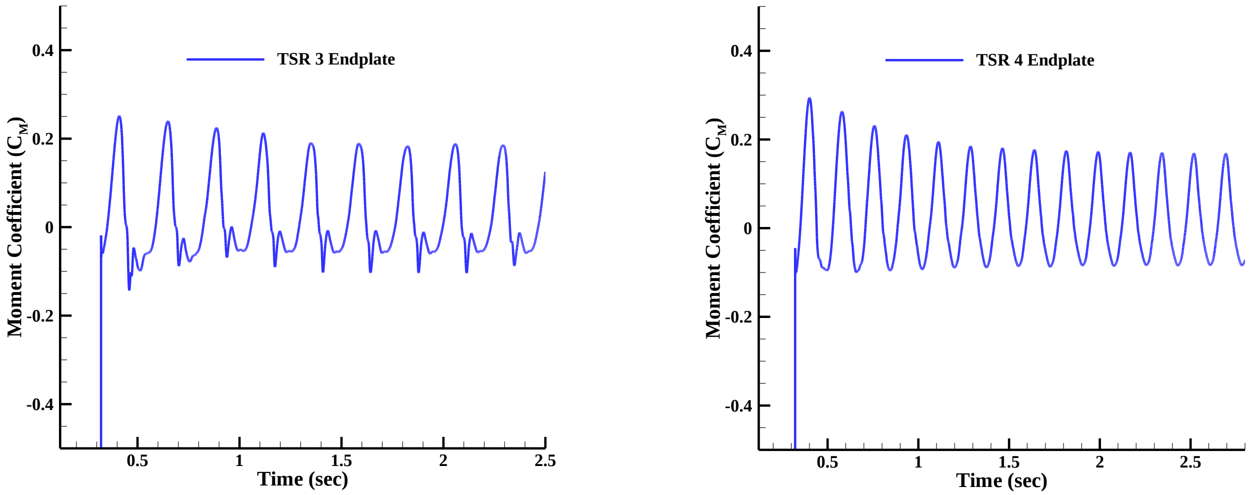

Figure 5. Moment Coefficients (C_M) values for the turbine featured by the endplates at TSRs of 3 and 4

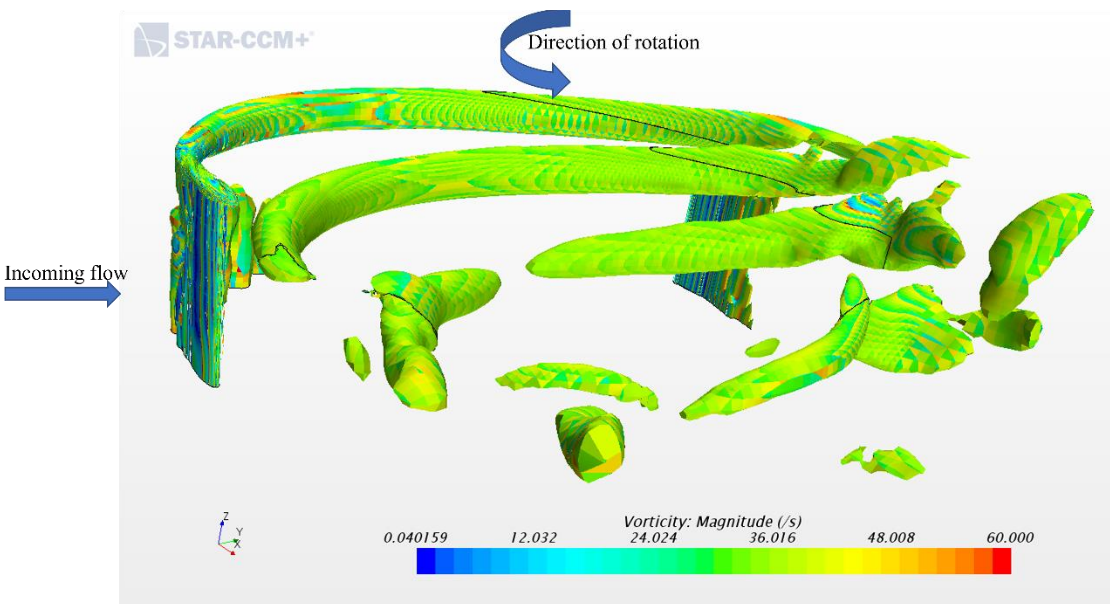

Figure 6. vorticity iso-surfaces of the blades when endplates have been added to them

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