CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Optimization of Magnus Wind Turbine Blades to Increase Operational Efficiency

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ARTICLE INFO

Article history:
Received 19 July 2024
Received in revised form 21 August 2024
Accepted 23 September 2024
Available online 31 December 2024

Keywords:
Magnus wind turbines; cylindrical blades; efficiency; vortex disruption; angles of inclination; turbulence model

ABSTRACT

The problem of vortex disruption from the cylindrical blades of Magnus wind turbines is an urgent topic, which subsequently reduces the efficiency of the installation. Also, these cylindrical blades have a disadvantage in the form of low lift and high drag, as a result of which low operating efficiency is observed. Thus, the purpose of this work is a numerical study of the addition of a fixed blade to the cylindrical blades of a two-bladed wind turbine. Numerical studies were carried out for various angles of inclination of fixed blades from 0° to 60° using the Realizable k-ε turbulence model. The results of the study showed that with an increase in the angle of inclination of the fixed blade, the flow is disrupted, which is clearly visible at the maximum speed of rotation of the blades and the wind wheel, which causes a drop in lift, leading to a decrease in the efficiency of the wind turbine. Based on this, 0 degrees is the optimal angle of inclination of the fixed blade of a wind farm.

1. Introduction

In connection with global efforts to reduce carbon dioxide emissions and combat climate change, renewable energy sources play a crucial role. Among which, wind energy occupies the second place after solar energy, producing electricity in large quantities with minimal impact on the environment.

The proof of this is that the global production potential of wind energy, both onshore and offshore, can generate 872,000 TWh of electricity per year [1]. It is known that wind resources at an altitude of 80 m with a speed of 6.5 m/s and above are usually considered commercially viable. However, not all densely populated areas can boast such powerful wind resources, usually they average 4-5 m/s. Based on this, an urgent issue is the development and study of wind turbines designed for low wind speeds. One such type of installation is the Magnus wind turbine with cylindrical blades, as highlighted in previous studies [2,3].

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https://doi.org/10.37934/cfdl.17.6.205219

Traditionally, wind turbines with a horizontal axis of rotation are widely used in comparison with the vertical axis of rotation due to increased output power, providing approximately 10-20% greater output efficiency [4]. However, recent studies, such as those by Aneesh *et al.,* [5] carried out numerical studies of Magnus wind turbines at different speeds and tip velocity coefficients. An interesting outcome is to obtain high values of the ratio of coefficients at low values of the tip speed ratio. Nevertheless, many existing Magnus wind turbines have low efficiency compared to traditional blade installations [6]. The reason for this is the low lift and high drag force, compared to traditional bladed wind turbines.

Research by Marzuki *et al*., [7], has shown that one method to improve the performance of Magnus wind turbines is to manipulate the surface roughness of the cylindrical blades. Marzuki et *al.,* [8] and Tanasheva *et al.,* [9], methods such as adding sandpaper-like textures or artificial grooves to increase the efficiency of wind turbines were proposed.

It is known from previous studies [3,10-14] that optimizing the power elements by modifying the shape of the cylindrical blades and adding additional components such as disks and plates can significantly increase the output power of the installation. Adding a plate to the rotating cylinders solves the problem of suppressing vibrations forming behind the cylinder and also controls the vortex flow that occurs after the cylinder [15-19].

Currently, numerical modelling has a significant place in the field of wind turbine research, which allows us to study the aerodynamic properties of wind turbine blades with higher accuracy [20]. Chabaud [21] investigated the flow structure around a wind turbine using numerical methods of gas dynamics based on solving a system of Navier-Stokes equations. Using mathematical equations to calculate the flow can significantly reduce time and material costs compared to the experiment.

Furthermore, studies by Majuni *et al.,* [22] have examined the impact the effect of the vortex formation on the performance of a small wind turbine, at a constant speed of 4 m/s and a rotation speed of 600 rpm. This highlights the importance of understanding and controlling aerodynamic phenomena in wind turbine arrays to enhance overall efficiency.

The power of a wind turbine depends on several factors, as highlighted in previous studies [23-25], including the swept area, the speed and turbulence of the airflow and the uniform distribution of the wind velocity field around the wind rotor. The velocity distribution pattern is a key factor in analysing wind turbine performance. In his study, Mahrous [26] examined the effectiveness of different blade configurations based on the velocity distribution, torque and power output results. His findings revealed that modifying the blade design led to an increase in output torque by nearly 48%.

The parameters of the wind velocity vector distribution, estimated using modern CFD analysis, allow for reliable predictions of wind turbine efficiency during the mathematical simulation stage, as demonstrated in previous studies [27-30].

Despite significant advances in the study of the aerodynamic characteristics of rotating cylindrical blades, unresolved issues remain related to the optimization of the blades of Magnus wind turbines. Further research on the flow behaviour and interaction of rotating blades with turbulent air flows within the number range of $1\cdot10^4>Re>4\cdot10^4$ is needed. Studying these aspects is important for improving the efficiency of wind turbines using the Magnus effect and developing more energy efficient solutions.

Therefore, the objective of this study is to conduct a numerical investigation the effect of addition of a fixed blade to the cylindrical blades of a Magnus wind turbine, in order to increase operational efficiency.

2. Methodology

The numerical study was carried out using the Ansys Fluent program, based on a three-dimensional method for calculating the flow around a wind turbine, using numerical methods for solving non-stationary Reynolds averaged Navier-Stokes equations., using the Realizable k-ε turbulence model.

2.1 The Problem Statement

The problem of air flow around a wind wheel with two combined blades is considered, with the determination of the optimal angle of the fixed blade. The blades are made in the form of rotating cylinders with a fixed blade. The position of the fixed blade varies from 0° to 60°, in increments of 15°. The problem is solved numerically using CFD modelling.

2.2 Creating the Geometry of a Wind Turbine with Different Positions of the Fixed Blade

The first stage for conducting numerical simulation of wind turbine flow is the construction of a geometric model. In the course of numerical studies, a three-dimensional model of a wind turbine with two blades was created.

The model of a wind turbine consists of combined blades made in the form of fixed blades and cylinders, a central shaft on which the working power elements are fixed, as well as a mast on which the main shaft is fixed.

The geometric dimensions of the mathematical model are shown in Table 1.

Table 1
Geometric dimensions of the wind turbine model

Parameters	Meaning
Cylinder length	205 mm
Cylinder diameter	50 mm
Fixed blade length	225 mm
Fixed blade width	25 mm
Wind wheel diameter	500 mm
Mast length	420 mm

Figure 1 shows how a fixed blade forms an angle (0°, 15°, 30°, 45°, 60°) relative to the distance of the axis of rotation of the cylinder.

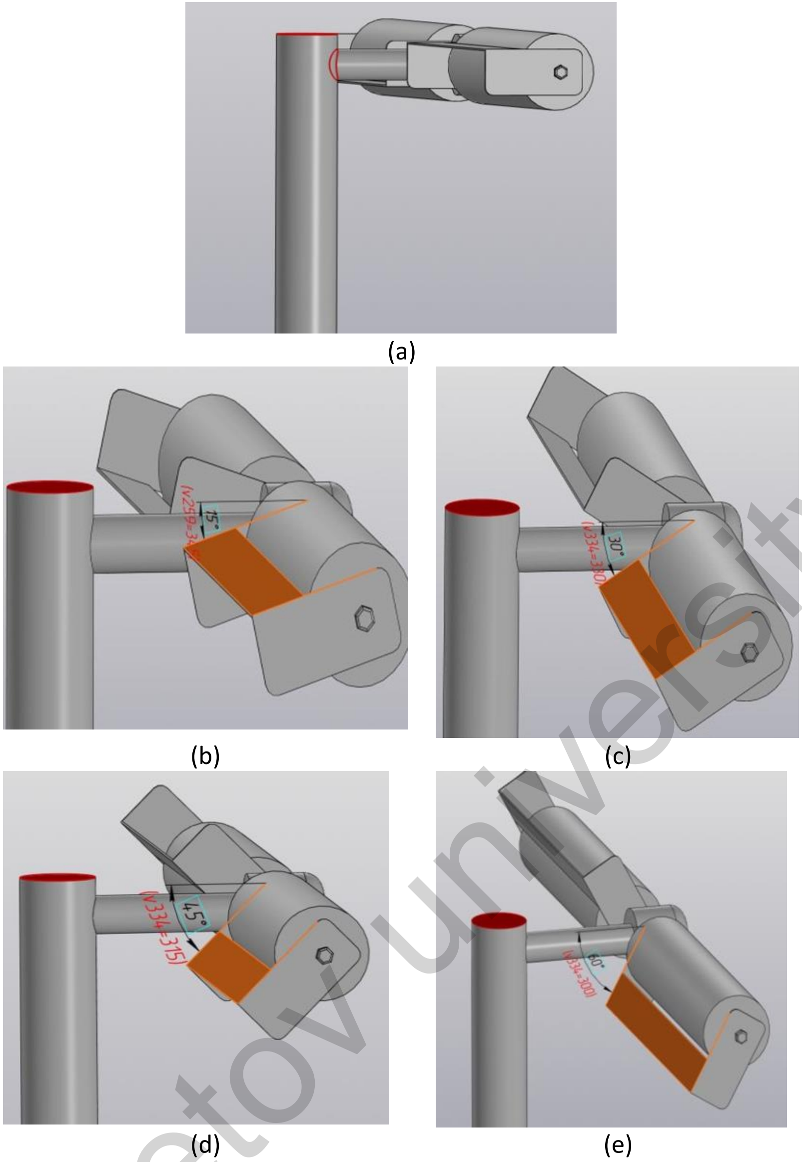


Fig. 1. The location of the blades at different angles: (a)-0 degree (b)-15 degree (c)-30 degree (d)-45 degree (e)-60 degree

2.3 Boundary Conditions

In this study, the boundary conditions play a crucial role in defining the behaviour of the wind flow around the cylindrical blades of the Magnus wind turbine.

The boundary conditions used in the analysis are presented in Table 2.

Table 2
Boundary conditions

Initial parameters	
Type of air	incompressible
Flow Type	Isothermal
Gas density (kg/m^3)	1,1691
Gas viscosity (kg/ms^{-1})	1.84×10^{-5}
Viscous regime	turbulent
Inlet	
Type	Inlet speed
Initial pressure gauge (Pa)	0
Air flow velocity (m / s)	3, 5, 7, 10, 15
Turbulence intensity (%)	5
Coefficient of turbulent viscosity	10
Outlet	
Type	Outlet pressure
Pressure gauge (Pa)	0
Reverse flow of turbulent intensity (%)	5
Coefficient of backflow of turbulent intensity (%)	10
Blade surface	
Type	Wall
Shift condition	No slipping
Periodic conditions	
Type	Rotation
Wind wheel rotation speed (rpm)	300, 500, 700

The simulation is based on the assumption of incompressibility of the isothermal air flow, taking into account the turbulent viscosity regime.

2.4 Creation of Computational Areas around the Studied Models

The initial stage of numerical simulation is the creation of computational areas around the mathematical model to set boundary conditions and rotation conditions (Figure 2).

A cylindrical subdomain (1) with a thickness of 5 mm has been created around each power element to set the conditions for the rotation of the blades, a cylindrical subdomain (2) with radius of 0.1 m around the z axis has been created around the cylindrical subdomains, as well as an area in the form of a parallelepiped (3) with dimensions of 0.7 m; 0.7 m; 1.5 m; 0.7 m;0.7m; 3m around the cylindrical subdomain (2) (Figure 2) to rotate the conditions of the entire wind wheel.

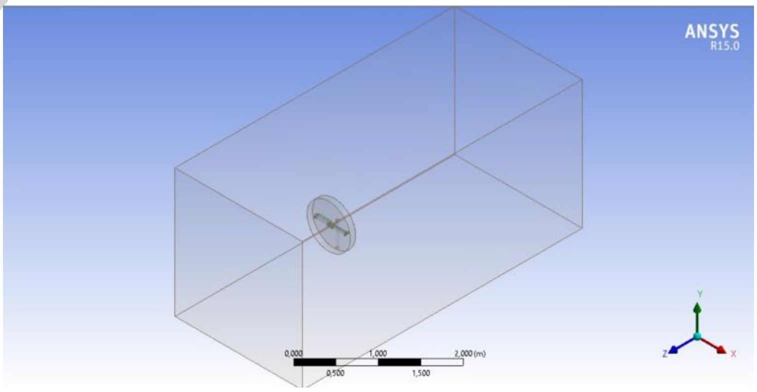


Fig. 2. Model of a wind turbine with calculated areas

To determine the optimal number of grids, three types of grids with different numbers of cells were studied, as well as the effect of the number of cells on the calculation results. Table 3 shows the results for torque at a flow rate of 15 m/s and a blade rotation speed of 700 rpm.

Table 3
Grid detail values

Grid Type	Number of cells	Torque
Grid 1	234025	23,324 N·m
Grid 2	269842	26,078 N·m
Grid 3	297851	26,268 N·m

As shown in Table 3, grid 2 with the number of cells 269842 gave the best results and was used in further calculations, since a further increase in the number of cells does not significantly affect the results and grid independence is observed.

Of course, the volumetric wind turbine grid obtained in the Ansys Meshing routine consists of 269,842 tetrahedral elements.

Figure 3 shows a finite-volume grid of wind turbines obtained in the Ansys Meshing routine. The grid consists of 269,842 tetrahedral elements.

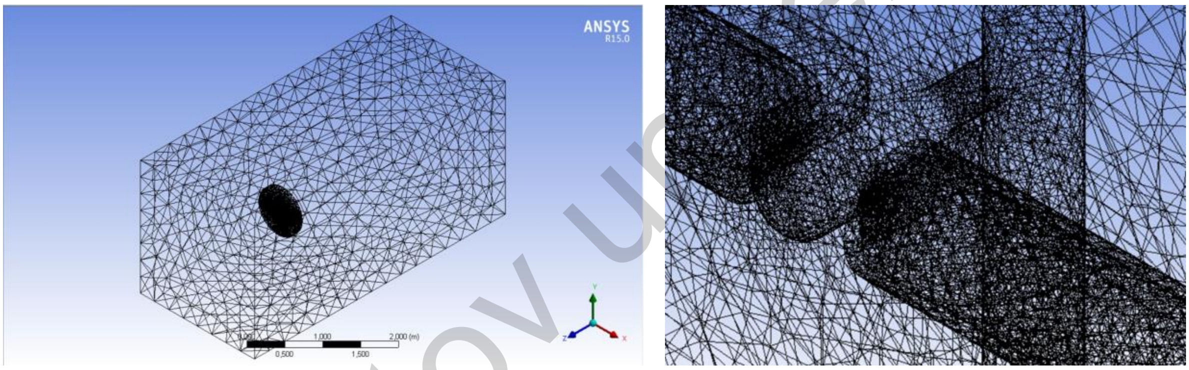


Fig. 3. Finite-volume grid

3. Results

3.1 Aerodynamic Characteristics

The studies were carried out for 5 models of a wind turbine with fixed blade positions at angles of 0.15, 30, 45 and 60 degrees, with flow modes from 3 to 12 m/s, as well as with Reynolds numbers $1\text{-}4 \cdot 10^4$.

Figure 4 shows the results of the calculated aerodynamic drag coefficients depending on the Reynolds number.

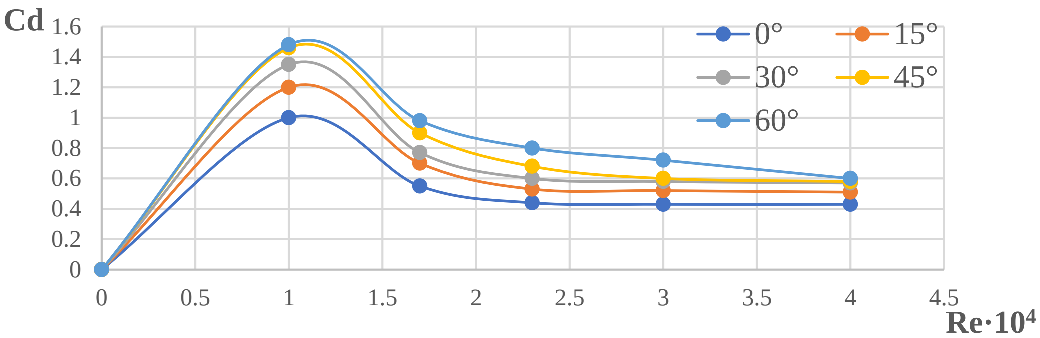


Fig. 4. Dependence of the drag coefficient on the Reynolds number at different angles of inclination

As can be seen from Figure 4, when the fixed blade is positioned relative to the cylinder at an angle of 0 degrees, optimal values of the drag coefficient of 1.48 are obtained with a Reynolds number of $1{\cdot}10^4$. At low values of Re up to 1·104, the drag coefficient increases rapidly for all angles of attack, the explanation for this is that at low speeds the inertial forces are small and viscous forces prevail, causing an increase in resistance. At the point Re = $1{\cdot}10^4$, a peak coefficient is observed for all angles, which is characteristic of the transient flow regime and subsequently a turbulent regime begins. At high Reynolds numbers Re>$1{\cdot}10^4$, the dependence line gradually decreases due to a decrease in the influence of viscous forces and the flow regime becomes completely turbulent. Starting from Re>$2{\cdot}10^4$, the coefficient stabilizes, which proves the steady-state turbulent regime.

The explanation for this is that with an increase in the angle of the blades, the flow is disrupted from the sides of the cylinders, which subsequently increases the drag force of the blades and the wind wheel.

Next, a graph of the dependence of the rotor torque acting on a movable wind turbine with two wind turbines on the velocity of the incoming flow is constructed numerically (Figure 5).

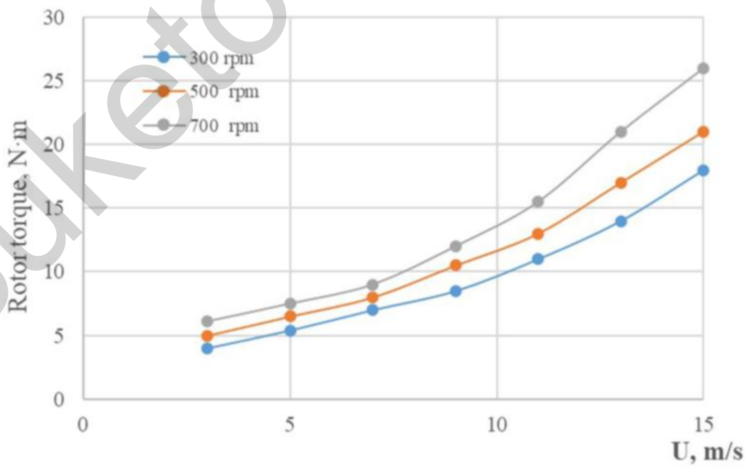


Fig. 5. Graph of the dependence of the rotor torque acting on a movable wind wheel with two blades on the velocity of the incoming flow

As can be seen from Figure 5, the magnitude of the rotor torque increases in a straight line with increasing wind flow velocity. The dependency lines can be divided into 3 zones. Zone 1 is the initial region at U<5 m/s, showing a slight dependence of the rotor torque on the air flow velocity and the number of revolutions of the blades, where the influence of wind is minimal on the torque values.

Zone 2 at 5<U<10 m/s, where a quasi-linear region occurs, in the case when the wind speed has the maximum effect on the torque. Zone 3 U>10 m/s is a saturation region where a slow growth of the dependence line occurs and also indicates an approach to the maximum values of the aerodynamic efficiency of the turbine. The maximum torque value of a two-bladed wind turbine is 26 Nm at a wind speed of 15 m/s and a blade rotation speed of 700 rpm.

The results obtained do not contradict the results of the Lukin *et al.,* [31] (Figure 6).

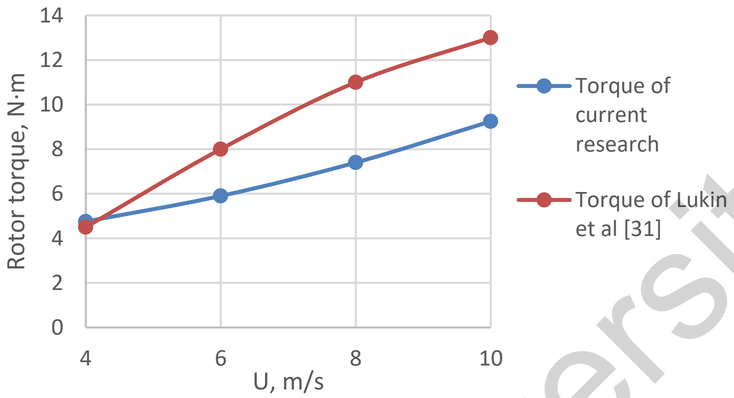


Fig. 6. A comparative graph of the obtained numerical data of the rotor torque at 300 rpm with known experimental data [31]

As can be seen from Figure 6, the growth pattern of the dependence line coincides and corresponds to the general trend. Nevertheless, there are differences between the obtained numerical and experimental data [23]. The maximum error starting from 8 m/s is about 29%. Lukin *et al.,* [31], an experimental evaluation of the layout of a wind turbine with cylindrical blades with a radius of 6.5 cm was carried out, while a layout with a blade radius of 2.5 cm was used in numerical modelling. Thus, the radius of the blades in numerical calculations is 2.6 times smaller, which is equivalent to a decrease of 61.54%. This significant scale factor could have influenced the differences in the results, since the size of the blades significantly affects the aerodynamic characteristics and flow distribution around the wind turbine.

Despite these discrepancies, the numerical data obtained demonstrate the overall efficiency of the wind turbine, which is confirmed by improved aerodynamic characteristics due to the addition of a fixed blade to a design with cylindrical blades.

3.2 Flow Pattern

Further below are the results of the flow pattern of the wind turbine under different modes. Figure 7 show the flow patterns of a rotating wind wheel with two blades at n = 300 rpm at an angle of 0 degrees and different wind speeds.

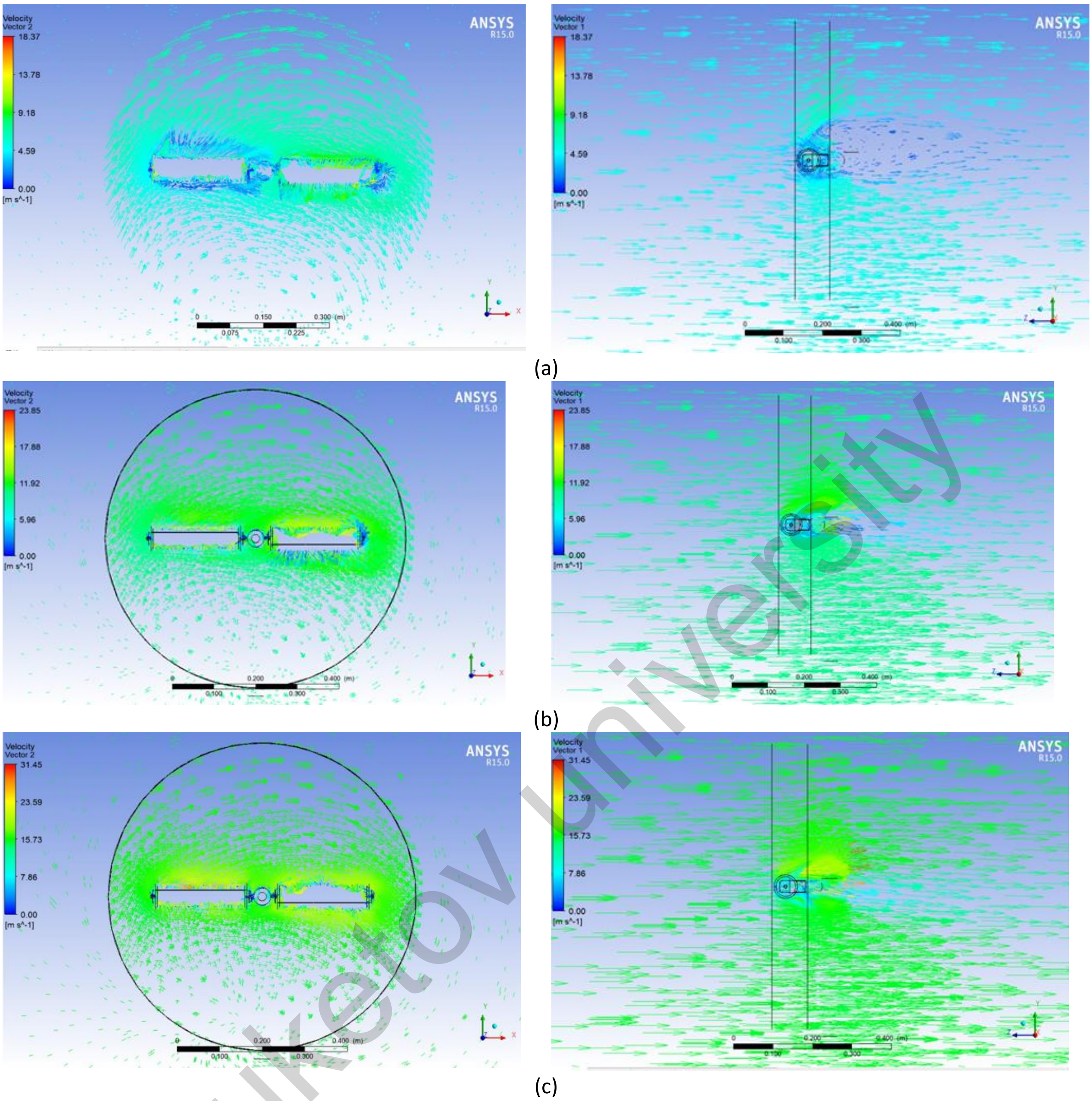
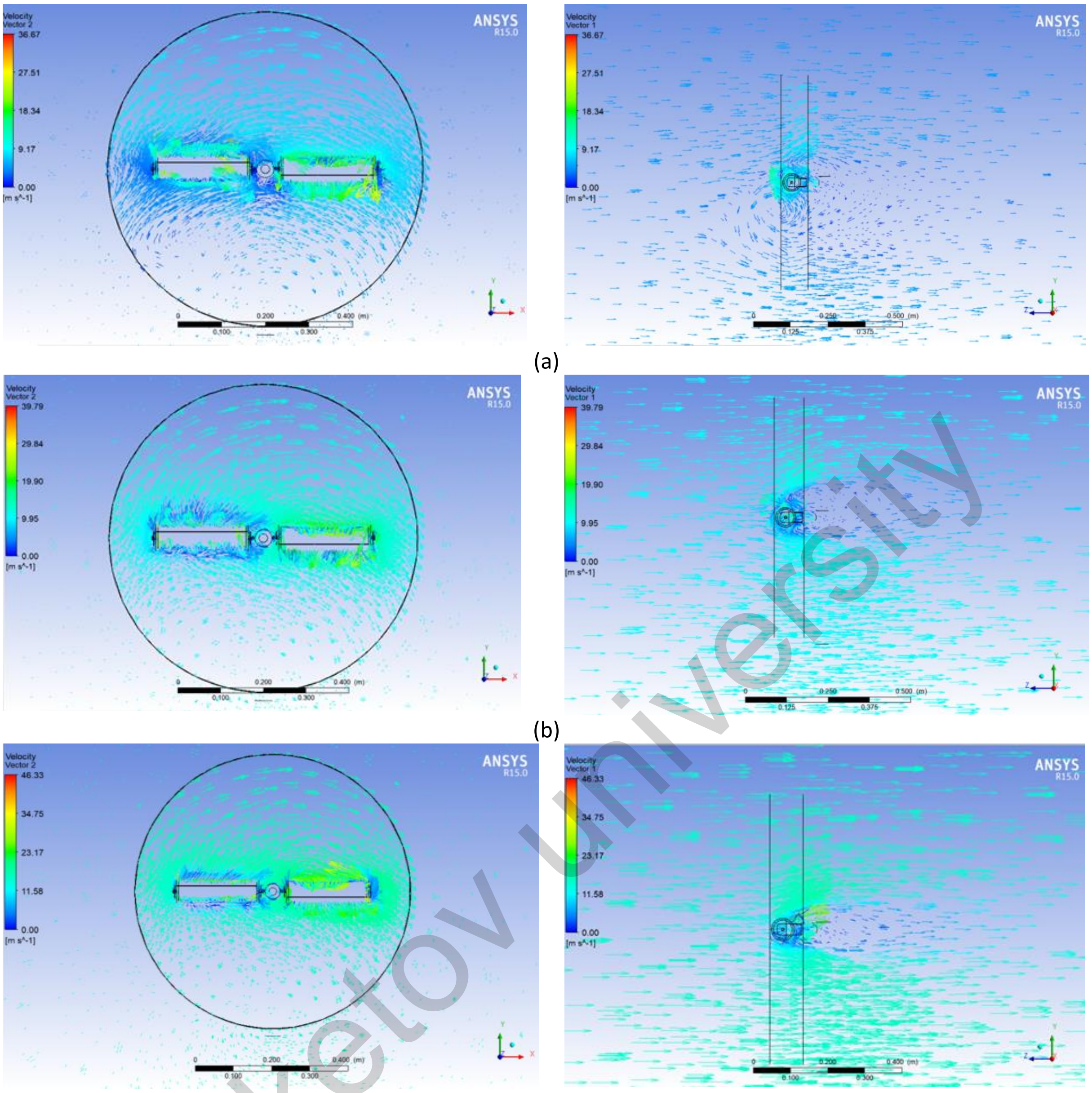


Fig. 7. Flow pattern of a wind turbine at n=300 rpm: (a) at u= 5 m/s (b) u= 10 m/s (c) u=15 m/s

As can be seen from Figure 7, in the upper left corner there is a colour gradation from blue (minimum) to red (maximum), which is a panel of symbols. The axis of rotation of the combined blades coincides with the x axis. The wind wheel rotates around the z axis. The direction of rotation of the wind wheel is set clockwise.

When the wind wheel is exposed to the airflow on the blades, aerodynamic forces arise that cause the wind wheel to rotate. It is determined that vortex formation is formed behind the central shaft of the wind wheel.

Figure 8 below show the flow patterns of a wind turbine at n =700 rpm at an angle of 0 degrees.



(a)

(b)

(c)

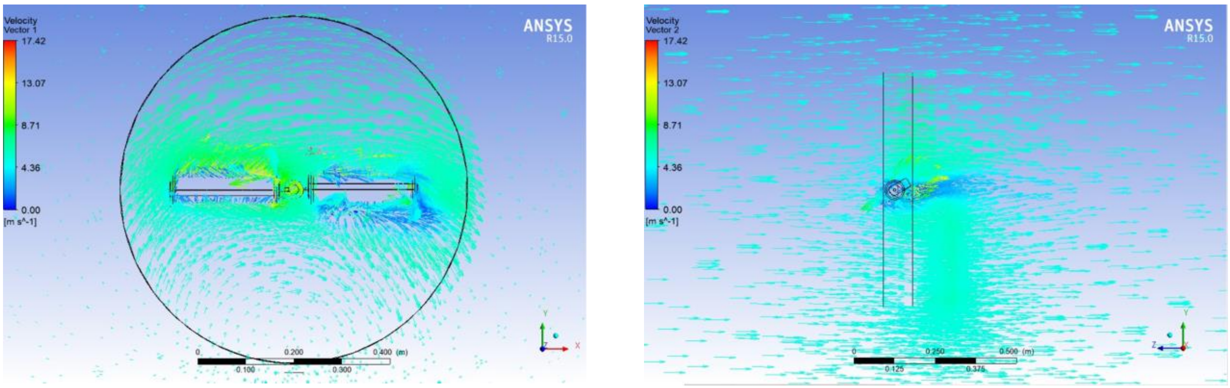
Fig. 8. Flow pattern of a wind turbine at n=700 rpm: (a) at u=5 m/s (b) u=10 m/s (c) u=15 m/s

As can be seen from Figure 8, it can be seen that at high speeds of the blades and the wind wheel, the vortex formation behind the central part of the wind wheel increases at a given speed.

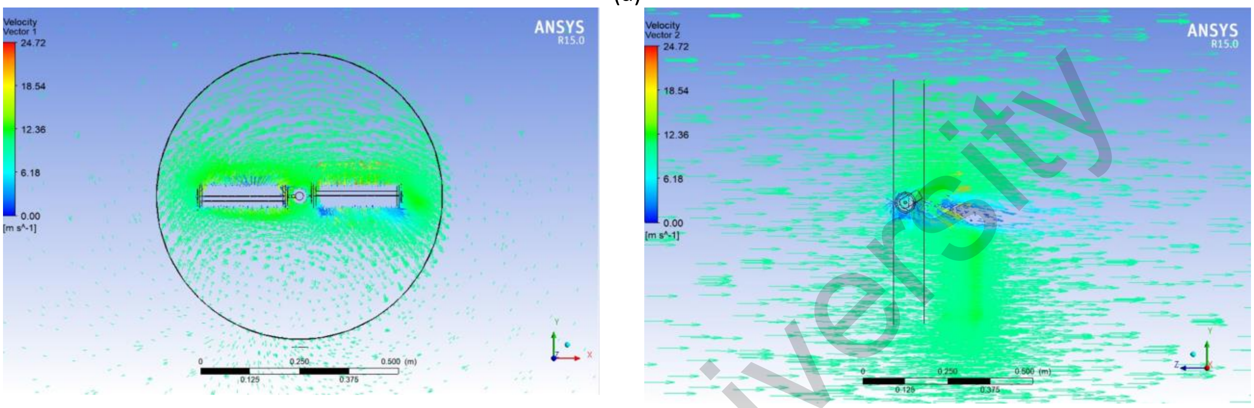
The colour scale shows the distribution of speeds from low (blue) to high (red) values. The direction of the incoming air flow is directed from left to right along the z axis.

The vortex formation formed behind the wind wheel gradually dissipate, which leads to a decrease in their intensity at a distance from the turbine. This process plays an important role in stabilizing the flows behind the wind wheel and affects the overall aerodynamic balance.

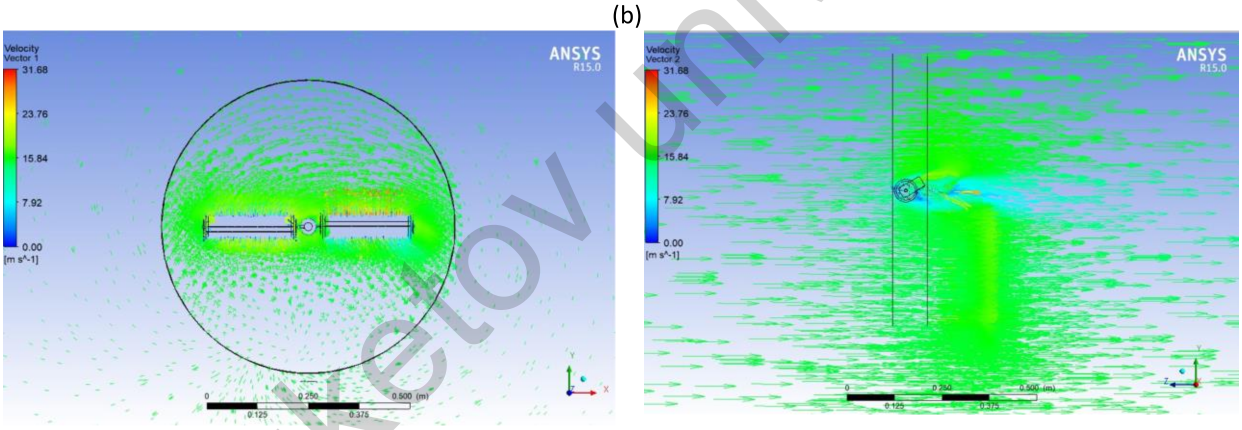
Figure 9 and Figure 10 below show the results of modelling wind turbines with a fixed blade at an angle of 30 degrees at n =300 rpm and 700 rpm.



(a)

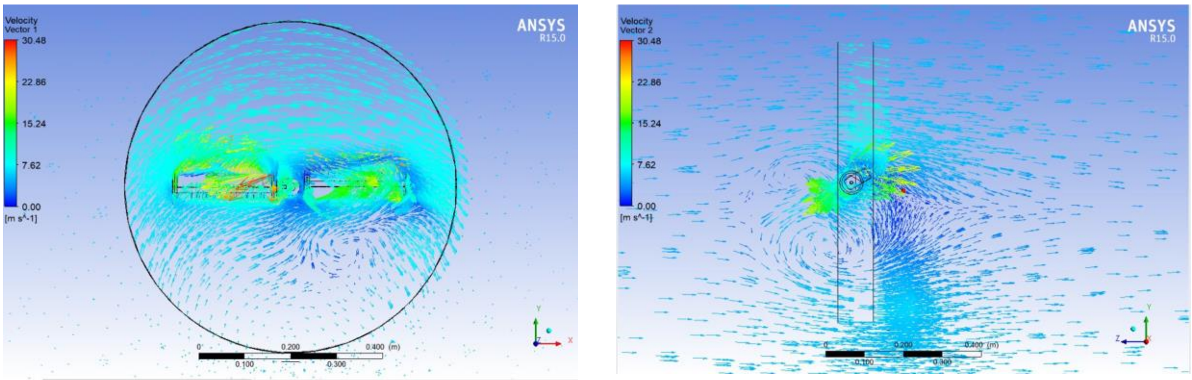


(b)

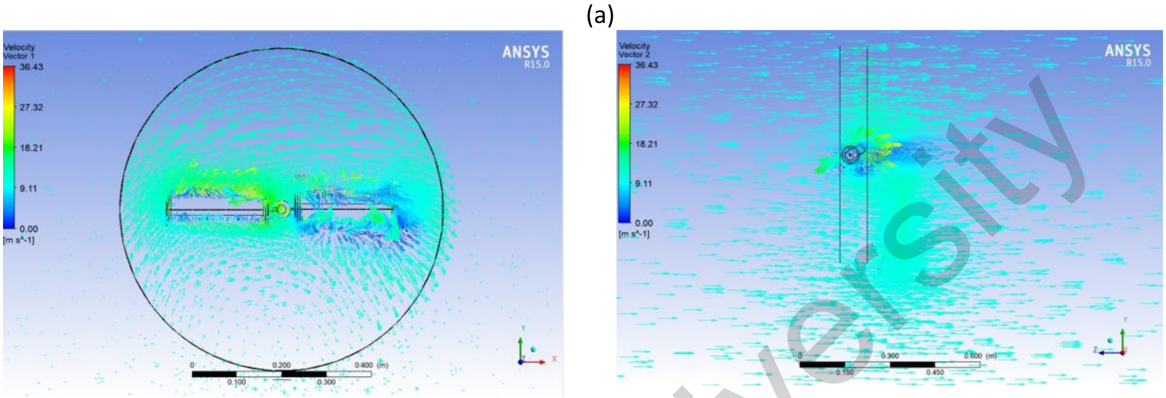


(c)

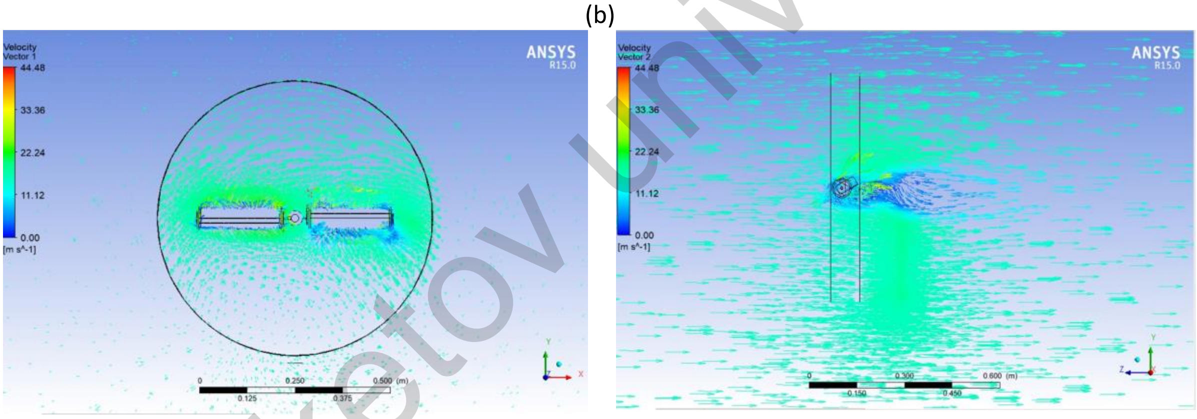
Fig. 9. Flow pattern of a wind turbine at n=300 rpm: (a) at u= 5 m/s (b) u=10 m/s (c) u=15 m/s



(a)



(b)



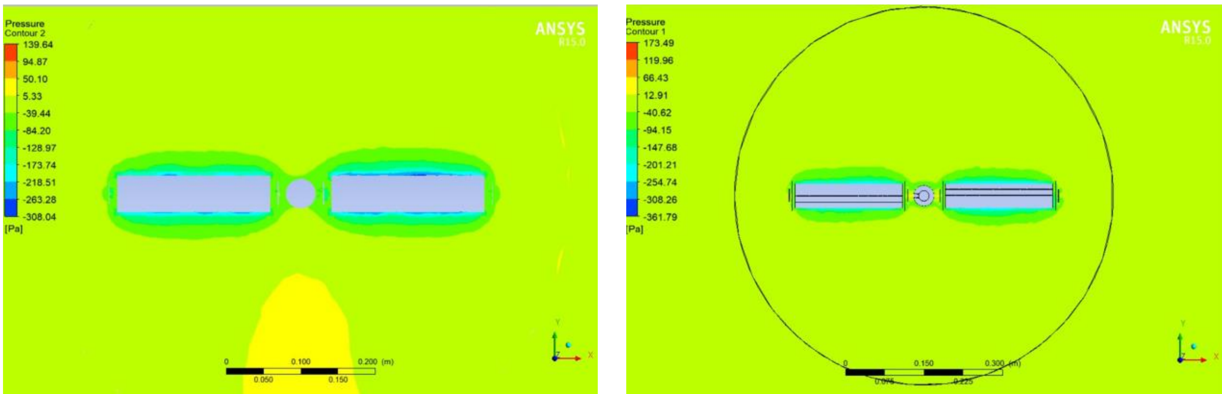
(c)

Fig. 10. Flow pattern of a wind turbine at n=700 rpm: (a) at u= 5 m/s (b) u=10 m/s (c) u=15 m/s

As can be seen from Figure 9 and Figure 10, when the fixed blade is positioned at an angle of 30 degrees, the flow is disrupted, which is clearly visible at the maximum number of revolutions of the blades and the wind wheel. The reason for this violation is the separation of the boundary layer caused by its destruction at an unfavourable pressure gradient. With such a gradient, the pressure on the surface of the blade increases, which leads to a deceleration of the flow and its separation from the surface of the blade.

When detached, the air flow ceases to fit snugly to the blades of the wind turbine, thereby forming turbulent currents, which in turn reduces the lifting force. A drop in lift entails a decrease in the efficiency of the wind turbine, as the conversion of kinetic wind energy into mechanical turbine rotation energy decreases. This phenomenon has a negative impact on the overall performance and energy efficiency of the system. Based on this, a favourable angle of inclination of the fixed blade is an angle of 0 degrees for a two-bladed wind turbine.

Figure 11 shows the pressure distribution at a wind speed of 15 m/s and 500 rpm, with a fixed blade angle of 0 and 30 degrees.



(a) (b)

Fig. 11. Pressure distributions around the wind wheel at a wind speed of 15 m/s and 500 rpm: (a) fixed blade at an angle of 0 degrees (b) fixed blade at an angle of 30 degrees

As can be seen from Figure 11(a) and Figure 11(b), the high-pressure zone (yellow areas) indicates increased aerodynamic drag, which creates lift. Low pressure zones (blue and green zones) dismantle areas of turbulence and vortex formation. The higher the difference between the high-pressure zones behind and after the blade, the greater the lifting force that generates torque. At an angle of 0 degrees (from -308.04 to 139.64 Pa), smoother low-pressure zones behind the blades indicate a milder turbulent flow, which may mean that the system will operate with less aerodynamic losses. At an angle of 30 degrees (from -361.79 to 173.49 Pa), sharp boundaries of low-pressure zones behind the blades are observed, indicating strong vortex formation. Based on this, the most optimal angle of the fixed blade is 0 degrees.

4. Conclusions

As a result of the numerical study, a comprehensive assessment of the aerodynamic characteristics of a wind turbine with two combined blades was carried out and the influence of the angle of the fixed blade was studied (0°,15°, 30°,45° and 60 °) on the efficiency of the installation.

It is determined that the angle of the fixed blade has an effect on the coefficient of drag, torque and aerodynamics of the wind turbine, thereby affecting the efficiency of the wind turbine. From the aerodynamic dependencies, it was determined that with an increase in the angle of inclination of the blades, the force of frontal acceleration increases, which is a problem when operating a wind turbine. It was found that the maximum torque of 26 Nm at a wind speed of 15 m/s and a blade rotation speed of 700 rpm was obtained at an angle of 0 degrees.

Numerical modelling has shown that vortex structures form behind the blades and the central part of the wind wheel as the angle increases, leading to additional aerodynamic losses.

The study confirmed that adding a fixed blade at an optimal angle to the cylindrical blades can significantly improve the efficiency of the turbine.

The numerical results obtained can be applied in fields such as wind power, aerodynamics, etc., in particular, to optimize the design and performance of Magnus wind turbines.

Acknowledgement
This research was funded by a grant from Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (AP23483857 "Development and creation of a new design prototype wind power plant with a complex geometric shape of the blades").

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