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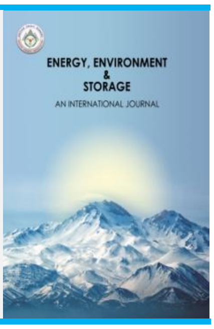

Investigation of the Solidity Ratio in a Horizontal Wind Turbine

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ABSTRACT:A wind turbine-generator system; Parameters such as wind speed, turbine blade diameter, number of blades, turbine height, tip speed ratio and solidity ratio are affected. In this study, horizontal axis wind turbine with diameter of 130 cm and blade solidity ratio values of 7%, 8,6% and 9,8% were constructed and the tests were made according to different blade speed ratios. The required blades were obtained from PVC pipes of different diameters. The experimental study was actualized in Erciyes University Mechanical Engineering, Engines Laboratory. For each profile, bladerotational speeds and wind speeds at various distances have been studied. It has been determined that the wind speed is reduced by the distance difference and accordingly the number of blade speed is decreased visibly. In the wing profiles with different bladesolidity ratios resulting from the work done, the wing structure with the solidity ratio of 8.6% gave the best performance. C_L and C_D coefficients of the profiled specimens were analyzed by FLUENT™, a program of computational fluid dynamics. One of the factors that should be taken into consideration in the production of wind turbines is the blade solidity ratio.

Keywords*:* Solidity, Aerodynamics, Tip speed ratio, Wind turbine

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1. INTRODUCTION

In today's world where fossil fuels are being consumed rapidly, the use of renewable energy sources is of great importance in order to meet the energy needs of the world. The most important of these renewable energy sources are wind, waves, solar rays, hydraulics, biogas and geothermal. These are resources that are widely used and prone to development. Wind energy, one of the renewable energy sources, is one of the most promising sources for electricity generation.

China, the USA, Germany, Spain and India lead the way in electricity generated from wind energy in the world. The total wind energy installed power of these countries constitutes 72% of the world wind energy installed power [1,2]. Turkey ranks 7th in Europe and 13th in the world in terms of wind power plant installed capacity [3].

Turkey, which is surrounded by seas on three sides, has great wind energy potential, especially the Marmara coastline and the Aegean coastline. At the same time, stable wind quality rapidly increases the wind orientation in our country.

Different types of wind turbines are used to generate electricity from wind energy. Recently, modern horizontal axis wind turbines are more preferred for electricity generation. The lifespan of these types of wind turbines varies according to turbine quality and local climatic conditions.

In wind turbine design, the efficient operation of the system, in other words, the aerodynamic performance parameters have a great role. For this reason, scientists and researchers around the world have made a wide variety of studies on this subject. Yılmaz et al. [4] experimentally investigated the performances of different wing profiles in their study. As a result of the results they obtained, the angles of attack of different wing structures determined the CL/CD ratios.

In his study, Govind [5] tried to overcome the problem in the aerodynamic torque limit of horizontal axis wind turbines by adding a vertical axis rotor to the system. As a result of the research, he achieved an increase in efficiency in the system he designed as a hybrid.

Baloutaki [6] turbines systematically placed wind tunnels in different arrays and took measurements. They provided the most suitable conditions in triple arrays and determined that the distance between the two turbines should be one rotor diameter.

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Oueslati et al. [7] carried out their experiments numerically by suddenly changing the blade pitch angle in a horizontal axis wind turbine. As a result of their studies, they determined that sudden changes cause an increase in the resistance coefficient.

Specially designed standard blade sections consist of two curved surfaces. The lengths of the sections are called the blade section beam length (chord) and are denoted by *c*. The vertical length between the two surfaces is called the blade section thickness and is denoted by *t*. The front part of the section that meets the flow is called the leading edge, and the other part is called the trailing edge. The line connecting these two ends is called the blade section beam line (chord) [1,8].

Abdelsalam et al. [9] investigated two system design Horizontal axis wind turbine experimentally using open air jet test ring. The first of their proposal classical rotor and non-linear chord and twist. Another one islinearized rotor system. They implemented on diameter of 1 m rotor by changing free stream air velocity form 5 m/s to 10 m/s. Moreover, the pitch angles were changed. According to results the maximum Cp values are 0.446 and 0.426 for classical and linearized rotor design respectively.

Vaz and Wood [10] used a diffuser based on Blade Element Momentum (BEMT) theory in order to optimize. As a result of this procedure that concluded that the power output increased by 35%.

Duquette and Visser [11] examined blade number and the solidity effect on the performance of HAWT with different theories such as BEMT, rigid wake mothod (RWM) according to Kotb [12] and expanding wake model (EWM) based on Gould and fiddes [13].

Duquette et al. [14] studied an experimental investigation to examine solidity and number of blade on a 50 W HAWT in open circuit wind tunnel. The solidity was changed between 0.07-0.24 by altering number of blades. Similarly, Change in solidity, blade number and pitch angle were studied by Rector and Visser [15]. They used 3 and 6 blades for turbine rotors. Rsults indicated that the performance incresead by blade number and solidity at low flow regimes. On the other hand, 3 bladed rotor was more efficient that 6 bladed system.

Wang and Chen [16] investigated the effect of number of blade on the performance characteristics of ducted wind turbine using CFD with k-ε turbulence model with wall function.They stated that with the increase in the number of blades, starting torque increases and reduces the cut-in speed.

The fluid (air) coming to the blade section with free stream flow velocity, V creates a pressure difference between the lower and upper surfaces because of the specially designed geometry of this section. Due to this pressure difference, a dF_L lift force occurs perpendicular to the flow direction. The angle that the velocity, V makes with the blade chord line is called the angle of attack and is denoted α. Here, the symbol dF_L is used instead of F_L, since the lift force is written for the wing element with length dr. The unit of $F_L$is N (Newton), while the unit of dF_L is N/m (since it is the force acting per unit length). In the wing section, a second force occurs besides the lift force. This force occurring in the direction of flow is called drag force and is represented by dF_D.

C_L is the lift force coefficient, where V is the air velocity, dF_L lift force on the wing element and dF_D drag force:

$$C_L = \frac{dF_L}{\frac{1}{2}\,\rho\, V^2 c\, dr} \tag{1}$$

C_D, drag coefficient;

$$C_D = \frac{dF_D}{\frac{1}{2}\,\rho\, V^2 c\, dr} \tag{2}$$

In these equations, C_L and C_D coefficients are dimensionless.

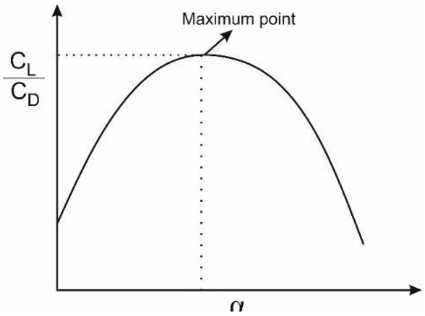

Figure 1. Design angle of attack point.

The angle with the highest lift/drag ratio is taken as the design angle for wind turbines. Figure 1 shows behavior of blade characteristics and at which angle of attack it gives the maximum C_L/C_D value.

The biggest disadvantage of wind turbines is that the constantly variable wind speed causes voltage and power (frequency) fluctuations on the load side. In this study, it was aimed to eliminate these negativities by determining the wing structure with optimum blade solidity. In order to determine that the wing solidity is at the optimum level, the wing tip velocity ratios of the profiles were used.

2. MATERIAL AND METHODS

In this section materials and methods were explained in two categories as experimental and numerical section.

2.1. Experimental Set-up

In order to determine and compare the blade solidity, while three different profiles were used the same sweeping area were determined in the experiment. These designed blades are made of PVC material and are cut from pipes with diameters of 70, 90 and 100 mm, respectively. The blade profiles with different radii of curvature were moved with the help of two fans rotating at 250 rpm, and the speed of the blades was determined with the help of digital tachometer (Figure 2).

Figure 2. Digital tachometer.

Figure3. Anemometer.

Free stream wind speeds generated by the fans used to rotate the turbine blades were measured by anemometer as shown in Figure 3. Since it is connected to the propeller and the main body with a cable, it does not interfere with the flow area.

The solidity ratio was obtained by means of equation (3). After determining the resulting wind speeds, the blade tip speed ratios in each manufactured blade were calculated using equation (4).

$$Swept\ Area = \frac{\pi D^2}{4} \tag{3}$$

$$\sigma = \frac{Blade\ Swept\ Area}{Swept\ Area} x100 \tag{4}$$

$$\lambda = \frac{R\omega_t}{V_W} \tag{5}$$

Findings obtained from the above equations are given in Table 1 below.

Table 1. Data of the different models.

	Model-1	Model-2	Model-3
∅ (mm)	70	90	100
σ (%)	6,9	8,6	9,8

The real and schematic experimental setup is shown in Figure 4a and figure 4b. Also, details of the wind turbine were given in Figure 5. The wind speed was determined by moving the turbine closer to the fan (with a distance *L*). The values of the wings measured by means of anemometer and tachometer and the wing tip speed ratio values and blade revolution numbers calculated based on these are given in Figure 6 and Figure 7.

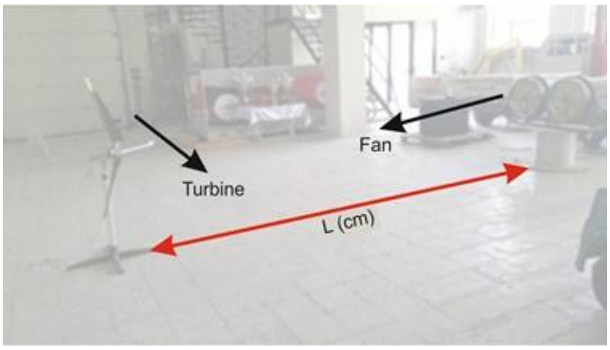

Figure 4a. Real demonstration of experimental set-up.

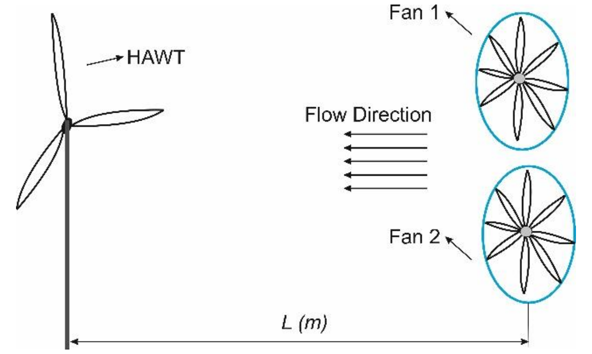

Figure 4b. Schematic representation of experimental set-up.

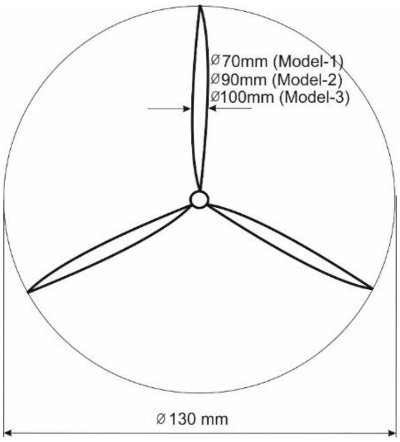

Figure 5. Detail presentation of wind turbine.

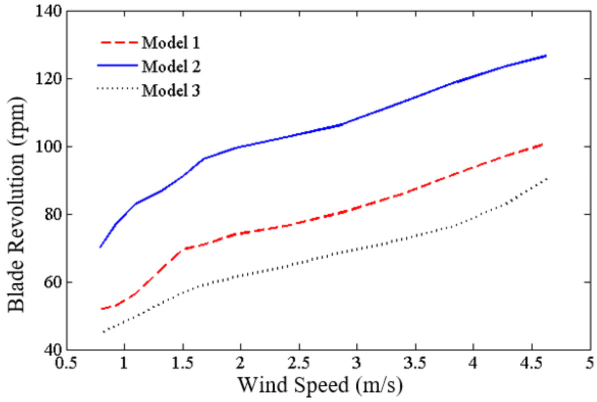

Figure 6. The number of revolutions of the manufactured turbine depending on the wind speed.

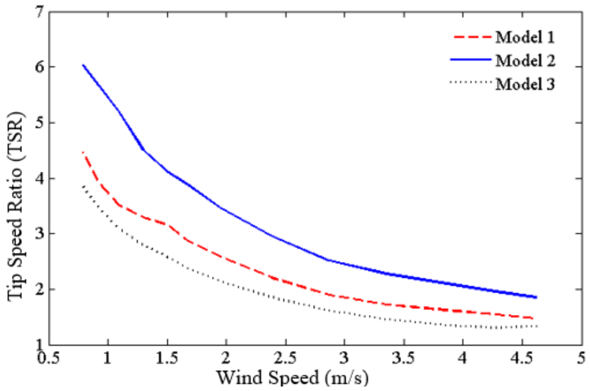

Figure 7. Blade tip speed ratio values depending on the wind speed of the turbine.

With the increase in wind speed, the number of revolutions of the turbine increases at every three solidity rate (Figure 6). The highest rotational numbers were obtained with 8.6% ratio. The blade tip speed ratio decreases with increasing wind speed (Figure 7). The blade tip speed ratio increases with the increase of the turbine speed and decreases with the increase of the wind speed. The increase in wind speed is more than the increase in the number of revolutions. Therefore, it was concluded that the profile with 8.6% solidity ratio is the most suitable.

2.2. Numerical Study

The C_L and C_D coefficients were determined by means of the FLUENT program, depending on the velocities of the designed and manufactured blades at the determined distances. In the analysis, “second order upwind discretization” solution was chosen in free environment and the equations were solved with “SIMPLE Coupled” solution algorithm. In addition, Spalart-Allmaras turbulence model was used in the analysis. In the modeling, the airfoils are placed inside the control volume, which is an infinitely large flow medium.

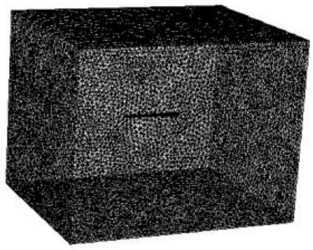

Figure 8. Mesh of the control volume.

Testing of the mesh independence is important to check the accuracy of the numerical results [17]. In this experiment, between 2-6 million meshes were used and obtained results showed that there was less difference by using the more grid. So, 2 million meshes were adjusted to investigation. Table 2 shows the approximately number of mesh tried in the numerical experiments.

Table 2. Number of mesh.

C_L	Number of Mesh
0,09	400000
0,15	600000
0,22	800000
0,35	1000000
0,55	2000000
0,552	3000000
0,557	4000000
0,558	5000000
0,559	6000000

The control volume is designed as a rectangle. The mesh of the that zone was demonstrated in Figure 8. For the calculation of the C_L and C_D coefficients, the convergence criteria were taken as 0.0001. The variation of C_L and C_L/C_D values obtained for three different profiles by means of FLUENT program depending on wind speed and Reynold numbers are given in Figures 9 and 10.

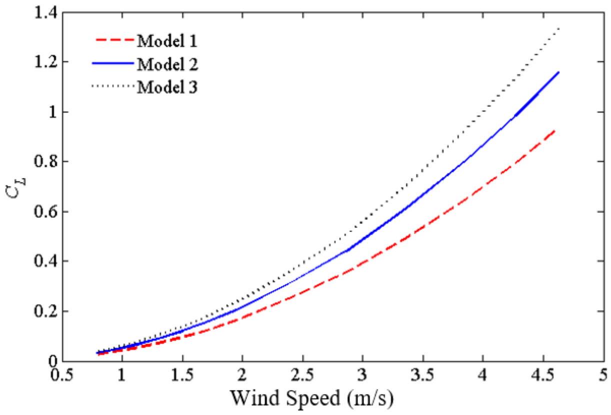

Figure 9. C_L values of turbine blades according to wind speed.

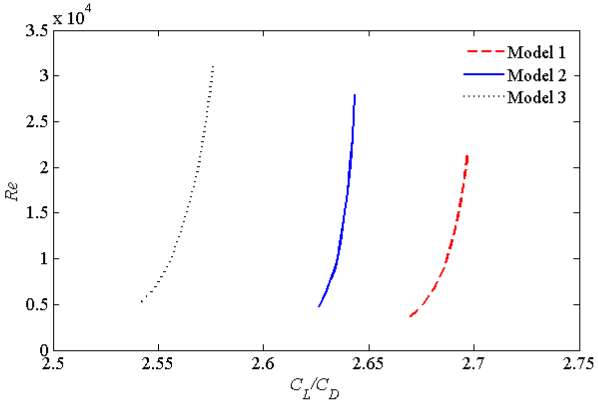

Figure 10. Changes in C_L/C_D versus Reynolds number.

The numerically calculated CL coefficient was the highest in model-3 (σ=9.8%). It is seen that as the solidity ratio increases, the lift force on the wing increases more than the drag force. However, the highest value of CL/CD was found in model-1 (σ= 6.9%). The drag coefficient increases as the solidity ratio increases.
While the pressure distributions occurring at the maximum wind speed on the wing are given in Figure 11, the velocity values of the airfoil are shown in Figure 12.

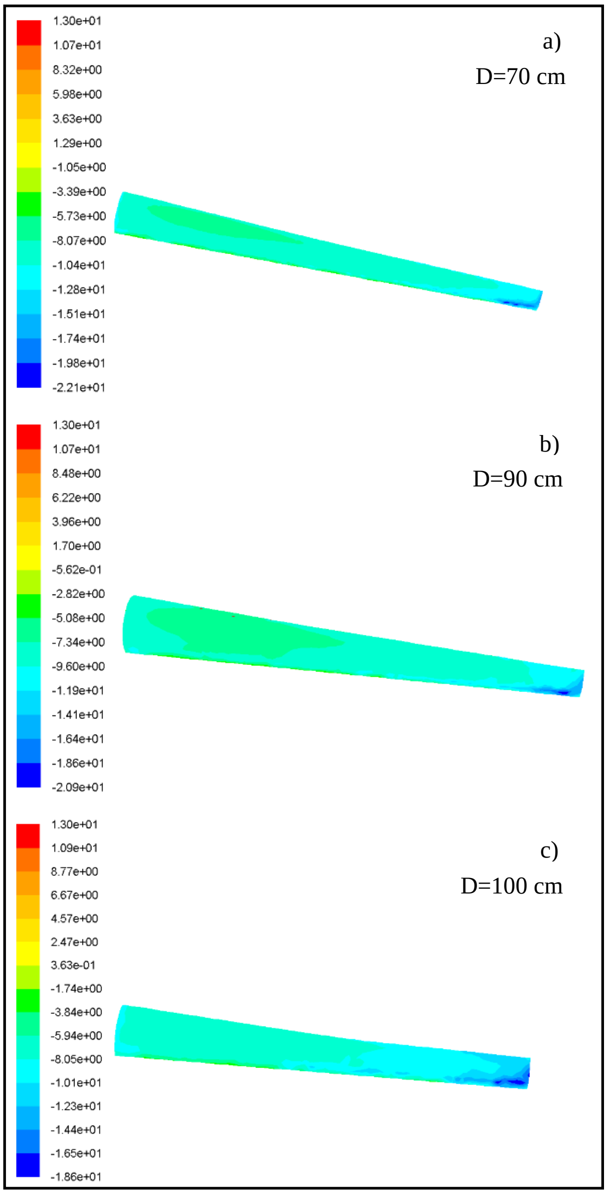

Figure 11. Pressure distribution of blade at 4.6 m/s wind speed, a) D=70 cm, b) 90 cm and c) 100 cm.

According to the results of the numerical analysis, although the free stream flow velocity remained constant, the high pressure zone formed at the top of the blades with 70 and 90 mm diameters decreased as the blade diameter increased to 100 mm, as can be seen in Figure 10 and Figure 11. Similarly, the increase in the blade diameter provided a decrease in the pressure values occurring at the ends.

The velocity vectors of the wind acting on the airfoil are shown in Figures 12. As same procedure applied the free flow velocity remains constant, the change in blade diameter affects the values exposed on the profile. In the profile above 90 mm, the velocity at the wing tip decreased, and then a slight increase was observed.

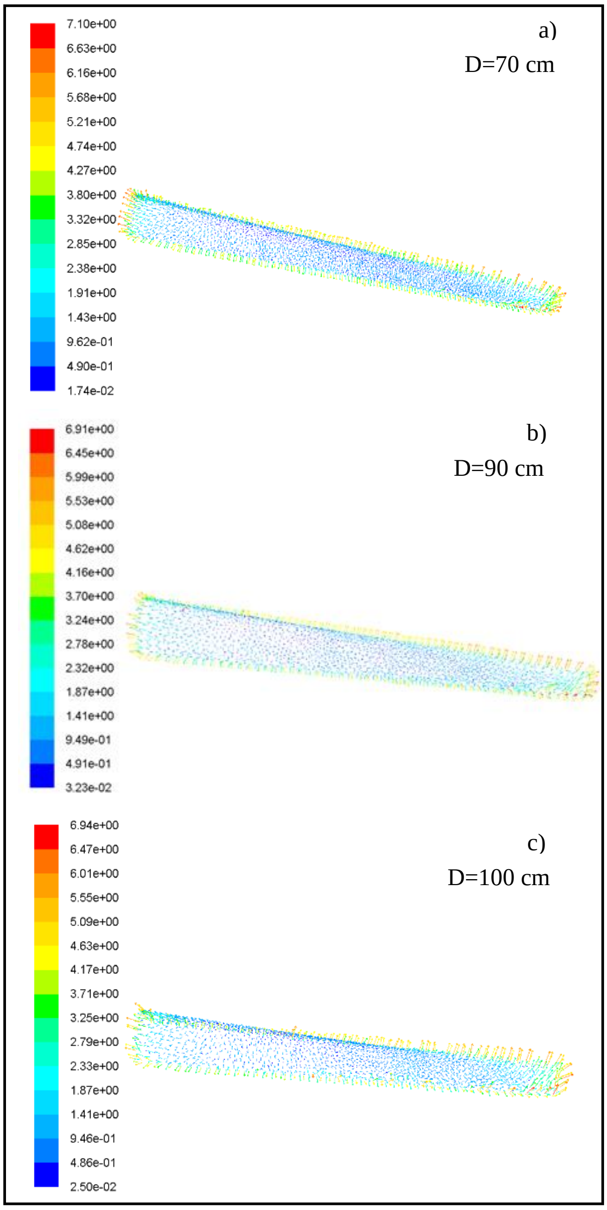

Figure 12. Velocity Vectors of blade at 4.6 m/s wind speed, a) D=70 cm, b) 90 cm and c) 100 cm.

3. RESULTS AND DISCUSSIONS

In this study, the effect of solidity ratio on horizontal axis wind turbine performance was investigated. The study was carried out at three different solidity ratios and the aerodynamic performance of each airfoil was examined numerically. Obtained results are shown below;

In numerical study;
- In model-3 (σ=9.8%) with the highest lift and drag coefficient surface area (solidity ratio);
- It was determined that the highest C_L/C_D value was in model-1 (σ=6.9%).

In the experimental study;
- The best performance was found in model-2 with the highest blade tip speed ratio (σ=8.6%).

In numerical calculations, the best airfoil seems to be model-3 according to C_L, and model-1 according to C_L/C_D ratio. However, in the experimental study, the best performance was obtained from model-2. Since Model-1 does not have sufficient surface area, Model-3 cannot give the entire wind force to the turbine due to its high frictional resistance and drag coefficient. Due to; In the manufacture and design of a turbine, along with the necessary numerical studies, experimental studies should be carried out to determine the optimum blade solidity value and production should be carried out accordingly.

Nomenclature

σ	Solidity Ratio [-]
D	Rotor diameter [m]
λ	Tip Speed Ratio [-]
R	Rotor Radius [m]
ω_t	Rotor Angular Velocity [rad/s]
V_W	Wind Speed [m/s]
Re	Reynold Number $[= \rho V L/\mu]$
ρ	Density [kg/m^3]
μ	Viscosity [kg/m s]
L	Characteristic Length [m]
C_L	Lift Coefficient [-]
C_D	Drag Coefficient [-]
c	Chord Length [m]

REFERENCES

[1] Anderson J.D., *Fundamentals of Aerodynamics*, McGraw Hill Book Company, New York, 1986.

[2] Baloutaki M.A., Carriveau R., Ting D.S.K., A win tunnel study on the aerodynamic interaction of vertical axis wind turbines in array configurations, Renewable energy 96 (2016) 904-913.

[3] https://www.enerjiatlasi.com/ulkelere-gore-ruzgar-enerjisi.html (Accessed date: 02/06/2021).

[4] Yılmaz İ., Çam, Ö., Taştan M., Karcı A., Farklırüzgartürbinkanatprofillerininaerodinamikperformansınındeneyselolarakincelenmesi, Politeknikdergisi, (2016); 19 (4): 577-584.

[5] Govind Bala, increasing the operational capability of a horizontal axis wind turbine by its integration with a vertical axis wind turbine, Applied energy (199) (2017), 479-494.

[6] Baloutaki M.A., Carriveau R., Ting D.S.K., A win tunnel study on the aerodynamic interaction of vertical axis wind turbines in array configurations, Renewable energy 96 (2016) 904-913.

[7] Oueslati M.M., Dahmouni A.W., Nasrallah S.B., Effects of sudden change in pitch angle on oscilatting wind turbine airfoil performances, *engineering analsys with boundary elements*, 81 (2017) 21-34.

[8] Martin O.L. Hansen, Aerodynamics of Wind Turbine Chapter 2: 2-D Aerodynamics, Second Edition, Earthscan, UK and USA,(2008).

[9] A.M. Abdelsalam, W.A. El-Askary, M.A. Kotb, I.M. Sakr, Computational analysis of an optimized curved-bladed smallscale horizontal axis wind turbine, J. Energy Resour. Technol. Trans. ASME 143 (6) (2021).

[10] J.R.P. Vaz, D.H. Wood, Aerodynamic optimization of the blades of diffuser-augmented wind turbines, Energy Convers. Manag. 123 (2016) 35–45.

[11] M.M. Duquette, K.D. Visser, Numerical implications of solidity and blade number on rotor performance of horizontal-axis wind turbines, J. Sol. Energy Eng. 125 (November) (2003).

[12] M.A. Kotb, M.M. Abdel Haq, A rigid wake model for a horizontal axis wind turbine, Wind Eng. (1992) 95–108.

[13] J. Gould, S.P. Fiddes, Computational methods for the performance prediction of HAWTs, J. Wind Eng. Ind. Aerodyn. 39 (1–3) (1992) 61–72.

[14] M.M. Duquette, J. Swanson, K.D. Visser, Solidity and blade number effects on a fixed pitch, 50W horizontal axis wind turbine, Wind Eng. 27 (4) (2003) 299–316.

[15] M.C. Rector, K.D. Visser, Solidity, blade number, and pitch angle effects on a one kilowatt HAWT, in: 44th AIAA Aerospace Sciences Meeting and Exhibit, 2006, no. January, (2006), pp. 1–10.

[16] S. Wang, S. Chen, Blade number effect for a ducted wind turbine, J. Mech. Sci. Technol. 22 (2008) 1984–1992.

[17] S. Caner and A. S. Orhan, Numerical Investigation of the effect of finned obstacle on heat transfer characteristics in a rectangular channel, Energy, environment and storage, (2021), 01-01-1-6.