

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**INVESTIGATION OF WAKE
CHARACTERISTICS OF A DARRIEUS TYPE
WIND TURBINE**



by
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İZMİR

INVESTIGATION OF WAKE CHARACTERISTICS OF A DARRIEUS TYPE WIND TURBINE

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**by
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İZMİR**

M.Sc THESIS EXAMINATION RESULT FORM

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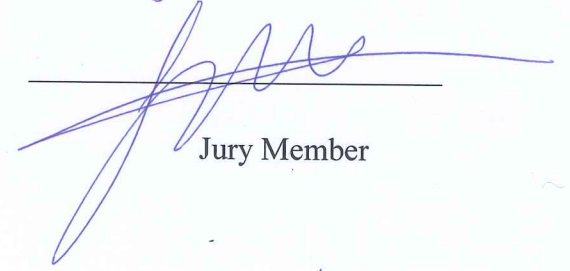


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INVESTIGATION OF WAKE CHARACTERISTICS OF A DARRIEUS TYPE WIND TURBINE

ABSTRACT

It is essential to investigate turbine behaviors and wake characteristics of vertical axis turbines in different working situations in a systematic way. In this reason two different H-rotor Darrieus type vertical axis wind turbines was investigated using ANSYS Fluent software by two dimensional and three dimensional computational fluid dynamics simulations. First turbine was a two NACA0018 bladed reference turbine for validation which was studied before both experimentally and numerically. Second turbine was a three NACA4418 bladed prototype. The dimensions of the domains depend on the diameter of the turbine and chord length which was derived from similar studies in the literature. Turbulence model $k-\omega$ SST is used to solve time-dependent Reynolds-Average-Navier-Stokes equations in unsteady simulations. Continuity and momentum equations was solved with SIMPLEC algorithm. Different parameters such as mesh independency, time step sizing, third dimensional effects on turbine performance and wake formation in near and far wake in various operating conditions were investigated. Two and three dimensional computational analysis were performed on reference turbine and near and far wake behaviours were investigated. Three dimensional computational analysis were performed on prototype turbine and performance characteristics on different conditions and near wake behaviours were examined. Turbine behaviors in different free stream wind speed conditions and rotational speed conditions were compared.

Keywords: Vertical axis wind turbine (VAWT), wake characterization, three-dimensional computational modelling

DARRIEUS TİPİ BİR RÜZGAR TÜRBİNİNİN ART İZİ KARAKTERİSTİKLERİNİN İNCELENMESİ

ÖZ

Farklı çalışma durumlarında türbin benzetimlerinin sistematik şekilde incelenmesi önemlidir. Bu sebeple düz kanatlı Darrieus tipi iki farklı dikey eksenli rüzgar türbini, iki ve üç boyutlu modelleme ile ANSYS-Fluent paket programı kullanılarak incelenmiştir. İlk türbin önceden yapılmış olan deneysel ve sayısal çalışmalarda kullanılmış NACA0018 kanat yapısına sahip iki kanatlı bir türbindir. İkinci türbin ise NACA4418 kanat yapısına sahip üç kanatlı prototip türbindir. Model geometrileri daha önce literatürde kullanılmış olan türbin çapına bağlı olarak değişiklik gösteren bir büyüklüğe sahiptir. Sayısal analizlerde zamana bağlı Reynolds-Ortalama Navier-Stokes denklemleri $k-\omega$ SST türbülans modeli yardımıyla çözümlenmiştir. Süreklilik ve momentum denklemleri SIMPLEC metodu ile çözümlenmiştir. Ağdan bağımsızlık, zaman adımının türbin başarımı üzerindeki etkisi ve üçüncü boyutun yakın ve uzak art izi üzerindeki etkisi gibi farklı etkenler farklı koşullarda incelenmiştir. Referans türbin geometrisinin iki ve üç boyutlu modellemelerinin sayısal çözümlenmesi ile yakın ve uzak art izi incelenmiştir. Prototip türbin modelinin iki boyutlu benzetimi ile farklı çalışma şartlarında türbin başarımı ve yakın art izi incelemesi yapılmıştır. Farklı serbest rüzgar hızlarının ve farklı dönüş hızlarının türbin davranışları üzerindeki etkisi incelenmiştir.

Anahtar Kelimeler: Düşey eksenli rüzgar türbini, art izi karakterizasyonu, üç boyutlu hesaplamalı benzetim

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CHAPTER ONE

INTRODUCTION

In this chapter, commonly used wind turbine types are explained, general informations about vertical axis wind turbines and Darrieus type wind turbines are mentioned. Aerodynamics of vertical axis wind turbines in terms of forces acting on a blade, positional differences of the blade and variation of the forces with respect to blade position are explained. Power extraction from turbine is defined with respect to acting forces and blade position. Leading studies about vertical axis wind turbines are summarized. The aim and novelty of this thesis are explained.

1.1 Wind Turbine Types

There are several types of turbine architectures that are used to harvest wind energy. Those architectures are predominantly classified according to the orientation of their rotational axes, as horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Wind farms with different orientational axes wind turbines are shown in Figure 1.1.



Figure 1.1 HAWT(left), VAWT (right), (Greenlivingtips, 2015; Theecologist, 2015)

HAWTs usually rotate based on lift force while VAWTs either rotate based on lift force or drag force, based on the turbine architecture. Modern three-bladed horizontal axis wind turbines are preferred according to vertical axis wind turbines for decades because of their working range and efficiency. This preferability is probably came up with historical background of development phase of HAWTs (Paraschivoiu, 2002). Studies have shown that a separated single VAWT has a much lower power coefficient, which described as mechanical power output of the turbine divided by

total cross-sectional free-stream air energy capacity, and cost third more than a HAWT of same power output (Hau, 2006).

VAWTs have many different varieties according to geometry. Although there are many different types of vertical axis wind turbines Darrieus-type wind turbines (generally speaking lift based turbines) are usually more effective in wide range of wind speeds than Savonius-type wind turbines (drag based turbines), nonetheless drag based turbines are starting to operate in low wind speeds than lift based turbines (Figure 1.2)(D'Ambrosio & Medaglia, 2010).



Figure 1.2 Savonius type (drag based) VAWT(left); troposkien Darrieus type (lift based) VAWT (right) (D'Ambrosio & Medaglia, 2010)

1.2 Darrieus Type Wind Turbines

Various Darrieus type wind turbines with different geometries have been tested for decades. For example Troposkien (nearly parabolic) which was the first invented Darrieus type wind turbine (Figure 1.2). With this extraordinary shape, effects of tip losses and tip vortices are minimized. Another one is Helical Darrieus type, which has more stable force outputs than other variations of Darrieus type wind turbines, due to its unique geometry (Figure 1.3). An alternative is H-rotor (could be named as giromill or straight bladed) Darrieus type which has a simple geometry. Because of its simplicity H-rotor Darrieus type is investigated in this thesis to understand bare airfoil characteristics and force distribution around the blade of a VAWT clearly (Figure 1.3).

Darrieus type wind turbines would have different number of airfoil blades such as 1, 2, 3, 5, etc. (Ragheb,2015; D'Ambrosio & Medaglia, 2010)



Figure 1.3 Three bladed helical Darrieus type VAWT(left); three bladed H-rotor Darrieus type VAWT (right) (Ragheb,2015; D'Ambrosio & Medaglia, 2010)

Even if the Darrieus concept is known till early 1930s (Darrieus, 1931), it was recently rediscovered due to its capability to accept wind from any direction, simplicity, low manufacturing costs (considering fixed cross-sections and no twist), the placement of generator near the ground, ease of use in rural and urban areas, where wind is turbulent and it has no dominant direction (Balduzzi, Bianchini, Maleci & Ferrara, 2016; Goude, 2012; Howell, Qin, Edwards, & Durrani, 2010; Sutherland, Berg & Ashwill, 2012). Due to this new trend, there is a potential to explore flow mechanisms and further improve performance of VAWTs (Paraschivoiu, 2002).



Figure 1.4 34 m Darrieus type vertical axis wind turbine located and tested in Sandia Labs.in Texas U.S. (Sandia, 2015)

Apart from prior Sandia Lab reports of 1970's, which was focused on performance of individual Darrieus turbines (Figure 1.4), the topic is not studied extensively in the literature, most of the modern publications being only recently published. For last two decades vertical axis wind turbines and their behaviors have been a scientifically popular field. Although there is still a tyranny of horizontal axis wind turbines in usage, there will be a conceptual change due to new research and developments. A new phenomenon is conceptually accepted by a group of researchers. This phenomenon is not only considering capacity of wind turbine but also taking energy production per area into consideration (Dabiri, Greer, Koseff, Moin & Peng, 2015). From this point of view there will be a conceptual change of using vertical axis wind turbines instead of horizontal axis wind turbines in rural areas, households, roofs etc. Reasons for this conceptual change were analyzed by many authors, they described the necessities as shortage of land scape in rural areas to install high capacity horizontal axis wind turbines; vertical axis wind turbines with smaller capacities will provide same amount of energy from the same installation area, in addition to that maintenance cost is an obstacle in urban areas for high capacity horizontal axis wind turbines on the contrary vertical axis wind turbines' maintenance are easier due to its rotor position (Karadeniz, 2015).

1.3 Darrieus Type Wind Turbine Aerodynamics

Investigation of VAWT aerodynamics is essential to understand wake behavior and power production. Blade positions of the turbine have a significant role in VAWT aerodynamics and positions of the blade have different denominations. Upwind is the position which is the wind is coming from and downwind is the direction which is the wind is blowing. Free stream wind passes through the turbine blades not only upwind direction but also downwind direction in VAWTs. Windward is the direction which is turbine blade is facing the wind and leeward is the direction which is facing away from the wind (Figure 1.5). Another dependency of VAWT aerodynamics is position of the blade with respect to tower of the turbine and it is called as azimuthal angle (θ). In this study, free stream wind direction is taken as $\theta=90^\circ$ and turbine is rotated counter clockwise (CCW) direction (Figure 1.5).

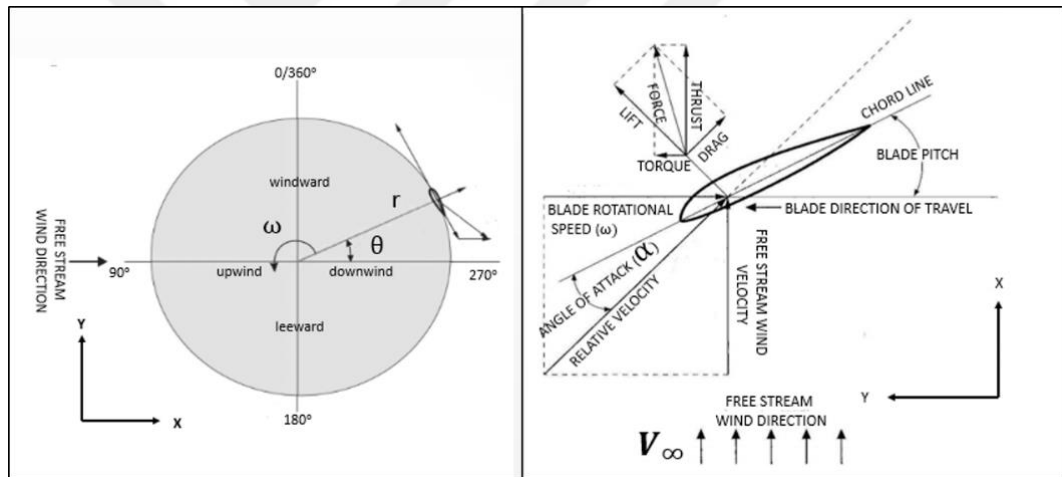


Figure 1.5 Blade positions with respect to free stream wind direction (left) and aerodynamic forces acting on a turbine blade due to free stream wind velocity (right)

The blade is encountered with different loadings while rotating in a upcoming wind. Relative velocity of the blade and angle of attack (α) cause aerodynamic loadings on the blade. Relative velocity can be expressed as the resultant vector of velocity of rotational speed and free stream wind velocity:

$$\vec{V}_{Rel} = \vec{V}_{\infty} + \vec{V}_{Rot} \quad (1.1)$$

Where rotational velocity is proportional to angular velocity and turbine radius.

$$V_{Rot} = \omega \times r \quad (1.2)$$

Where ω is angular velocity ($\text{rad} \times \text{s}^{-1}$) and r (m) is radius of the turbine. Angle of attack is the angle between the direction of relative speed of the blade and blade chord line (Figure 1.5). In this study turbine blades has no pitch angle so blade direction of travel is taken as chord line in other words rotational path of the turbine blades. Angle of attack is expressed in terms of rotational speed, radius, free stream wind velocity and blade position (θ).

$$\alpha = \tan^{-1} \left(\frac{V_{\infty} \times \sin \theta}{\omega \times r + V_{\infty} \times \cos \theta} \right) \quad (1.3)$$

Tip speed ratio (λ) is a dimensionless parameter to identify turbine behavior and can be represented as:

$$\lambda = \frac{\omega \times r}{V_{\infty}} \quad (1.4)$$

Vertical axis wind turbine blades are subject to rapid, cyclical variations in angle of attack and relative velocity which can induce dynamic stall. High angle of attacks could cause dynamic stall and boundary layer separation on incoming and outgoing flow around the blade. Angle of attack with respect to azimuth angle, varies with changes in tip speed ratio. Increment in tip speed ratio lowers the maximum angle of attack (Figure 1.6).

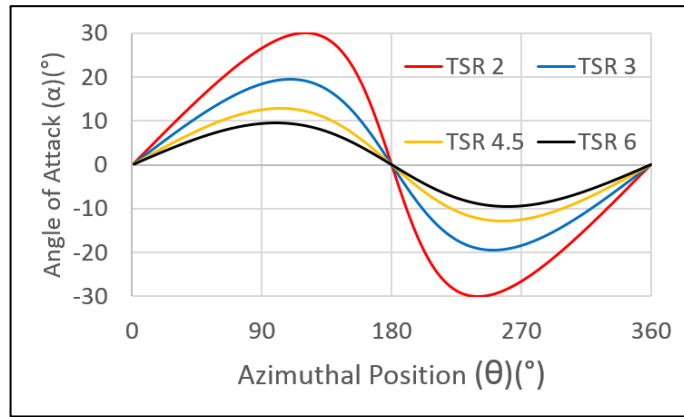


Figure 1.6 Angle of attack variation as function of azimuth angle in different λ 's

Lift Force (F_L) and Drag Force (F_D) are the aerodynamic loadings on the blade. Lift force is the component of the force that is perpendicular to the relative velocity and drag force is the force component which is in the direction of the relative velocity. Flow direction in simulation represented as cartesian coordinates X and Y. X refers to

direction of flow and Y is perpendicular to flow (Figure 1.5). The lift and drag forces are important to analyze the aerodynamic characteristics of the airfoils. Lift and drag forces could be reworded as normal and tangential forces. Forces acting on a blade could be represented as force coefficients for normalization. Tangential (C_T) and normal (C_N) force coefficients were computed for all azimuthal positions during the last revolution for each blade individually. Based on the cartesian force coefficients (C_X and C_Y) calculated in the simulation, C_T , and C_R were calculated as follows;

$$C_T(\theta) = -C_X(\theta) \times \cos \theta - C_Y(\theta) \times \sin \theta \quad (1.5)$$

$$C_N(\theta) = -C_X(\theta) \times \sin \theta + C_Y(\theta) \times \cos \theta \quad (1.6)$$

The normal component of the force is used for structural design of turbine which is not within the scope of this study. The tangential force coefficient is used to calculate torque acting on blade by following equation,

$$T_B = \frac{N \times c \times H \times r \times \int_0^{2\pi} C_T(\theta) \times \delta\theta}{2 \times \pi} \quad (1.7)$$

where N is the number of blades, c(m) is the chord length, H(m) is rotor height. Torque is also expressed as a function of $C_{M, avg}$ which is the average of moment coefficient that is calculated for a single blade and for one rotation.

$$T_B = \frac{1}{2} \times C_{M, avg} \times \rho \times V_\infty^2 \times A \times r \quad (1.8)$$

Where ρ is the air density ($\text{kg} \times \text{m}^{-3}$), A is the swept rotor area (m^2) which is the height of the turbine times the diameter. From equation (1.7) and (1.8):

$$C_{M, avg} = \frac{N \times c}{2 \times \pi \times \rho \times r \times V_\infty^2} \int_0^{2\pi} C_T(\theta) \times \delta\theta \quad (1.9)$$

The power is produced from the aerodynamic torque acting on the rotor. Power coefficient (C_p) can be explained as power extracted from turbine divided by maximum possible power of the swept rotor area.

$$C_p = \frac{P}{P_{\max}} \quad (1.10)$$

The shaft power represented as:

$$P = \omega \times T_B \quad (1.11)$$

or

$$P = \omega \times \frac{1}{2} \times C_{M,avg} \times \rho \times V_{\infty}^2 \times A \times r \quad (1.12)$$

Maximum possible power of the swept rotor area is:

$$P_{\max} = \frac{1}{2} \times \rho \times V_{\infty}^3 \times A \quad (1.13)$$

Equation (1.10) can be written as below with the usage of equations (1.4), (1.12) and (1.13):

$$C_p = \frac{P}{P_{\max}} = \frac{\omega \times \frac{1}{2} \times C_{M,avg} \times \rho \times V_{\infty}^2 \times A \times r}{\frac{1}{2} \times \rho \times V_{\infty}^3 \times A} = \frac{\omega \times C_{M,avg} \times r}{V_{\infty}} = \lambda \times C_{M,avg} \quad (1.14)$$

A fluid's behavior depends on the dimensionless Reynolds number. It is one of the controlling parameters in all viscous flows where a numerical model is selected according to pre-calculated Reynold number. Tip speed ratios depend on wind speed and rotational speed as mentioned before, so there are two controllable way to change λ , changing wind velocity with keeping rotational speed constant or vice versa. Therefore, two different simulation sets are obtained in this study; one of them for constant ω (constant rotational speed) and the other for constant V_{∞} (constant free stream wind velocity). Although direction and magnitude of relative velocity of the blade changes with respect to azimuthal position, average of the vectorials of relative velocities in one revolution is rotational speed of the blade. In constant rotational speed simulations chord based average Reynolds number is used to simplify the fluid behavior which stated as follows:

$$Re_{C,avg} = \frac{\rho(\omega r)c}{\mu} \quad (1.15)$$

1.4 Literature Review

Scientific reseaches about airfoils, VAWTs, VAWTs aerodynamics and VAWTs performance have been done by scientists and manufacturers since invention of airfoils and wind turbines. It has been seen that there are many parameters when it is desired to examine wake behavior, turbine performance and aerodynamic loadings on airfoils by computational simulation. Effects of these parameters have been revealed

by examining both the experimental results and the numerical results were obtained from the previous studies on these parameters.

1.4.1 Airfoil Studies

Airfoil selection for the turbine blade is one of the important parameter. Most of the manufacturers and researchers used NACA (later NASA) type airfoils and most of the studies which were analyzed based on NACA type airfoils. In early-stages airfoil design was meant to be used in aeronautics, therefore former studies have been done for high Reynolds numbers. In a pioneering work 78 different airfoils were studied for high Reynolds number. Lift coefficient, drag coefficient and lift to drag ratio as a function of angle of attack were obtained experimentally. It was observed from Table 1.1 increasing the thickness of a symmetrical blade will increase the angle at which the maximum ratio of lift over drag occurs but decrease the maximum ratio of lift over drag coefficient in Reynolds Number 3.2×10^6 (Jacobs, Ward & Pinkerton, 1933).

Table 1.1 Lift over drag ratio according to blade type

Blade Type	Free Stream Wind Velocity ($\text{m} \times \text{s}^{-1}$)	Maximum Coefficient of Lift over Coefficient of Drag ratio (C_L/C_D) _{max}	Reynolds Number	Angle of (C_L/C_D) _{max} (°)
NACA0006	20.88	23.6	3210000	4
NACA0009	20.88	23	3210000	5
NACA0012	20.85	22.4	3230000	5.2
NACA0015	20.85	21.2	3200000	5.3
NACA0018	20.97	19.8	3150000	5.6
NACA0021	20.91	18.8	3190000	6
NACA0025	20.82	17	3230000	7

In a report, aerodynamic characteristics of four different types of symmetric airfoils (NACA0009, NACA0012-Max thickness 12% at 30% chord, NACA0012H-Max thickness 12.2% at 22.5% chord, NACA0015) at three different Reynolds numbers (0.36×10^6 , 0.5×10^6 , 0.7×10^6) have been examined experimentally. In addition to those experiments, NACA0012 aerodynamic characteristics was examined in Reynolds number 1.76×10^6 . With the data according to the information gathered from experiments a code was developed to identify the behavior of 7 symmetrical NACA type airfoils at different Reynolds numbers (from 0.01×10^6 to 10×10^6). This was a

pioneering work for VAWTs aerodynamics in low Reynolds numbers condition. It is observed that for the NACA0018 case increase of free stream wind velocity (which also means increase of Reynolds number) increases the stall angle (Sheldahl & Klimas, 1981).

1.4.2 Airfoil Studies related to VAWT performance

Kirke & Lazauskas (1991, 1993) made a mathematical model for VAWT's and validated it with wind tunnel data. With the use of this model they aimed to understand the behavior of self-acting variable pitch turbines and compare them with fixed pitch turbines. Self-acting variable pitch VAWTs have better performance according to this study. Authors also mentioned about problems they have faced at measuring small turbines' performance in a wind tunnel. In order to reach the working ranges of those small turbines high rotational speeds required and therefore construction problems occurred at the manufacturing stage. This work is a land mark for most researchers who were studying small scale vertical axis wind turbines. In this particular work the authors mentioned that increase of blade thickness will increase the working range of the turbine at $Re=2.0 \times 10^5$ (Figure 1.7). Increase in thickness will cause a shift towards to lower λ_s in self starting conditions for the same Reynolds number. Although increase in solidity ratio lower the maximum power coefficient, turbine operates in lower λ_s (Figure 1.8).

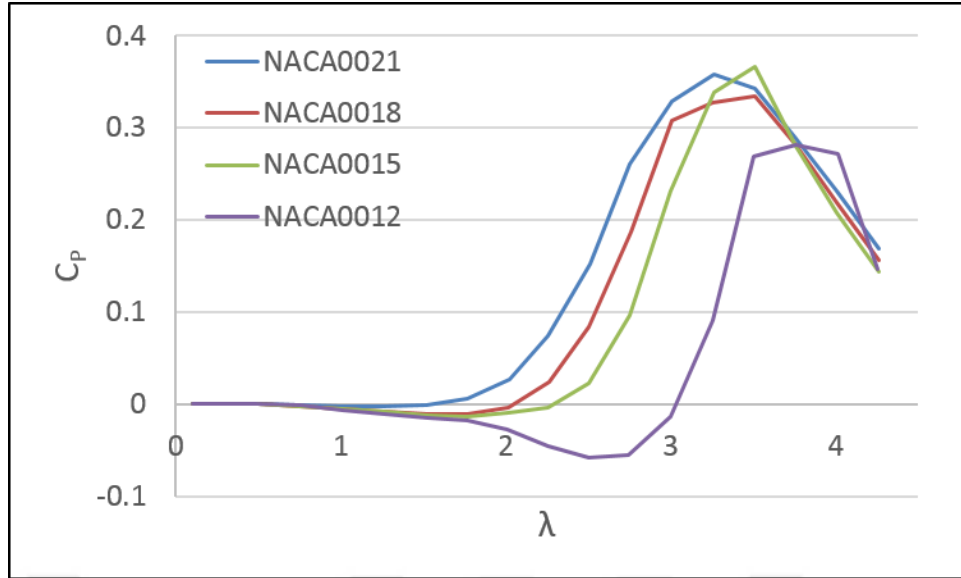


Figure 1.7 Power coefficient variation as a function of λ in different airfoil type (adapted from Kirke & Lazauskas, 1991)

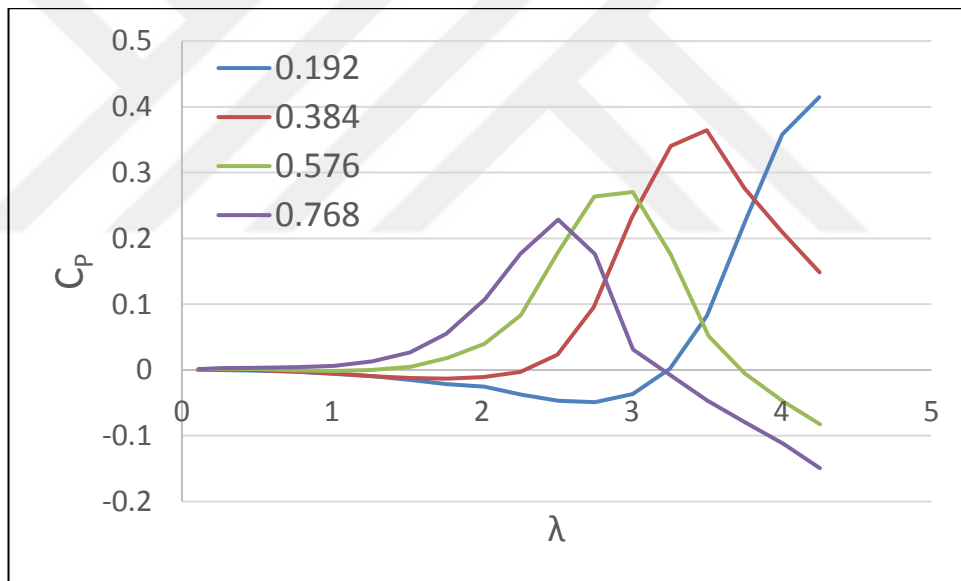


Figure 1.8 Power coefficient variation as a function of λ in different solidity ratio (adapted from Kirke & Lazauskas, 1991)

A study was focused on improving NACA 0018 type airfoil which is commercially using in VAWTs. RFOIL program was used for earlier stage of this study. Literature about airfoils and previous studies was analyzed carefully in this study. This study was clearly identified thickness and camber as parameters that affect airfoil performance. According to this study, large increase in camber does not have beneficial outcome and thickness increase is not profitable for laminar and turbulent profiles. An airfoil

prototype was made which was named as DU 06-W-200. It was compared with NACA0018 type airfoil in different operating conditions in wind tunnel experiments (Claessens, 2006).

Another study was focused on airfoil shape and its optimization. A fully automated process was invented for maximum efficiency. In this particular work Fluent program was used as a analyzing tool for two dimensionally analyzation of a three bladed VAWT. They gathered torque data as a time dependent variable from program in order to reach maximum efficiency. Increasing thickness by 58% while decreasing solidity by 40% was given the best result with 6% increase in performance (Carrigan et al., 2012).

Muhammed et al. (2015) worked on two dimensional analysis of a H-rotor darrieus turbine with different mesh creating interfaces (Gambit and Ansys Workbench). In this study data was gathered for 25 different type of airfoils in different turbulence models and CP- λ graphs were created for those airfoil types. The experimental data was used to compare with the study did not match the data was gathered for this study. Over estimation of power coefficient of numerical study was bigger than twice of the experimental study was compared. Although overestimation in power coefficient of two dimensional numerical study is a fact among all comparisons with experimentally collected data, three dimensional numerically analyzed results are given close results with experimental data.

Macit (2015) worked on numerical investigation of the effect of the blade length and chord length on the performance of the VAWTs. At first, different blade types were analysed two dimensionally by changing the angle of attack at steady state with FLUENT 6.3. Secondly, the performance of a three bladed VAWT was analyzed with ANSYS-FLUENT 14.0 by changing the chord length and the rotor diameter of the turbine. In his studies he tried to identify three bladed VAWT's behavior in different blade length and rotor diameter and compared them with previous researches.

Eboibi et al. (2016) investigated the influence of solidity in VAWTs' performance at wind tunnel. PIV (Particle Image Velocimetry) method was used to determine dynamic stall and boundary layer in flow field. Hotwire anemometers were used for

wind velocity measurements. Two blades with different chord lengths were used to determine solidity effect. Turbine with low solidity has more wider range of work in different λ than high solidity turbine. On the other hand low solidity turbine reaches positive power coefficients at higher λ and it makes self-starting hard. Turbine with high solidity reaches higher power coefficients than the low solidity turbine. This experimental study will be used as a validation tool for further numerical investigation.

1.4.3 Experimental and Numerical Studies related to VAWT performance

Vittecoq & Laneville (1983) studied experimentally and numerically on dynamic stall effect on a two symmetric NACA0018 bladed H-rotor type Darrieus turbine and observed that dynamic stall causes decrease in C_p values at $\lambda \leq 3.5$ operating conditions.

Paraschivoiu (2002) explained wind turbine types, mathematical equations for generating electricity from VAWTs, aerodynamic models and turbine behaviors in water tunnel and wind tunnel experiments. Aerodynamic models and mathematical formulas were given for low Reynolds number and a comparison was made between those aerodynamic models. In this study it is also shown that how NACA0015 type airfoil behaves at different angle of attacks and deriving pitching moment correctly. Paraschivoiu stated that increment of Reynolds numbers increase the working range of the turbine and increases the C_p (Figure 1.9)(Paraschivoiu, 2002, chap. 5).

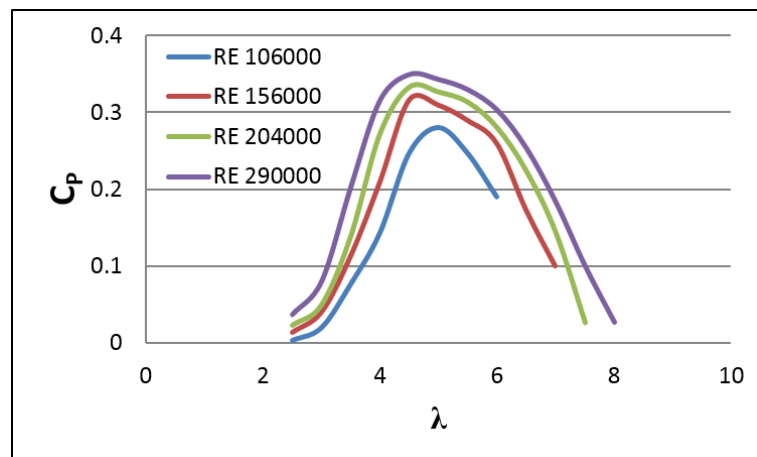


Figure 1.9 Power coefficient variation as a function of λ in different Reynolds number (adapted from Paraschivoiu, 2002)

De Coste et al. (2005) shown torque and thrust forces clearly with a MATLAB program in a project. Force that produce torque was computed for NACA0012 type airfoil and was compared at different λ s at different parameters. Number of blades, pitch angle and airfoil type were analyzed as parameters. Three bladed turbine was overwhelmed two bladed one in terms of self starting. Variable pitch situation was surpassed passive pitching and no pitching angle situations.

Bravo et al. (2007) made an experimental research on a small scale VAWT in wind tunnel. C_p vs. λ and Power vs. RPM data were gathered for different working conditions in this study. Test turbine was subjected to different free stream wind conditions. The minimum wind speed needed for power production was $6 \text{ m}\times\text{s}^{-1}$. Rated wind speed was $14 \text{ m}\times\text{s}^{-1}$ and $C_{p,\text{max}} = 0.3$ was calculated at $\lambda=1.6$.

Islam et al. (2011) worked about a small scale VAWT. Blade support type, solidity, blade material and airfoil type were taken as parameters and a parametric study was made for economical and beneficial point of view. The aim of the study was the usage of smaller scale VAWTs in urban areas etc. This work was especially important for production of small scale VAWTs. Different parameters which effect the turbine efficiency was shown clearly. Using endplates reduces the overall dimensions. Solidity is an important parameter to be optimized in terms of performance and requirement of excessive blade materials. Blade materials effect efficiency directly. Blade and strut types effect overall performance of the turbine.

In a pioneering work the use of counter-rotating VAWTs in pairs was investigated to achieve higher power output per unit land area than existing wind farms consisting of HAWTs. Full-scale field tests of 10-m tall VAWTs in various counter-rotating cluster configurations were conducted under natural wind conditions at summer. It was observed that power output per unit area of this experimental setup overwhelmed HAWTs desired output per unit area. With the conceptual change in energy production this study was named as remarkable (Dabiri, 2011).

Kinzel et al. (2012) investigated interaction between turbine pairs and arrays in field research. They analyzed the flow field within an array of 18 counter-rotating, vertical axis wind turbines. The turbine wakes and the recovery of the mean wind speed

between the turbine rows are derived from measurements of the velocity field using a portable meteorological tower with seven, vertically-staggered, three-component ultrasonic anemometers. The data provide insight to the blockage effect of both the individual turbine pairs within the array and the turbine array as a whole.

Castillo (2012) focused on the design of a small scale VAWT with wood as a construction material. Aerodynamic analysis were done by MATLAB program. The structural analysis of a small scale VAWT was taken into consideration also. In this study, the previous works in that area were clearly identified. This work could be used as a guide for future computational and experimental works.

Goude (2012) studied fluid mechanics of vertical axis turbines in his thesis. Stream tube and vortex models were clearly explained as a tool to understand vertical axis marine turbines. In this work single and coupled turbines and turbine arrays were analyzed by numerical modelling. Turbine behavior with respect to other turbines was taken into consideration in his previous papers.

Shyu et al. (2012) examined small scale VAWT with high efficiency and high power coefficient. Production process was focused on this study. Data of 4 kW prototype was collected in terms of efficiency and power.

Biadgo et al. (2013) investigated VAWT in two dimensional analysis. NACA 0012 airfoil type three bladed VAWT was examined by both DMST and CFD analysis. RANS (Reynolds Averaged Navier-Stokes) equations were solved for CFD analysis than results were compared with DMST to obtain force and torque values. In this work stream tube models and their evaluation was explained in a detailed way.

Sai et al. (2014) used Ansys Fluent 12.0 for CFD modeling of VAWT arrays in order to understand turbine behavior in arrays. This study has similarities with J.O. Dabiri's previous works. In order to save time they used circles as turbines to simplify the geometry of VAWT's. They investigated different array positions to identify how counter rotating turbine pairs and arrays behave.

Brusca et al. (2014) worked on aspect ratio of a VAWT to investigate its effect on turbine efficiency. They tried to find a new design procedure with respect to aspect

ratio to maximize turbine efficiency Using a calculation code based on the Multiple Stream Tube Model, symmetrical straight-bladed wind turbine performance was evaluated .In this work effect of aspect ratio to Reynolds number and effect of Reynolds number to turbine efficiency were derived from formulae.

Gömeç (2014) worked on two and three NACA 0021 bladed VAWT with different solidity ratio to identify the effect of solidity. He used Fluent as a CFD analyzing tool. He worked on time independency and mesh independency detailed. In addition to that power generated by these two different types of VAWT considered to be constant and same for simplify the results of these analysis. This MSc. Thesis was well prepared for the literature part.

Xin et al. (2015) reviewed experimental and numerical research methods in VAWT analysis and they divided this study into three main parts. Computational aerodynamics, computational fluid dynamics, and experimental approaches were compared with each other. Both advantages and disadvantages of those research methods, which were used for previous studies about VAWTs, were examined detailly. In computational aerodynamics part, momentum model, vortex model and cascade model were explained and compared. Finite difference model (FDM), finite element model (FEM) and finite volume model (FVM) were discussed in computational fluid dynamics part of this study.

Korprasertsak & Leephakpreeda (2015) worked on low speed VAWTs with wind boosters. Savonius type VAWT was used in CFD modelling and power analysis was made for two conditions; turbine without boosters and turbine with boosters. At low speeds, turbine with boosters was given better performance than the one without boosters.

Dyachuk & Goude (2015) worked on simulating two different dynamic stall models in DMST to identify VAWT behavior. Turbine behavior in low λ s were investigated computationally in order to compare it with previous experimental researches.

Balduzzi et al. (2016) worked on critical issues in the CFD simulation of VAWTs. Last five years two dimensional studies in CFD modeling of VAWTs were reviewed.

Turbulence models, solving algorithms, time step size on time dependent analysis, boundary conditions and their interactions with models, boundary layer thickness, mesh structure and number of elements in mesh formation were examined and parameter sets were constructed for solving two dimensional CFD model. Main goal of this study was identifying the most effective simulation settings to ensure a reliable fully-unsteady, two dimensional simulation of an H-rotor type Darrieus turbine.

Li et al. (2016) empirically studied performance and wake characteristics of a two-bladed NACA 0021 based H-type Darrieus rotor as a function of tip speed ratio for the first time. Both wind tunnel tests and field tests were conducted. All collected data except main free stream wind direction and narrow free wind directions were eliminated in field research. Main goal of this work was optimization of VAWT by optimizing different variables.

Chowdhury et al. (2016) investigated tilted position of VAWTs. In this work turbulence models were explained, mesh independency was confirmed, then data was gathered for two NACA0018 bladed VAWT for different tilt angles and was compared with experimental results. This study was done by CFD and the experimental data were not clearly identified.

Araya (2016) studied aerodynamic interaction of VAWT's in an array. He and his colleagues made both field research and water jet experiments to compare results. He used PIV method to collect data from water jet and used previous data from their work with Dabiri.

1.4.4 Experimental and Numerical Studies related to flow distribution and wake characterization of VAWTs

An experimental study was made for understanding the tip vortex behavior of a tilted two bladed VAWT in wind tunnel. Two main purpose of this study were, qualitatively define the flow dynamics and effects of skewness on the flow behavior and improve a database of measurements that can be used for the validation of numerical models, especially for free vortex models. Three different techniques were used for those measurements, smoke visualization of the tip vortex expansion, hotwire

measurements of the flow around the rotor, thrust force measurement of the VAWT to determine its variation with skew angle (Ferreira et al., 2006).

Ferreira et al. (2007) studied different turbulence models in numerical methods to understand dynamic stall formation in VAWTs and how dynamic stall affect turbine behavior. Four different types of turbulence models' results were compared with the results were obtained from experimental work with PIV. DES (Detached Eddy Simulation) turbulence model was the closest to experimental data, on the other hand URANS (Unsteady Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) data was collected from CFD was unusable for analyzing dynamic stall behavior. With the guidance of the turbulence model they have stated that change of force with respect to time have to be investigated and possible frequency distribution have to be analyzed by experimentation.

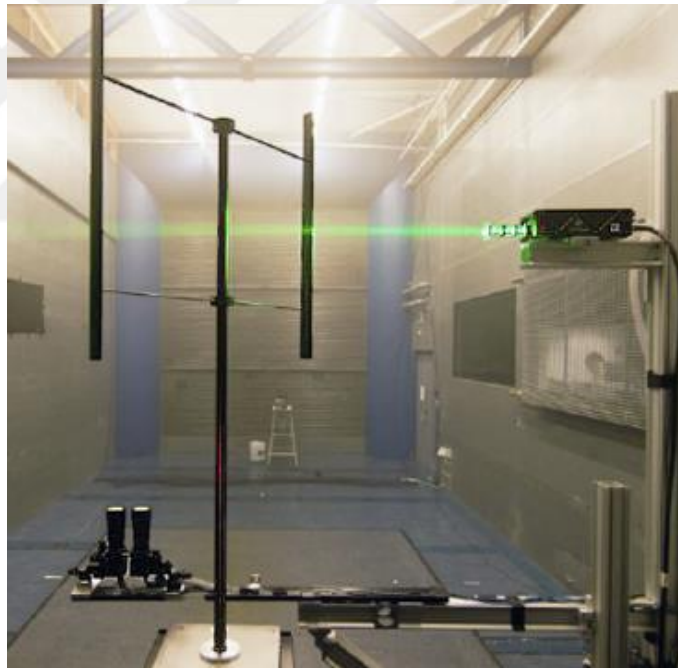


Figure 1.10 Experimental PIV setup that prepared (Tescione et al., 2014)

Tescione et al. (2014) worked experimentally on near wake flow of a VAWT. Data gathered for both two and three dimensional behavior of VAWT. Analysis was made by stereoscopic PIV (Figure 1.10). A two NACA 0018 type bladed H-rotor type VAWT model was constructed and it was used in wind tunnel tests. The wake and

wake recovery in turbine were tried out. Data was gathered from this work have been used in further studies.

Tescione et al. (2016) worked on three dimensional numerical modeling of VAWTs. MATLAB and CUDA-C programs was used for numerical modelling. Data collected from this numerical analysis was compared with experimental data. Consistent three dimensional numerical results with experimental data were collected in terms of wake characteristics and velocity formation around turbine.

Lam & Peng (2016) worked on wake characteristics of two bladed H-rotor Darrieus type VAWT. Ansys Fluent program was used for CFD analysis in two dimensional and three dimensional models. The data collected from analysis was compared with the study done by Tescione et al. (2014) and had sensible similarities. Tescione et al., investigated wake dynamics past the rotor detailly by stereoscopic PIV technique. Their investigation is for a single point operation where tip speed ratio is 4.5 and average tip speed based Reynolds number is 1.7×10^5 . The investigated rotor has a solidity of 0.11 and aspect ratio of 1. Their findings include asymmetry of wakes and enhanced diffusion due to turbulence and interaction between opposite-direction vortices, resulting in undetectable individual vortex structures and blade wakes after three diameters downstream distance and the only relevant structures being smooth counter-rotating pair of vortices at the edges. The strength of diffusion in VAWTs is found to be higher than HAWTs, thus quicker wake recovery is enabled. Lam & Peng (2016), investigated the same problem by 2D and 3D computational fluid dynamics (CFD). Good agreement between these two studies was observed. Reynolds number range in wind tunnel tests was between 1.62×10^5 and 3.12×10^5 . They found that performance is not only dependent on λ , but also average airfoil-relative Reynolds number has a strong impact on performance, where increasing Reynolds number increases performance coefficient. Field tests show scatter results due to variations in wind velocity (through Reynolds number effect) and turbulence. In this regard, it is detected that wake recovers more quickly in field tests than in tunnel tests due to the effects of turbulence. Also, power coefficient is lower in the field tests for optimum tip speed ratio while higher for low and high tip speed ratios. They identified the methodology and steps of CFD analysis in Fluent clearly.

1.5 Thesis Overview

The most common method was used to characterize a Darrieus-type wind turbine efficiency at a constant Reynolds Number depends on two dimensionless parameters; Power coefficient (C_P) and tip speed ratio (λ). New approaches in qualified characterization of C_P - λ curves which obtained with mean values have emerged due to new experimental methods and simulations. The approach which proposed torque coefficient ($C_T = C_P / \lambda$) changes with respect to angular position of the blade (θ) (Balduzi et al., 2016) is the closest 2D modeling result to approach the experimental results of C_T - θ change in the literature is proposed as the most suitable way to determine the performance of Darrieus type wind turbines. However, the results of the wake formation and transportation of vortexes are given only in the form of comparison of the simulations with each other and mostly qualitatively. There is also no comparison or suggestion regarding to 3D simulations with respect to experimental data in different working condition such as different Reynolds Number, different aspect ratios and different solidities.

Another characterization and comparison tool is to reveal turbine field traces and vortex formation and convection of vortexes around the blade, in the inner region of the turbine and in the flow field of the turbine background. Wake characteristics of a Darrieus type wind turbine with a symmetric blade geometry was examined experimentally (Tescione et al., 2014) and numerically (Lam & Peng, 2016) before. Same turbine geometry was used for this thesis. In order to be able to simulate efficient 3D CFD simulations in terms of calculation cost, it is necessary to carry out numerical studies in a certain systematic way. In the scope of the study, an appropriate solution method is applied considering the constraints such as convergence, solution correctness and analysis time. A study was presented by Balduzi et al. (2016), including only 2D simulations.

Although the two-dimensional analysis is advantageous in terms of the duration of the solution, at certain positions of the blade (dynamic stall situation while investigating tip vortex shedding) 2D analysis output is deviating from experimental results. This is why the reliability of the two-dimensional analyzes is valid only for a

mid span plane of a infinitely long VAWT. The solution area is investigated consists of the rotating zone which contains blade geometry and the stationary flow field area around it. For modeling rotating region sliding mesh was applied. The dimensions of the domain depend on the diameter of the rotating zone which is derived from similar studies in the literature. Appropriate definition of the control volumes in the domain, is one of the most important parameters affecting the convergence speed and solution accuracy of the analysis. In this context, finest mesh created around the rotating turbine blade in order to examine velocity changes and turbulence occurrences. To examine the effect of the mesh structure on the solution accuracy, analyzes is performed and the mesh dependency is examined. The time-dependent Reynolds Averaged Navier Stokes equations in numerical analysis is used in the ANSYS-FLUENT packet program. Continuity and momentum equations is resolved SIMPLEC. Pre-analysis of the method to be used for solution of speed-pressure couple the convergence speed, accuracy and resolution time is determined. Turbulence model SST $k-\omega$ method is used, within the thesis in order to carry out both boundry layer interactions and core region.

CHAPTER TWO

COMPUTATIONAL FLUID DYNAMICS FOR VAWTs

In this chapter numerical modelling parameters are discussed. Modelling approaches due to parameters such as turbulence model, algorithm, domain selection, mesh independency, time step sizing, convergence criteria are identified for 2D and 3D analysis. Turbine geometries and simulation domains are shown. Mesh independency and time step sizing for simulations are examined.

2.1 Modelling Approach

In this study, the computation domain and network structure were realized with transient Unsteady Reynolds-averaged Navier-Stokes (URANS) based CFD solutions except mesh independency study of a single blade. All computational domains were created with ANSYS Design Modeler program and computational grids were constructed with ANSYS Mesher software. FLUENT 18.2 software was used for solutions. SIMPLEC (Semi-Implicit Method for Pressure Linked Equations-Consistent) method is used for continuity and momentum coupling, and "second-order upwind" method is used for interpolating cell surface with cell center of all variables. 4-equation "Transition SST" model was used for turbulence estimation. This model is formed by adding the laminar-turbulence transition characteristic to the 2-equation $k-\omega$ SST (Menter's Shear Stress Transport) turbulence model by means of two additional equations. This transition model with two transport equations for the intermittency coefficient and for the transition criterion expressed by means of the local transition on set momentum thickness Reynolds number is strictly based on local variables. The model can be used for complex two or three-dimensional shear flows using unstructured grids (Balduzzi et al., 2016; Lam & Peng, 2016).

2.2 Reference and Prototype Geometries

In this part of the work both turbine geometries are discussed.

2.2.1 Reference Turbine Geometry

Although the interest on VAWT's has been increasing, there are only a few studies which have both 2D and 3D numerical results which can be comparable with experimental studies in literature. Tescione et al., (2016) studied a reference turbine model which is taken as a reference turbine, because all datas are obtained from PIV experiments and have high reliability. In addition to that Lam & Peng (2016), have investigated the same turbine under the same conditions by 2D and 3D CFD simulations. The turbine is a H-Darrieus type VAWT with two NACA 0018 blades that have not any initial pitching angle. It has 1 m diameter and height, 60 mm chord length and the solidity ratio of turbine ($\sigma = NC/\pi D$) is 0.04. Turbine has also a 40 mm diameter tower and two struts for each blade, but these are neglected in simulations to simplify the structure and to avoid time consumptions (Figure 2.1).

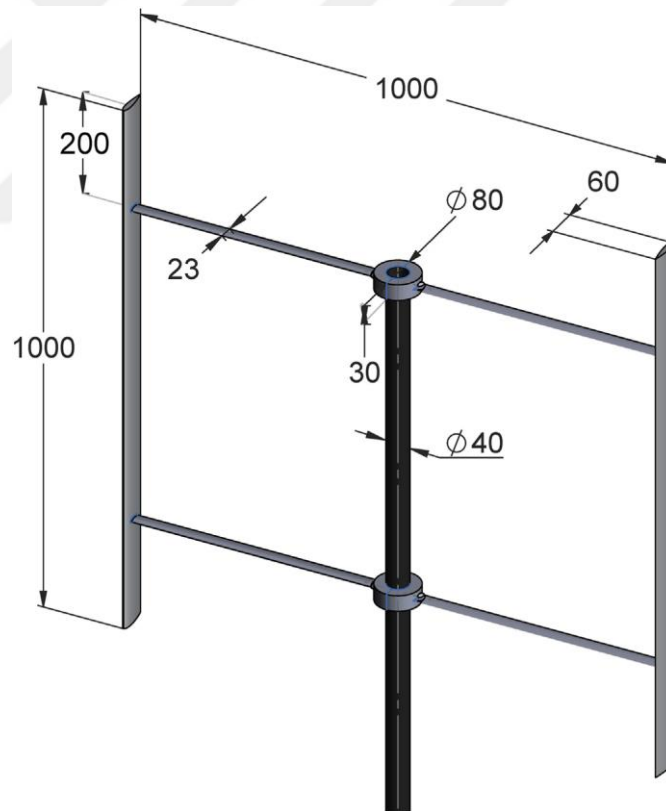


Figure 2.1 Reference turbine geometry and it's dimensions in mm (Tescione et al., 2014)

2.2.2 Prototype Turbine Geometry

General characteristics of a small scale H-rotor type Darrieus VAWT prototype was derived in terms of one dimensional characteristics analysis. Turbine has three NACA 4418 blades with chord length 0.3 m, blade length 2 m, turbine diameter 2.6 m (Figure 2.2). Turbine tower and struts are neglected in both two and three dimensional simulations to avoid time consumptions.

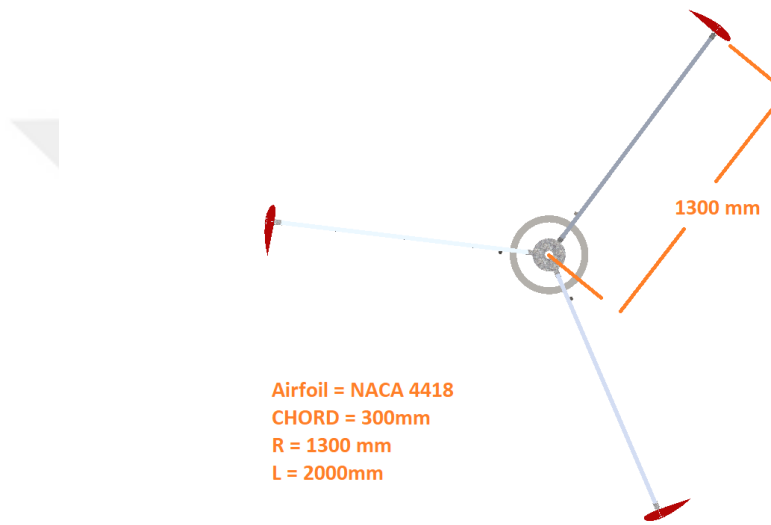


Figure 2.2 Top view prototype turbine geometry and it's dimensions in mm, after design parameters were chosen

2.3 2D and 3D CFD Domains

2.3.1 2D Domain Constructed For Single Blade Mesh Independency Analysis

Simulating real-like boundry layer conditions in blade simulation is necessary for realistic results of force distribution around the blade and observations of flow deviations correctly (Balduzzi et al., 2016; Lam & Peng, 2016; Gömeç, 2014). To accomplish that problem a NACA 0018 blade geometry which has a chord length 60 mm was modelled in 2D (Figure 2.3). Domain boundaries depends on chord length.

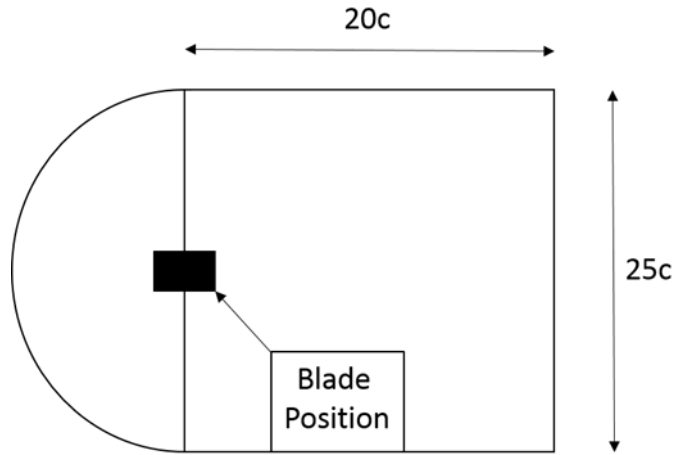


Figure 2.3 Single blade 2D computational domain

2.3.2 2D Simulation Domain for Turbine Analysis

2D computational domain is shown in Figure 2.4 which was also used by Lam & Peng (2016). All domain distances are depend on turbine diameter and chord length. The distance between the turbine center, the inlet and the side walls are taken as 5 turbine diameters. To observe far wake characteristic, the outlet of domain is 11 turbine diameters away from turbine center. Computational domain has three different regions as stationary domain inside the rotational domain, rotating zone and stationary domain between rotating zone and the boundaries. Diameter of inner and outer bound of the rotating zone is $(D - 4C)$ and $(D + 4C)$, respectively.

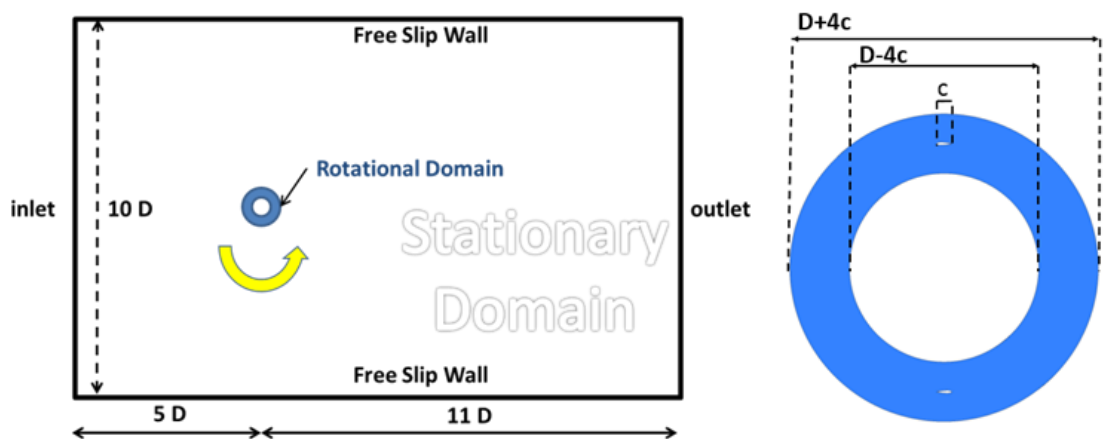


Figure 2.4 Dimensions of the 2D computational domain (left) and the rotational domain (right) with respect to chord length (c) and turbine diameter (D)

2.3.3 3D Simulation Domain for Turbine Analysis

At first 3D computational domain of Lam & Peng (2016)'s reference work which is shown in Figure 2.5 is selected as the computational domain which is exactly the same in two dimensional coordinate system and in addition to 2D domain a hollow cylindrical rotating zone created and centered 5D distance among z axis boundary walls (Figure 2.5). However 3D domain have been changed due to preliminary results from mesh independency study. New 3D CFD domain is cutted among mid-plane direction and a symmetry plane is constructed to obtain better results.

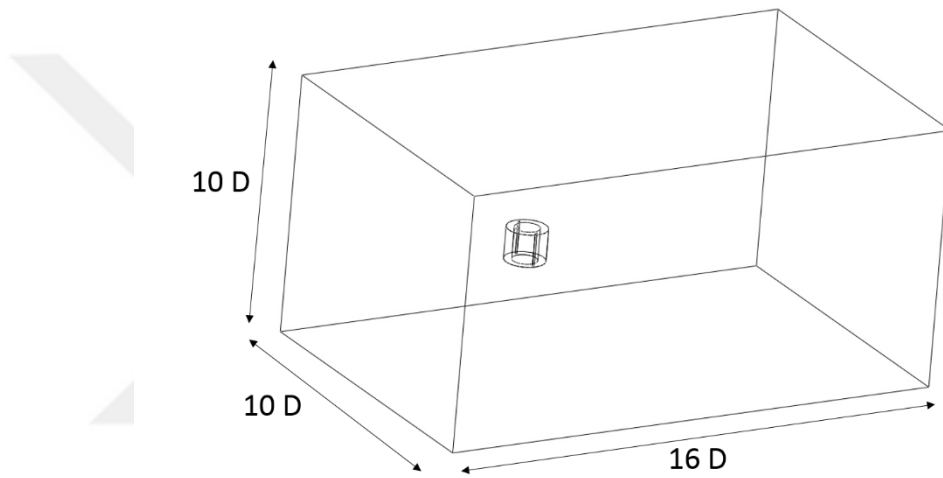


Figure 2.5 3D computational geometry and boundaries

2.4 Computational Grid and Mesh Independency

The mesh strategy is one of the most critical issues in CFD simulations. High-quality mesh enhances the robustness of convergence, the efficiency of calculation, and the accuracy of solution. On the other hand more elements requires more time for solution. Optimization is required to solve this issue. Convergence criteria must be determined before meshing. Convergence requirements depends on situations. Each part of this section has different convergence criterias.

2.4.1 Computational Grid of Single Blade Analysis and Blade mesh independency

Boundry layer solving in turbine simulations have a necessity because of correct data collection around the blade and simulating the flow direction of free stream wind

(Balduzzi et al., 2016; Lam & Peng, 2016; Gömeç, 2014). To overcome that problem a NACA0018 blade geometry which has a chord length 60 mm was modelled in 2D domain (Figure 2.3). Solver settings arrange to solve pressure based, steady state flow with Navier-Stokes solution algorithm. Pressure velocity coupling scheme is chosen as SIMPLEC. Second order interpolation schemes were used for all variables except for the pressure. 7 different meshed strategy is tried to solve lift coefficient acting on a blade with respect to angle of attack (Table 2.1).

Table 2.1 Meshing strategies used for single blade model

Mesh Strategy	Edge Sizing Across Blade (mm)	Inflation (Number of layers)	First Layer Thickness (mm)	Growth Rate	Total Number of Elements
1	-	-	-	1.2	12500
2	2.0	-	-	1.2	18000
3	1.0	-	-	1.2	21000
4	1.0	10	2.0	1.2	40000
5	1.0	10	1.0	1.2	48000
6	1.0	20	1.0	1.2	71000
7	1.0	20	1.0	1.1	85500

Reference work is chosen from Sheldahl & Klimas's previous study mentioned before. Most small scale VAWT's has a working range between 1.0×10^5 and 1.0×10^6 Reynolds number in this comparison was selected as 6.0×10^5 Reynolds number and lift coefficient data of NACA0018 from reference work was compared with simulation results. After this study the boundary layer conditions in 6th mesh strategy was selected to use in future work in order to avoid time consumption (Figure 2.6). 71×10^4 nodes were created at 6th mesh strategy with ANSYS Mesher Software.

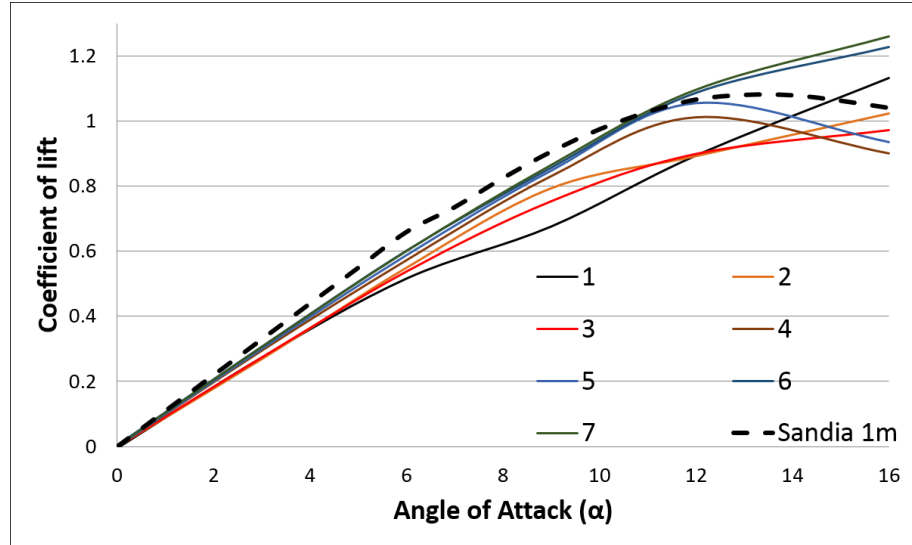


Figure 2.6 Comparison of mesh strategies with the data collected from Sheldahl & Klimas NACA0018 behaviour at Reynolds 6.0×10^5

Key findings about this work are:

- For a NACA0018 symmetrical blade which has a 60 mm chord length edge sizing must be identified and it must be equal or lower than 1 mm. In other words blade cross-sectional surface must be partitioned equal or more than 100 pieces for low Reynolds number conditions
- An infilation process must be used on blade surface layer which must be equal or higher than 20 layers.
- First layer thickness must be equal or lower than 1 mm. In other words first layer thickness must be equal or lower than 1 % of the chord surface length for low Reynolds number conditions.
- Growth rate has no significant affect on the boundry layer, after identifying infilation but it must be considered that not only forces acting on blade but also wake formations are concerned after blade movement.

2.4.2 2D Grid Formations for Reference Study and Prototype Geometry

For both 2D reference turbine model and prototype turbine geometry, different numbers of mesh were applied to the geometry and each one was analyzed to obtain mesh independency. The mesh of reference turbine model consists of a total of 5×10^5

unstructured tetrahedral, quadrilateral and wedge elements. Around 6×10^4 volumes are created in the inner zone, 1.5×10^5 volumes are created in the rotational zone where blades exist and 2.8×10^4 volumes are constructed in the outer domain. 20 boundary-layer inflation elements are used to resolve turbulent boundary layer, including the laminar sublayer ($y^+_{wall} < 3$), with layer growth rate of 1.1, ensuring smooth transition between wedge layers free-stream volumes (Figure 2.7). The mesh of prototype turbine model consists of a total of 2×10^5 unstructured tetrahedral, quadrilateral and wedge elements. Around 2×10^4 volumes are in the inner zone, 1.5×10^5 volumes are in the rotational zone where blades exist and 1.3×10^5 volumes are in the outer domain. 20 boundary-layer elements are used to resolve turbulent boundary layer, including the laminar sublayer ($y^+_{wall} < 3$), with layer growth rate of 1.1, ensuring smooth transition between wedge layers free-stream volumes (Figure 2.8). The difference between two situations depends on different chord lengths and model dependence of chord length.

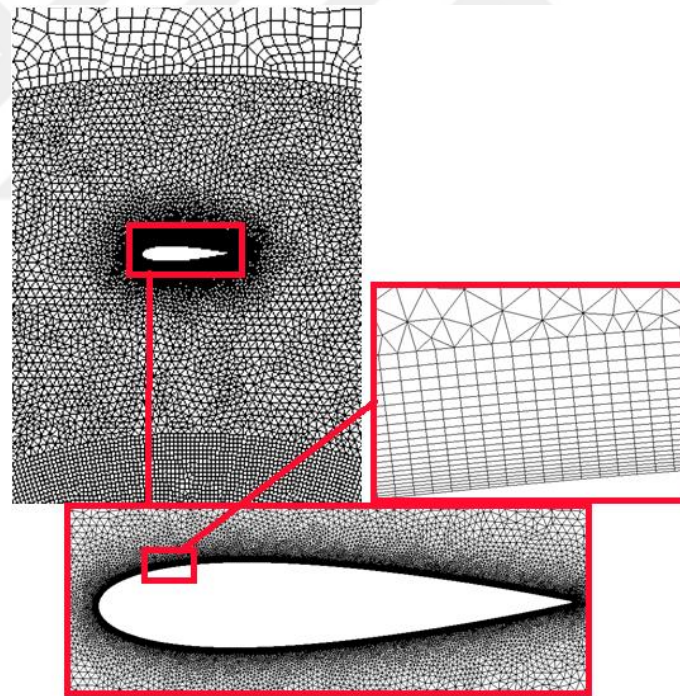


Figure 2.7 Computational grid of reference study in 2D, nodes in partial rotational zone (top left), nodes in blade surface layer (bottom), inflation in blade surface boundary layer (top right)

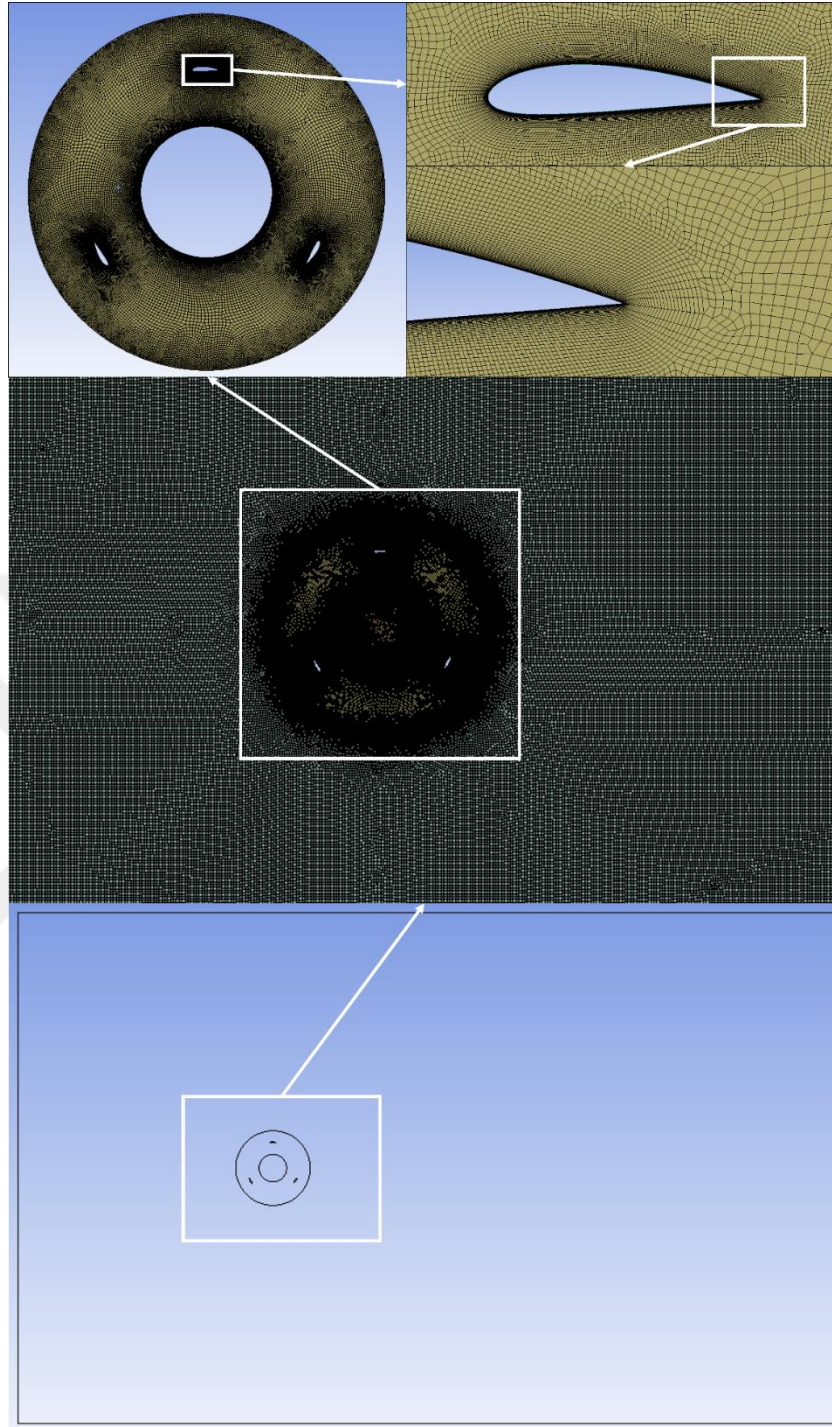


Figure 2.8 2D model and mesh structure used in prototype turbine geometry. Model (bottom), mesh structure of near rotating zone (mid), mesh structure of rotating zone (top left), mesh structure near blade and tail (top right)

2.4.3 3D Grid Formations for Reference Study and Prototype Geometry

3D models general meshing strategy depends on two incidents, time step sizing and mesh independency (Balduzzi et al., 2016; Gömeç, 2014). In 3D models two analysis in different λ 's (4.5λ for 2 bladed turbine and 3λ for 3 bladed turbine) were completed. In those two cases mesh independency and deviation of moment coefficient average were taken into consideration. Three different mesh strategy were used to satisfy mesh independency in three bladed 3D computational domain (Table 2.2) (Figure 2.9, Figure 2.10, Figure 2.11). First two models were created with Ansys Mesh generator with no restrictions therefore element sizes were too big to simulate flow field around turbine and blade boundry element conditions was not satisfied.

Table 2.2 Number of elements which are used in 3D model meshing strategy

Mesh Strategy	Number of elemens in rotating zone	Number of elemens in stationary zone	Total number of elements
1	37000	109000	147000
2	129000	323000	452000
3	1701000	933000	2634000

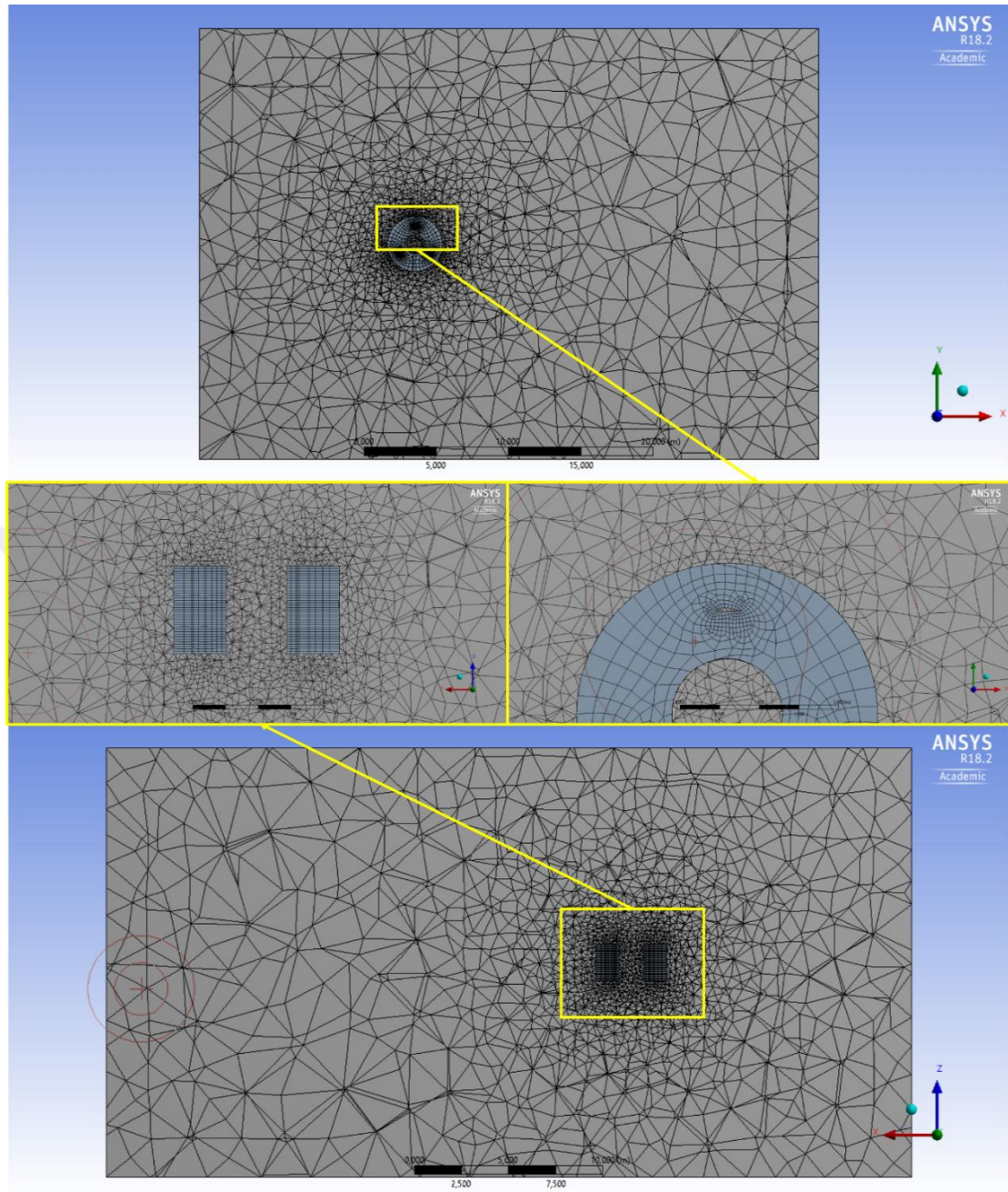


Figure 2.9 3D coarse mesh structure used in prototype geometry. Model mid plane among Z axis view (top), model mid plane among Y axis (bottom), detailed rotational zone mid plane among Z axis (mid right), detailed rotational zone mid plane among Y axis (mid left)

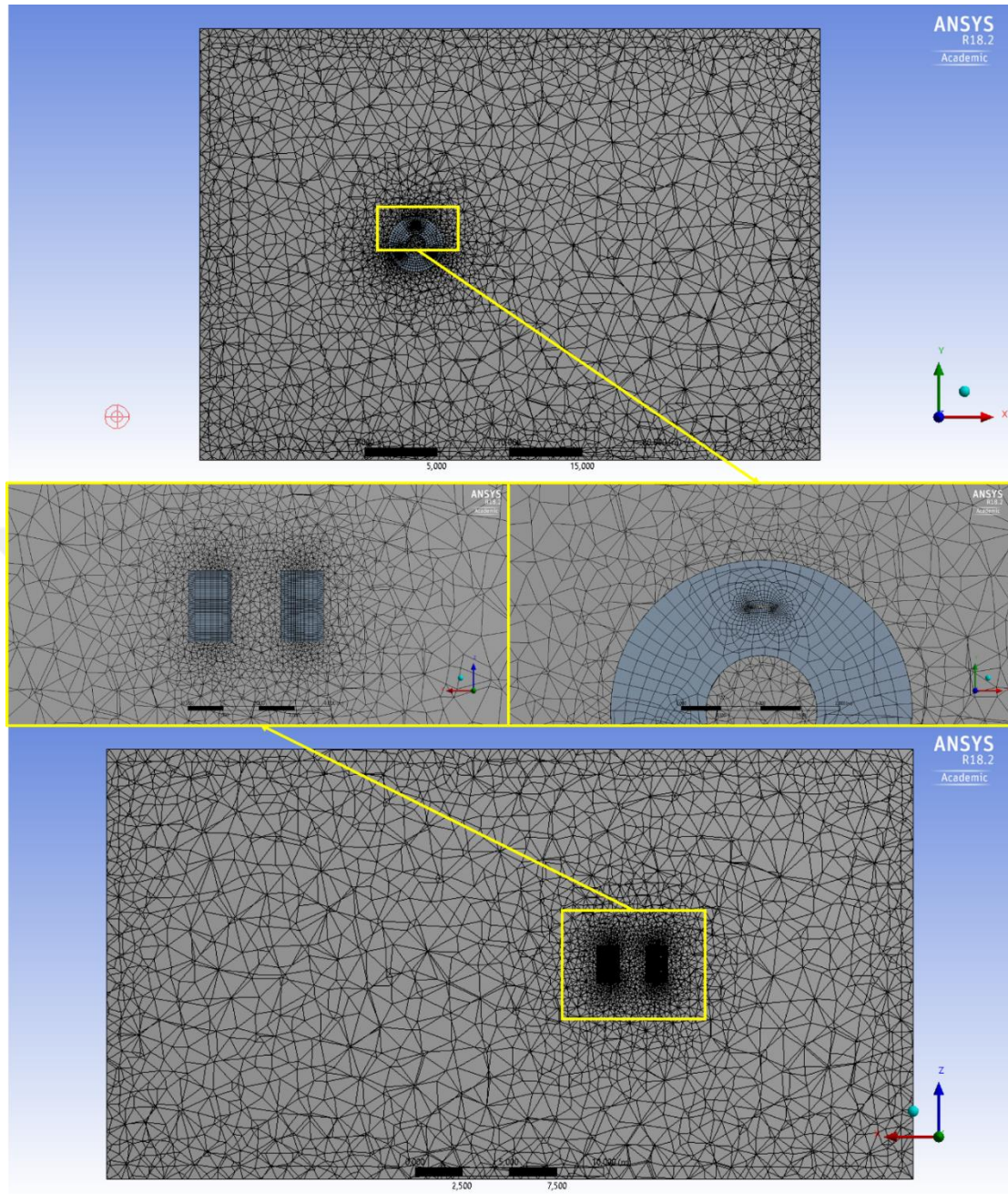


Figure 2.10 3D medium mesh structure used in prototype geometry. Model mid plane among Z axis view (top), model mid plane among Y axis (bottom), detailed rotational zone mid plane among Z axis (mid right), detailed rotational zone mid plane among Y axis (mid left)

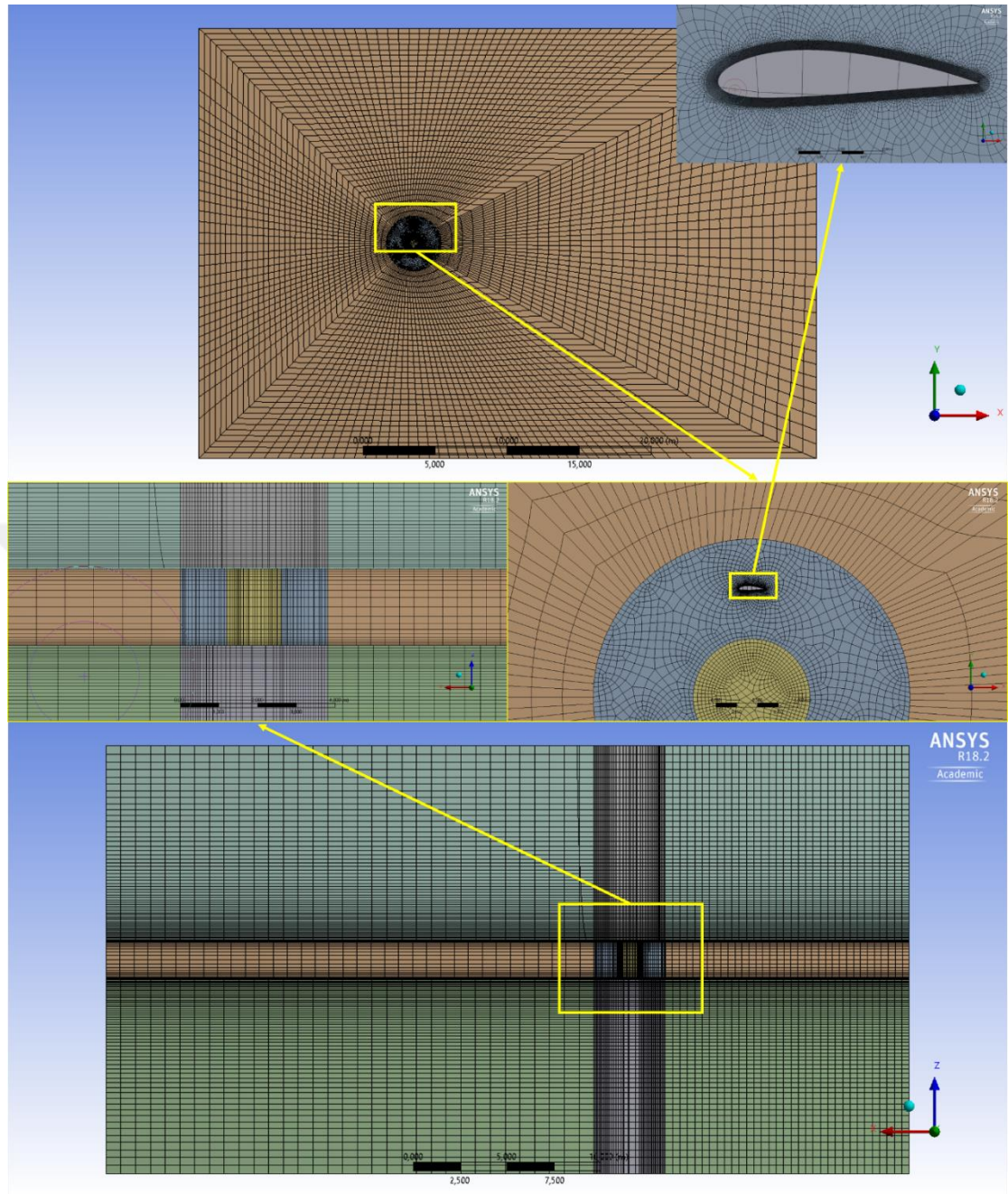


Figure 2.11 3D fine mesh structure used in prototype geometry. Model mid plane among Z axis view (top), model mid plane among Y axis (bottom), detailed rotational zone mid plane among Z axis (mid right), detailed rotational zone mid plane among Y axis (mid left)

In 3rd mesh structure mapped face meshing was used. The distance between nodes getting longer while become distant form rotating zone in this situation such that wake formations in that model give inadequate results. On the other hand two bladed 3D model was appropriate and has a better result while compared to reference studies. In two bladed 3D computational domain 3.4×10^6 elements were used (Figure 2.12).

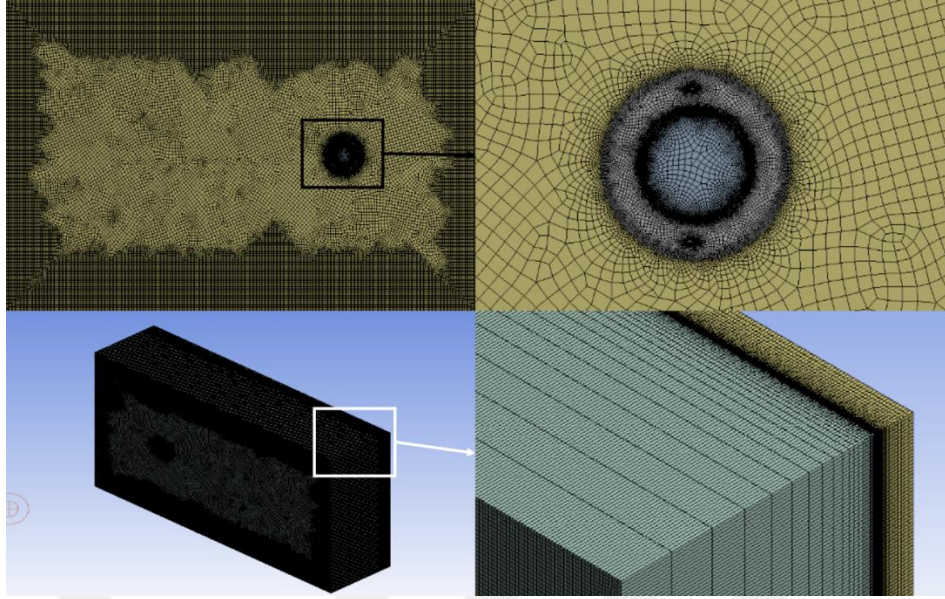


Figure 2.12 Computational grid of reference study in 3D, model (bottom left), top view (top left), sweep structure in z axis (bottom right), top view of rotational zone (top right)

2.5 Time Step Sizing

Unsteady analyses in CFD studies always has its own stability criteria. For instance Lam & Peng (2016) took 10th revolution of rotor to take coefficients of drag, lift, and moment, and 29th revolutions average for wake analysis and explained their reasons with graphics. On the other hand Balduzzi et al., (2016) mentioned that convergence criteria of most of the studies in this area is a full rotational torque average difference between two consecutive revolutions, and most studies took 1% difference between those 2 revolutions as a convergent solution. As Balduzzi et al., (2016) mentioned that convergence criteria depends on tip speed ratio and time step size. To achieve more accurate solutions in high λ levels time step size should be resized to a minimum level. In our study revolutionary speed of the rotor is constant and we can use the same time step size which we used in $\lambda=6$ for entire study. 3 different time step size have been analysed for not only convergence but also time required for solution. $\Delta\theta=2^\circ$, $\Delta\theta=0.5^\circ$ and $\Delta\theta=0.25^\circ$ have been examined as in Figure 2.14. There were a slight difference between $\Delta\theta=0.5^\circ$ and $\Delta\theta=0.25^\circ$ which is in between convergence limits. But time dependency to solve the model increase twice as it was before.

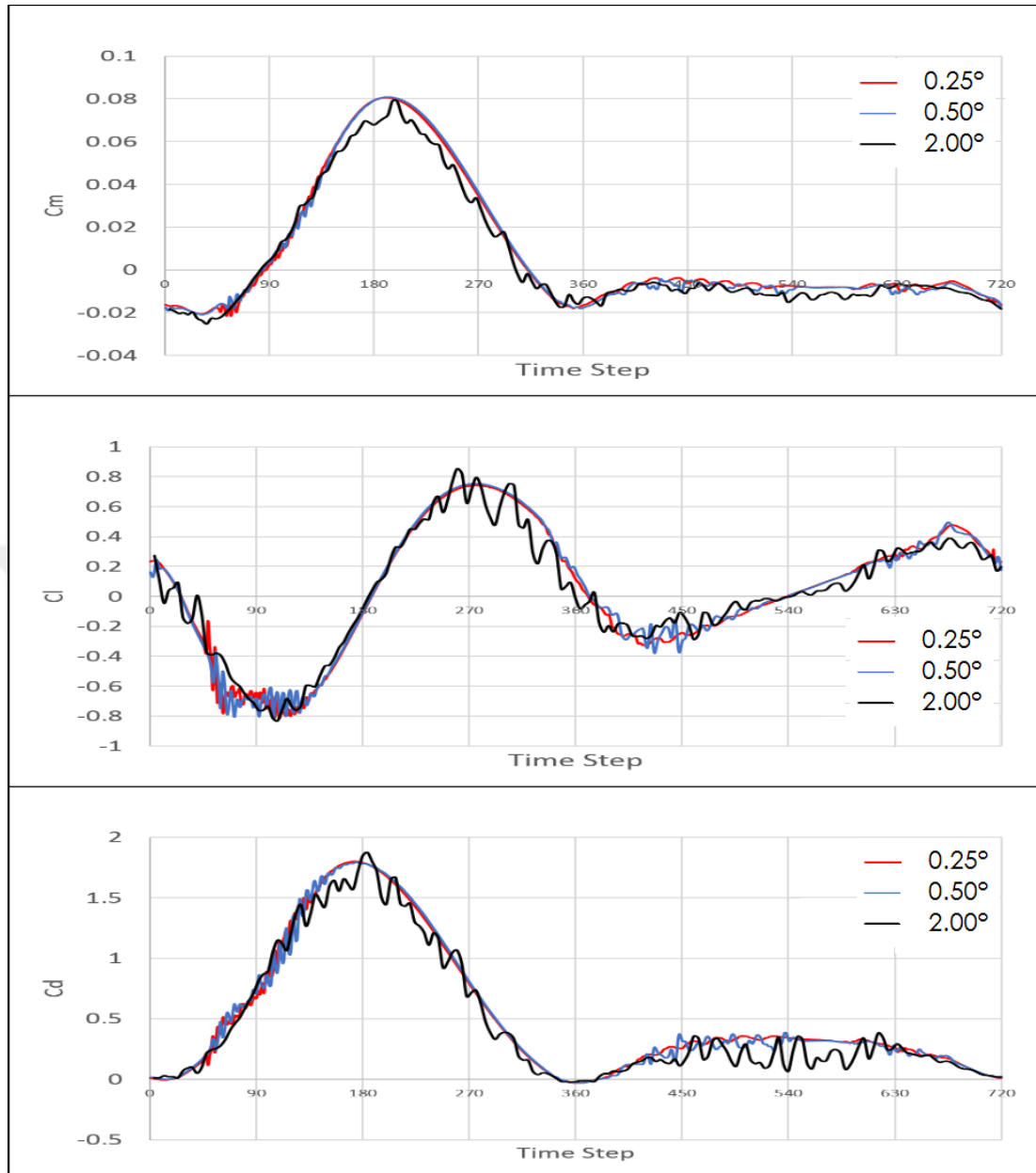


Figure 2.13 Time step sizing difference in reference turbine geometry 2D model. $\lambda=6$ case. Moment coefficient change with respect to time step size(top), lift coefficient change with respect to time step size(middle), drag coefficient change with respect to time step size(bottom)

CHAPTER THREE

RESULTS AND DISCUSSION

In this chapter validation of our numerical model with reference studies by comparison of near wake and far wake data. After validating our results with reference studies turbine wake in 2D simulation at different λ 's (3,4,5,6) will be discussed where comparable data from previous study exists. Later than 3D simulation results of reference geometry will be discussed. In addition to that results in prototype geometry will be discussed. 3D CFD analysis of different mesh strategies will be discussed. 2D wake distribution will be examined.

3.1 Validation of Numerical 2D Model

2D simulations have some limitations as infinite blade length and lack of tower and struts geometry and flow motions along z axis and vorticities could not be modeled. Nevertheless, turbine and wake characteristics can be basically observed and some correlations can be made an inference. For this purpose, validation is very important step for the simulations. Changes in power coefficient (C_p) with respect to tip speed ratio is an important criteria for wind turbines. Therefore, comparison of $C_p - \lambda$ data by experimental and 2D simulations results in available literature data is important to verification.

3.1.1 Aerodynamic Performance Validation

Tescione et al., (2014) fixed free stream velocity at 9.3 m/s and obtained the results at high rotational speed (799.3 rpm) in order to avoid stall effects in the experimental wind tunnel study. They predicted C_p for this operation point where λ is 4.5.

All $C_p - \lambda$ characteristic data of reference turbine are given in Figure 3.1. The predicted C_p data from Tescione et al., (2014) (for $\lambda=4.5$) and simulation results from Lam & Peng (2016) (for a range of $\lambda=3-6$) are given on the chart with results of this study. Lam and Peng (2016) continued Unsteady analyses until the 29th revolution and wake profiles were obtained by averaging the 30th revolution data to encounter convergence at far wake and increased data accuracy in terms of time-based effects.

This convergence method will be discussed in this chapter later but in graphical demonstrations same convergence method was used in near and far wake data collecting. Tip speed ratios depend on wind speed and rotational speed as mentioned before, so there are two controllable way to change λ : Changing wind velocity with keeping rotational speed constant or vice versa. Therefore, two different simulation sets are obtained in this study and all results are also presented on the same chart; one of them for constant Re_C (constant rotational speed) and the other for constant V_∞ (constant wind speed). Trends are similar to Lam and Peng's (2016) data especially for constant V_∞ and highest C_P values have occurred at between $\lambda=4$ and $\lambda=4.5$. It is clear that received data from the reference study of Lam & Peng (2016) was obtained for constant V_∞ . However, it could be seen in Figure 3.1 that results of constant wind speed and rotational speed have some differences and C_P value of constant wind speed at λ of 4.5 is closer to predicted from Tescione et al., (2014). For this reason, all simulations in this study are done by keeping wind speed constant.

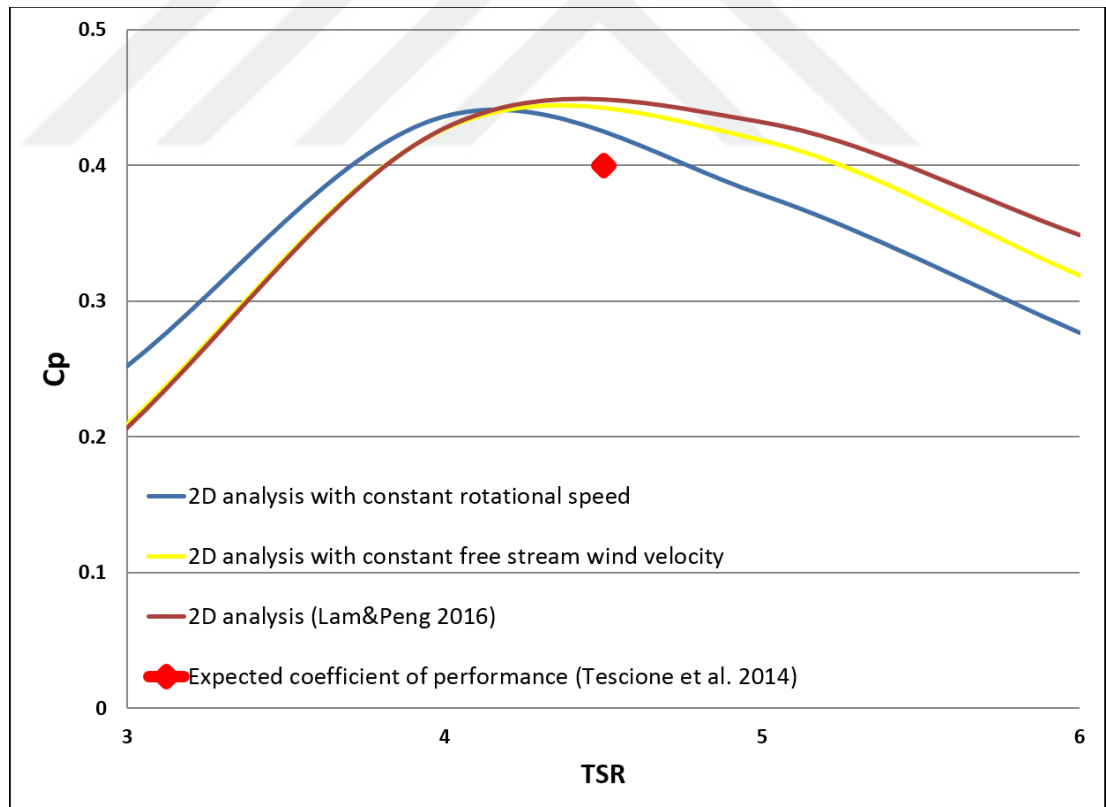


Figure 3.1 Comparison of 2D performance analysis with reference data

3.1.2 Wake Characteristics Validation

Stream-wise velocity profiles for both PIV data (Tescione et al., 2014) and 2D simulation results (Lam & Peng, 2016) are compared for $\lambda=4.5$ for the second part of the validation study. In reference studies normalization of velocity distribution with free stream velocity had been used. From now on we will use same normalization to compare turbine behavior and wake distribution in different situations such as different free stream velocities or different λ 's. Velocity profiles were obtained as an average of 150 phase-locked PIV measurements during the steady flow conditions in the reference experimental study. This produces a smoother data, filtering instantaneous fluctuations between the consecutive measurements and provides comparable results with the CFD study. Velocities in these profiles were calculated by average of one rotation and were shown in Figure 3.2. Firstly, it could be seen that asymmetry in PIV profiles are not successfully obtained by 2D simulation. In reality, turbine zone have more rotating body and complex flow. Probably, this complexity cause more wake orientation in downstream of turbine. However, 2D simulation results have some limitation due to infinite blade assumption and absence of struts between tower and blades and three-dimensional effects. Additionally, our model has no tower to understanding more clearly wake characteristic of turbine.

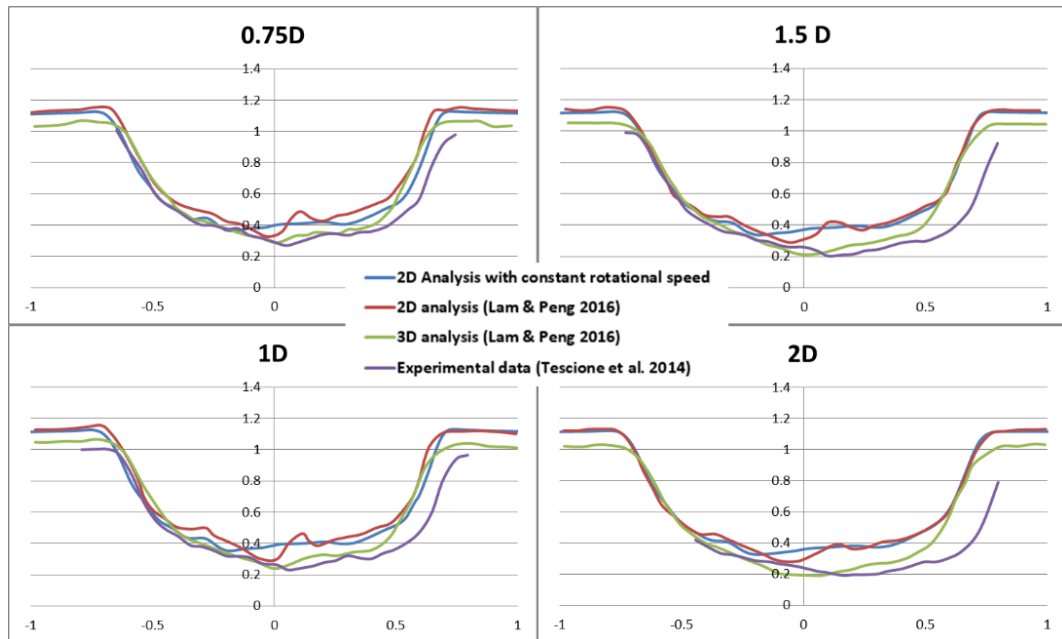


Figure 3.2 Comparison of normalized stream-wise velocity data at near wake ($x \leq 2D$) with reference studies

When 2D simulations wake results are compared, significant difference is not seen in wake characteristic. However, in experimental results, it could be seen more different wake profile and orientation in downstream flow of tower. Middle area of downwind, wake orientation towards windward side due to tower could be clearly observed. Another point to underline, stream-wise velocities above of $y/D = \pm 0.75$ locations are slightly different in PIV and 2D simulation results probably due to blockage effects. In real case, air could be traveled in top and bottom side of turbine, but it could not be modelled in 2D simulations. So, airflow has to pass narrower section area due to obstacle behavior of blades and tower and air velocity increases both environment and inner zone of turbine. In environment (above of $y/D = \pm 0.75$), increase of velocity could be clearly seen in stream-wise velocity charts. But in turbine zone, airflow is more complex. In order to understand wake dynamics around turbine normalized contour are used instead of wake profile graphics. In PIV result, turbine inner zone has six blade traces and interval of them become shorter towards downwind directional. It could be seen more clearly on cross-stream velocity contours in Figure 3.3.

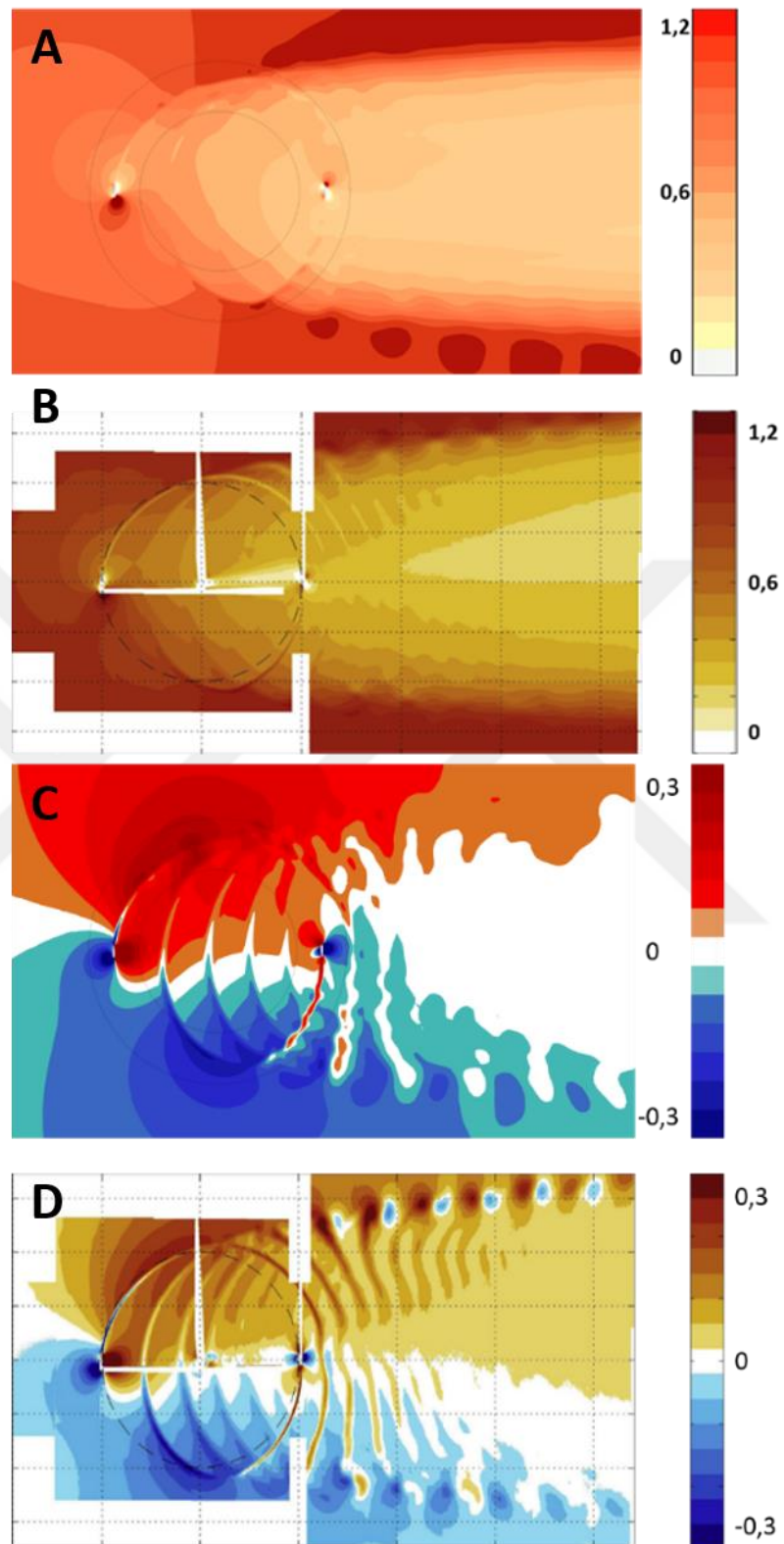


Figure 3.3 Comparison of normalized stream-wise and cross-stream velocity contours with the PIV study conducted by tescione et al., (2014) (A: stream-wise velocity contours CFD analysis; B: stream-wise velocity contours PIV analysis; C: cross-stream velocity contours CFD analysis; D: cross-stream velocity contours PIV analysis)

3.1.3 Validation of Turbine Performance with Number of Rotations

Velocity deficit is an important factor for defining wake characteristic, so wind and turbine rotating velocities and their interaction should be clearly understood in near wake. In Lam and Peng's study, coefficient of performance data are obtained at 10th rotation by averaging one tour, but it should be ensured whether number of rotations is enough or not. For understanding this doubt, it could be validated with changing of C_P by number of rotations. Balduzi et al., mentioned that C_P of turbine is changed till 20 rotations for λ of 1.1 and minimum number of rotations rises to 90 for λ of 2.2. From this point of view, it could be drawn an interference that higher λ 's need a greater number of rotations for stability. Convergence process of C_M that obtained in this study could be seen in Figure 3.4. C_m is approximately remained constant after 35 revolutions. This number of rotations is less than expected when it is compared with Balduzi et. al.'s study. It may be occurred due to difference in turbine geometry or domain size and should be detailly examined. Velocity profiles are also changed until 35th rotation, even so velocity profile remain approximately constant and changing ratio continue to decrease. Velocity profiles have small divergence especially in near side areas of the tower. After 100 rotation, duration of turbine working is reached to nearly 7.5 seconds and slow-moving airflow in downwind area come to near of the stabilization. So, it is more suitable that taking data from this point to get more accurate results.

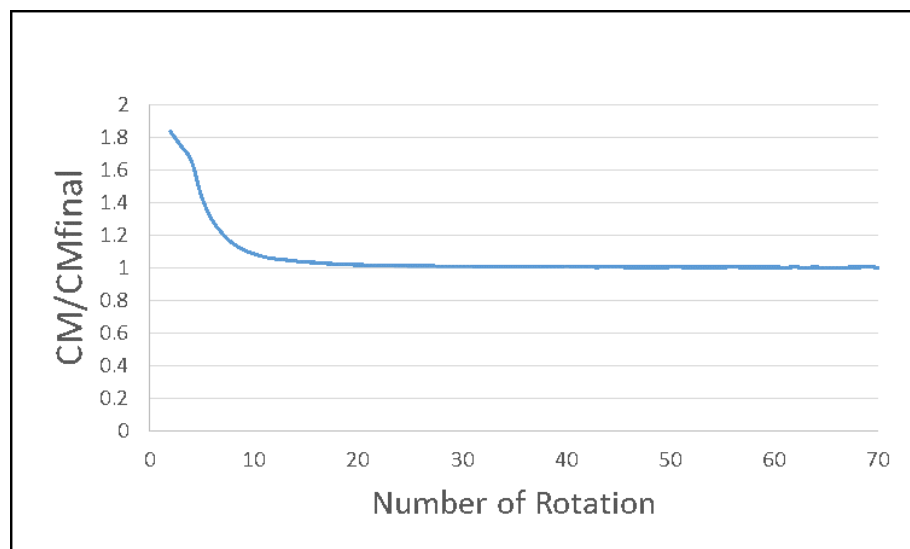


Figure 3.4 Convergence of moment coefficient with respect to number of rotation

3.2 Results

3.2.1 Reference Geometry Studies in Different λ 's

After comparing our study with previous studies we have conducted CFD data for different tip speed ratios in a constant chord based averaged Reynolds Number. λ 3 to 6, which is optimal working range of this turbine under this circumstances, have been analyzed in order to understand wake dynamics of a small scale VAWT. Out of this λ range C_P values dramatically dropped. Tescione et al. operated their conceptual turbine to gather a 0.4 C_P value at a 4.5 λ on the other hand Lam and Peng conducted data from λ 3 to λ 6 and C_P values changing from 0.21 to 0.42. Normalized stream-wise velocity graph of different λ 's in near wake shows that all near wake profiles (0.75 D to 2 D) shifted from origin to wind ward side because of counter clock wise oriented rotational motion of the turbine blades (Figure 3.5). In addition to that increase of the warp of the wake depends on increase of λ while chord based averaged Reynolds number is constant.

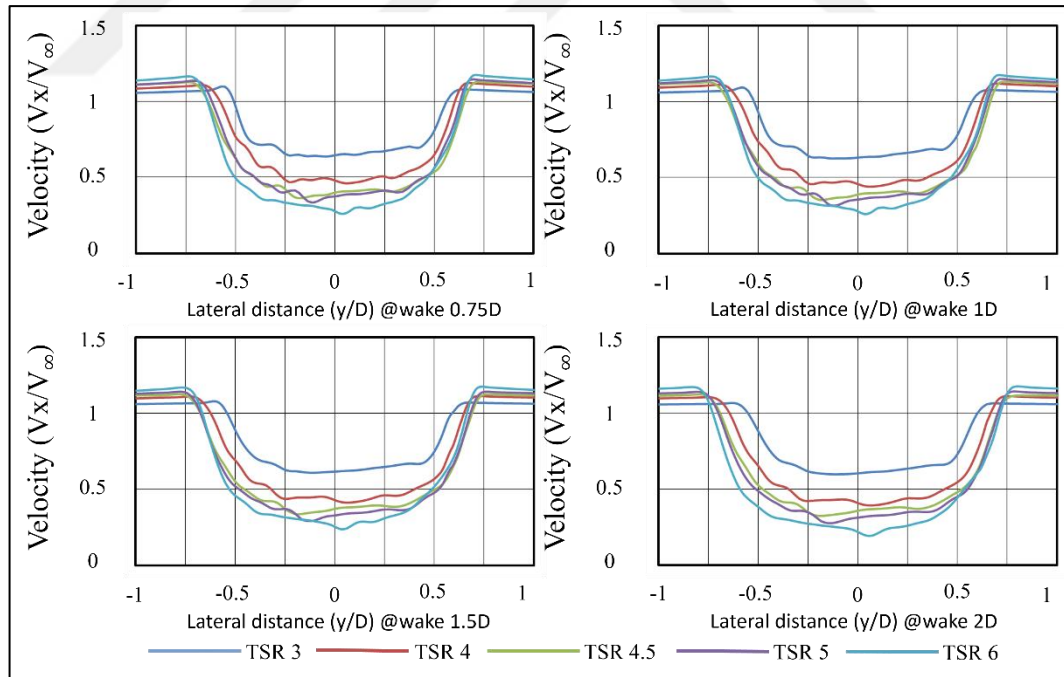


Figure 3.5 Normalized stream-wise velocity distribution at downwind side of the turbine

Normalized stream-wise and cross-stream velocity contours of near wake are shown in Figure 3.6 for different λ 's. At first view, orbit curves of turbine blades are observed

in the turbine inner zone. With increasing λ , wind speed decrease and blade traces could not be quickly pushed to downstream, so they are seen more often. Kinetic energy transport is become harder to penetrate turbine zone and downwind velocity deficit is increasing step by step with increasing λ and turbine behaves as a solid body. So, it is expected that wind turbine works more efficiently with rising of wind speed because of growing lift forces by passing more airflow on the blades. Until a significant wind speed value, this tendency is typically acceptable. But above of this point, dynamic stall occurs wider angle of attack and coefficient of performance starts to decrease. From Figure 3.7 to 3.11, stream-wise velocity contours for different blade location are shown for different λ . Dynamic stall of front blade could be seen only at $\lambda=3$ in between the 135° and 180° positions of θ unlike upper λ values. This indicates that stall case occurs in wide angle of attack region in lowest λ . Blade in downwind position encounters not any stall, because it exposes lower wind speed as far as blade in upwind location. In other words, blade in downwind work as higher λ . In addition, blade traces are asymmetrically moved along downstream because of difference in relative velocities. At 180° position of blade, moving air molecules accelerate positively, because of tangential velocity of turbine blades. As for position 0° , air molecules decelerate. Under this velocity gradient in moving air molecules, blade traces are dragged quicker in leeward side. It could be partially reason of wake asymmetry in downstream.

Another feature in stream-wise contours is wind pushing to environment of turbine both windward and leeward side. This skidding has two points to underline. Firstly, it is increased with increase of TSR. For lower wind speed, wind could not effectively penetrate to turbine zone and turbine behave as if a closed cylinder, so much more wind is canalized to environment of turbine. Cross-stream velocity contours in Figure 12 to 16 show also this affection more clearly. With increasing wind speed, cross-stream velocities decrease in environment of turbine and more kinetic energy of wind is canalized to turbine zone. This affect could be considered within some limits as a positive factor for turbine performance. Secondly, it has asymmetric structure. In cross-stream velocity contours, red and blue hues respectively show $+y$ directional and $-y$ directional velocity. In $+y$ direction, positive cross-stream velocities are higher and cover more area. So, it could be acceptable as a signal of Magnus effect.

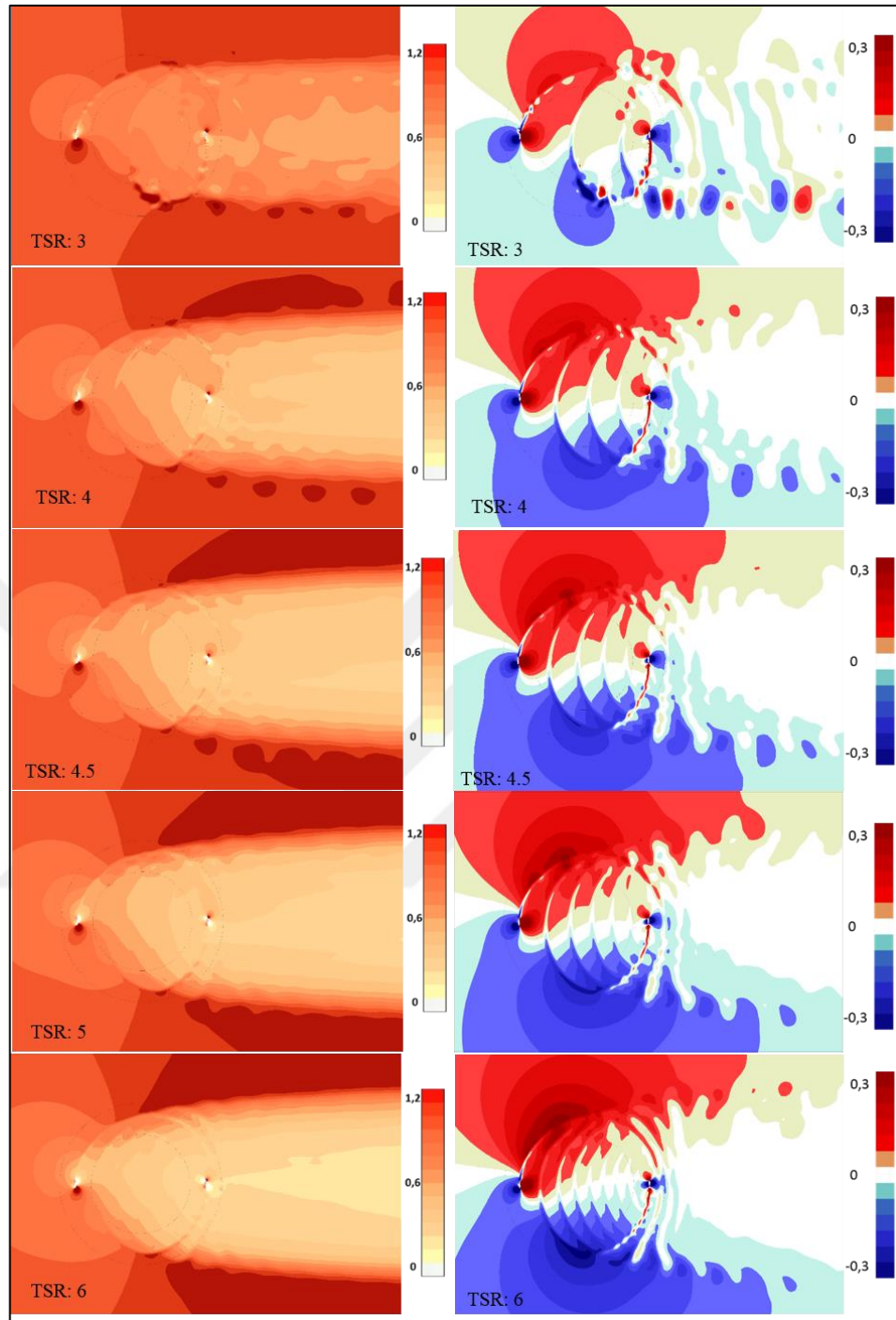


Figure 3.6 Comparison of near wake normalized stream-wise (left side) and cross-stream (right side) velocity contours at different λ 's

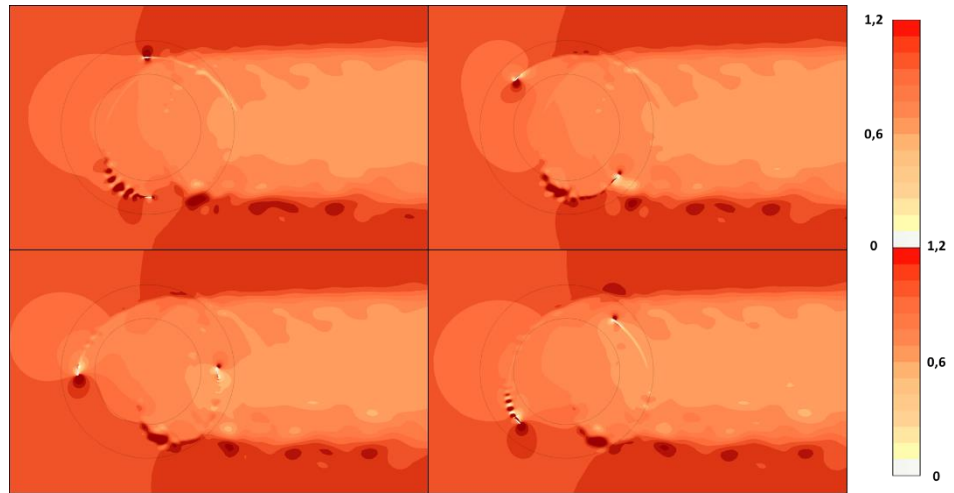


Figure 3.7 Normalized stream-wise velocity contours of different blade position while $\lambda=3$

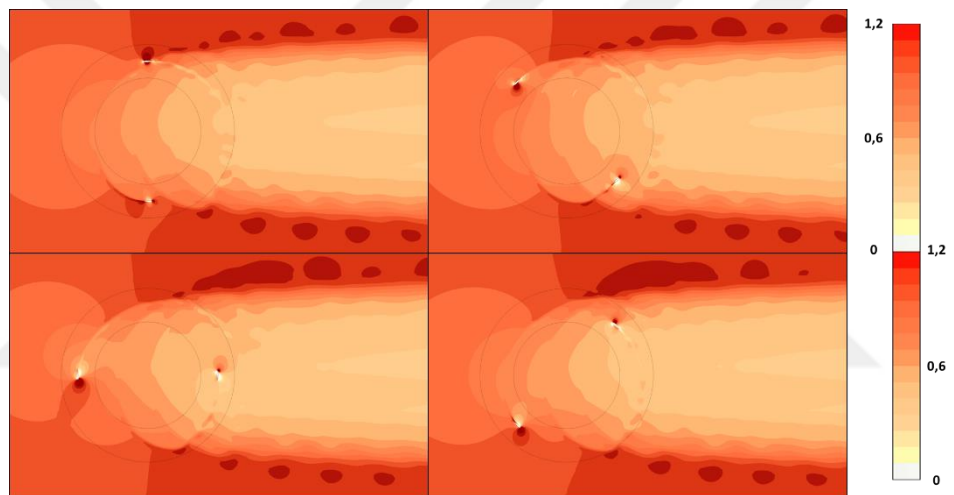


Figure 3.8 Normalized stream-wise velocity contours of different blade position while $\lambda=4$

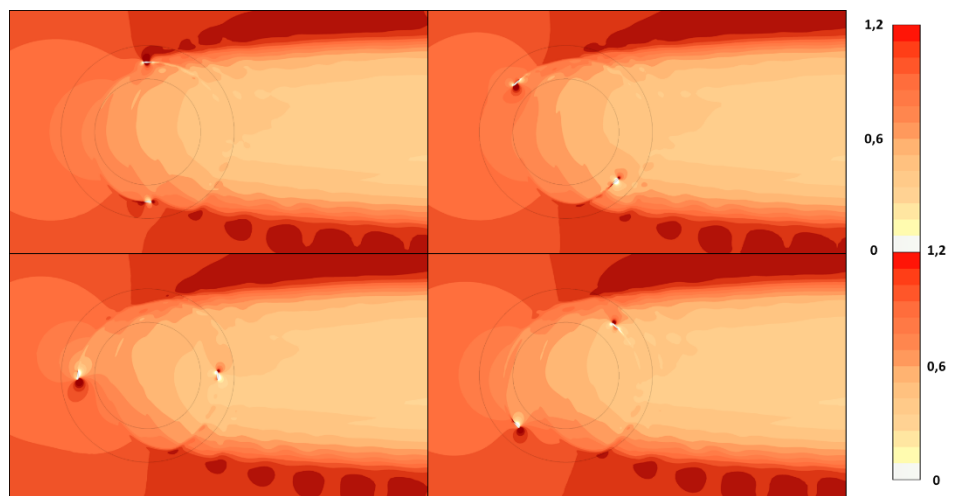


Figure 3.9 Normalized stream-wise velocity contours of different blade position while $\lambda=4.5$

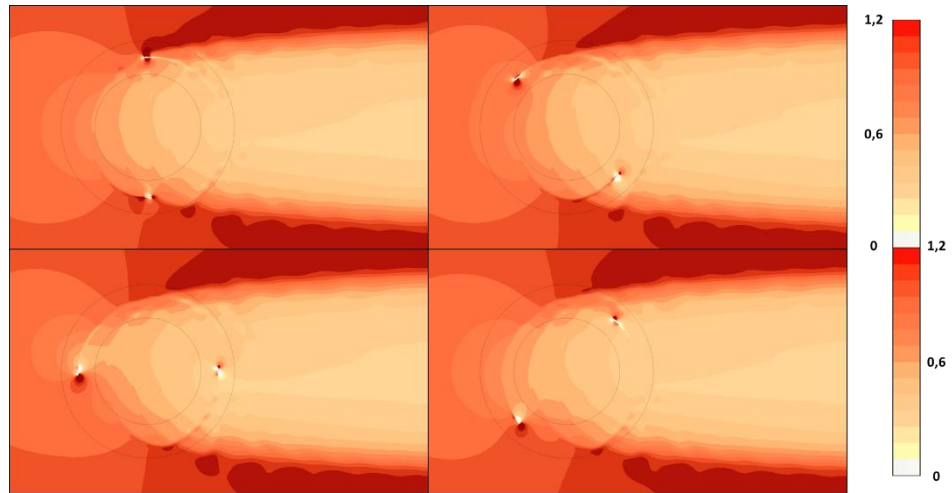


Figure 3.10 Normalized stream-wise velocity contours of different blade position while $\lambda=5$

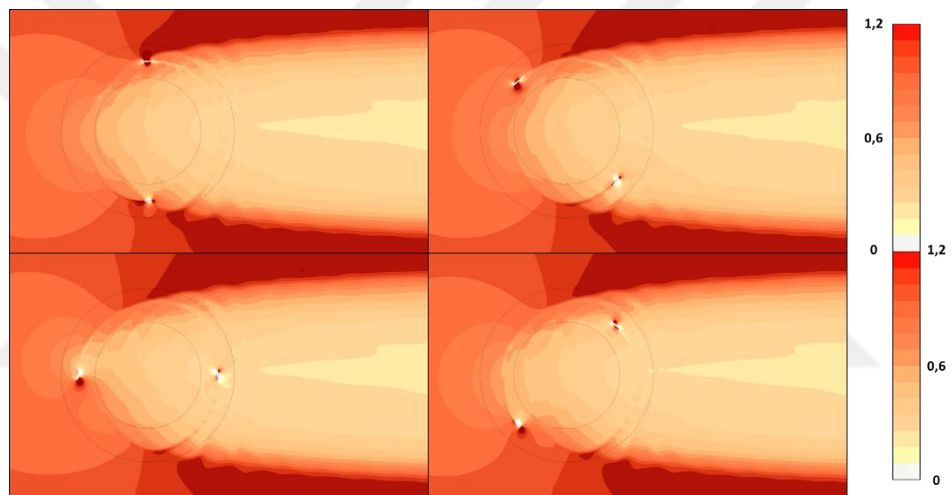


Figure 3.11 Normalized stream-wise velocity contours of different blade position while $\lambda=6$

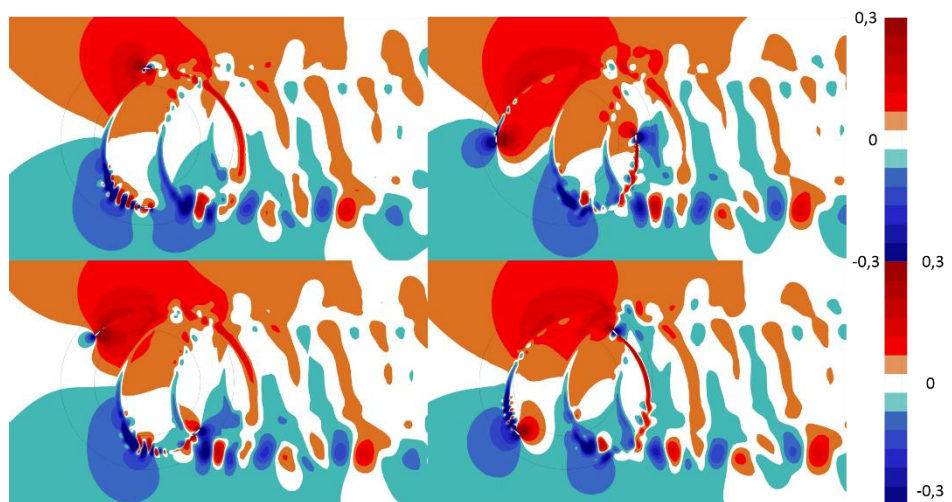


Figure 3.12 Normalized cross-stream velocity contours of different blade position while $\lambda=3$

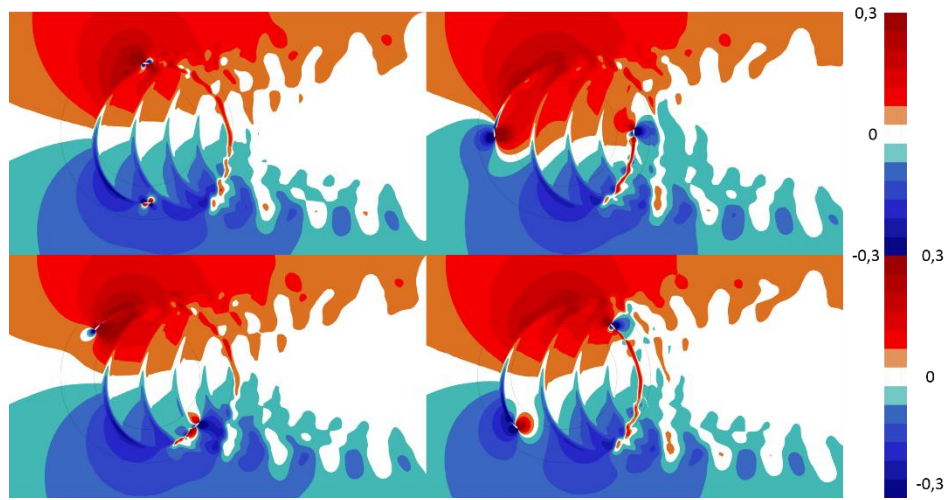


Figure 3.13 Normalized cross-stream velocity contours of different blade position while $\lambda=4$

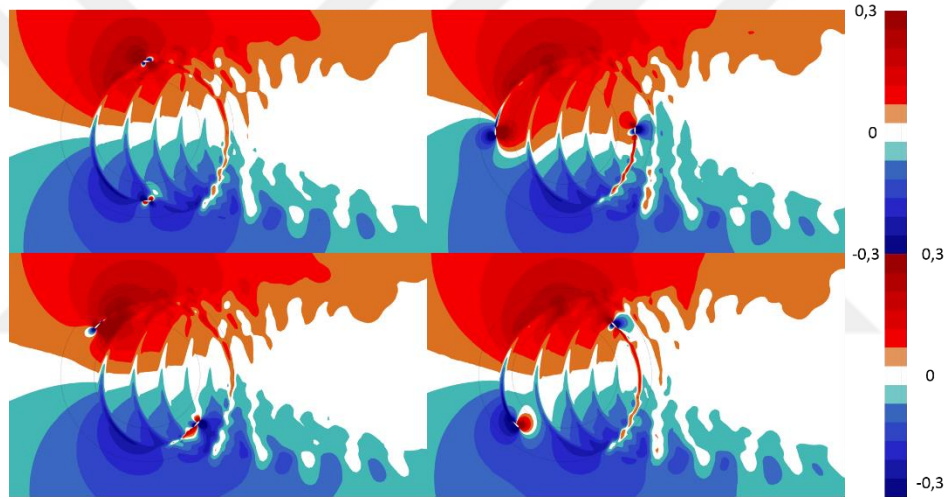


Figure 3.14 Normalized cross-stream velocity contours of different blade position while $\lambda=4.5$

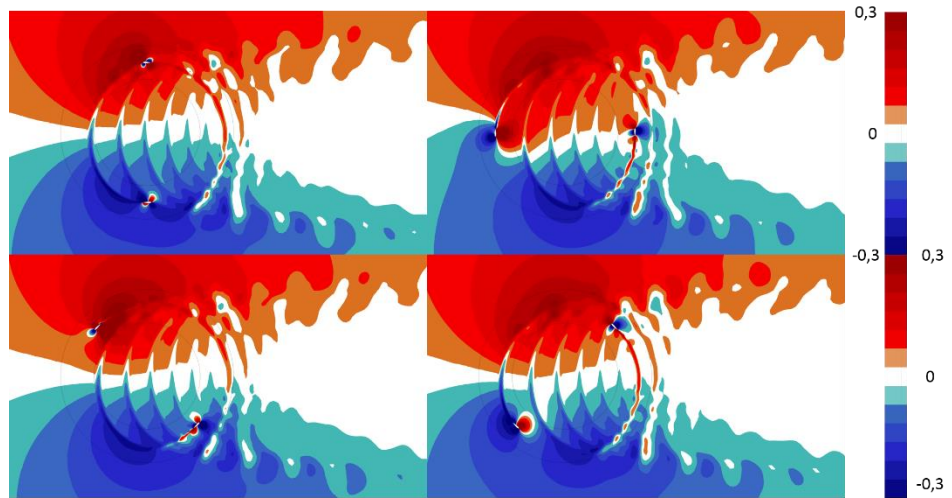


Figure 3.15 Normalized cross-stream velocity contours of different blade position while $\lambda=5$

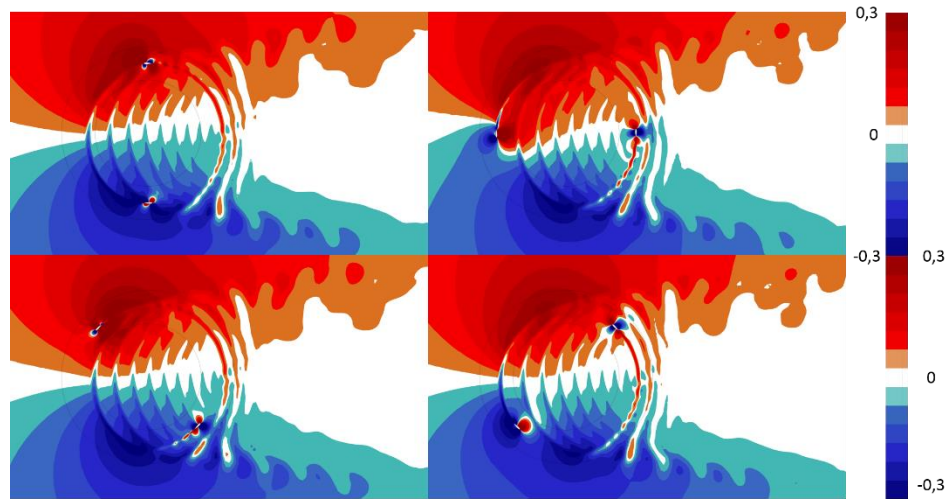


Figure 3.16 Normalized cross-stream velocity contours of different blade position while $\lambda=6$

Far wake characteristic of VAWT is an important factor for designing wind farm. It needs to be examined in depth, but uncertainty of two dimensional CFD limitations make it hard. On the other hand, reliable experimental results as PIV are not exist for far wake, so accurate interpretation of results is not possible. It could be compared only simulation results within themselves.

In Lam & Peng's study, all velocity data are obtained after 29th rotation by averaging one tour. As mentioned before there are two ways to change TSR, changing up coming velocity or changing rotational speed. In constant rotational velocity situation at TSR =3, turbine wakes reach to end of the domain in 29th rotation, but it must be needed more rotation especially 4 TSR and above. To obtaining more accurate velocities, simulations are maintained till turbine effect reached to the end of domain and all velocity data are obtained according to this situation. Because airflow goes slower forward in downstream as TSR increases and more time step is needed for stability . In Figure 3.17, it could be clearly seen that contours and wake profiles for 29th and 100th rotation at TSR of 4.5 are very incompatible. Farther than 6D, difference in velocity profiles become more and more. At 10D, velocity profiles are very different. In higher TSR's, velocity differences are started earlier as seen in Figure 3.18 and 3.19. More time should be passed for far wake stabilization. For TSR of 4, 4.5, 5 and 6, wake characteristics are ascendingly changed respectively after 9D, 8D, 6D and 4D distance in downwind and stabilization is especially critical for higher TSRs.

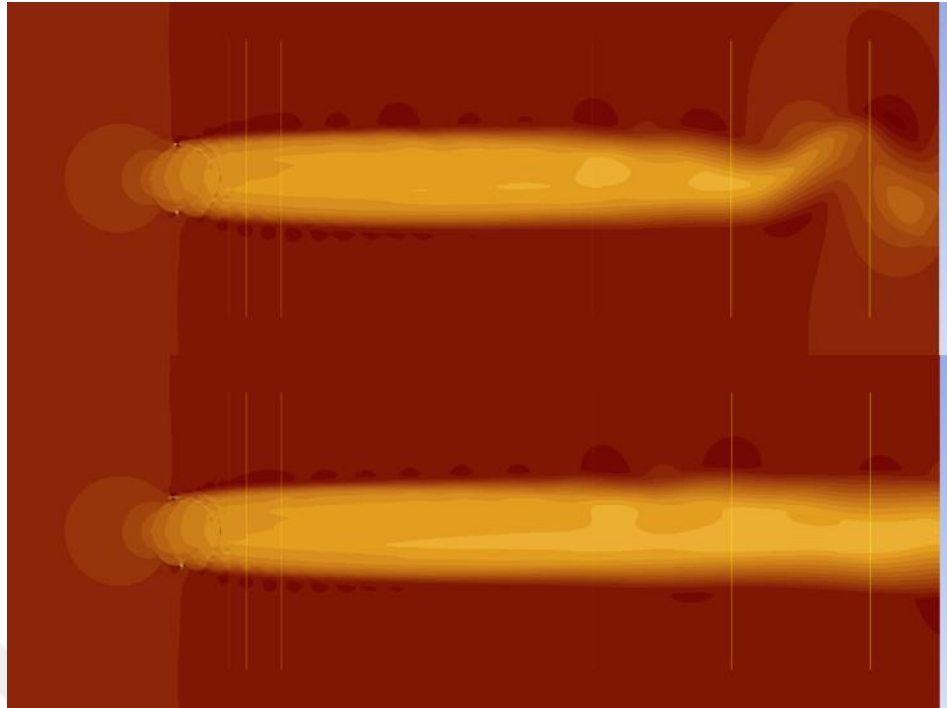


Figure 3.17 Wake charecteristic for 30th (top) and 100th (bottom) rotation of turbine (λ of 4.5) 2D CFD

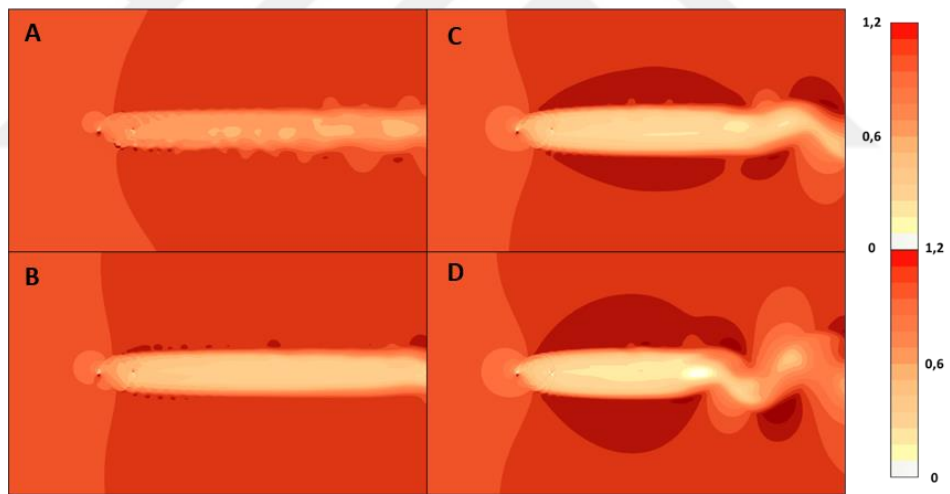


Figure 3.18 Comparison of far wake normalized stream-wise velocity contours at different λ 's (A: $\lambda=3$, B: $\lambda=4$, C: $\lambda=5$, D: $\lambda=6$)

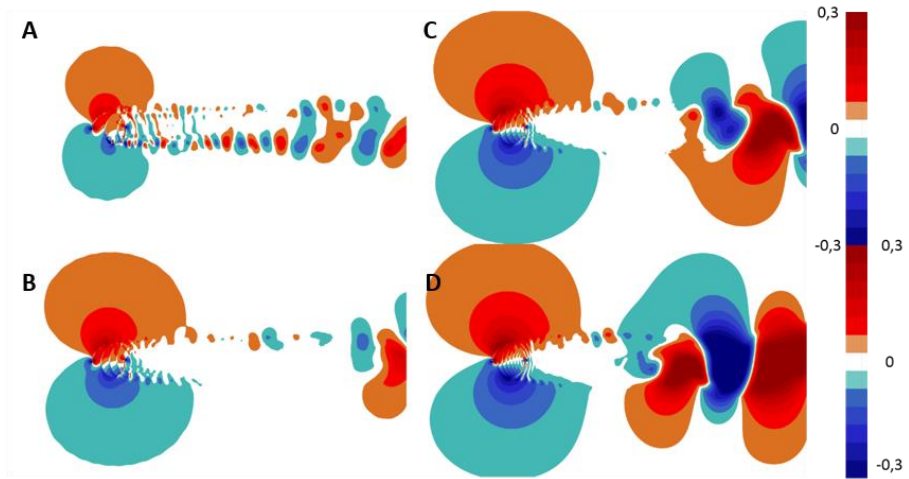


Figure 3.19 Comparison of far wake normalized cross-stream velocity contours at different λ 's (A: $\lambda=3$, B: $\lambda=4$, C: $\lambda=5$, D: $\lambda=6$)

On the other hand 3D CFD analysis show that after 25th revolution mid plane of the turbine far wake stabilized in $\lambda = 4.5$ (Figure 3.20). But far wake graphical data will not be given until another simulation completed with different λ because of tip vortex effects and lack of comparability. Near wake normalized stream-wise velocity distribution of 3D CFD simulation of the turbine is given in Figure 3.21. In near wake midspan plane normalized stream-wise velocity decreased with respect to 2D computation. In addition to that smoothness of the curve might counted as mesh independency in domain could not be accomplished.

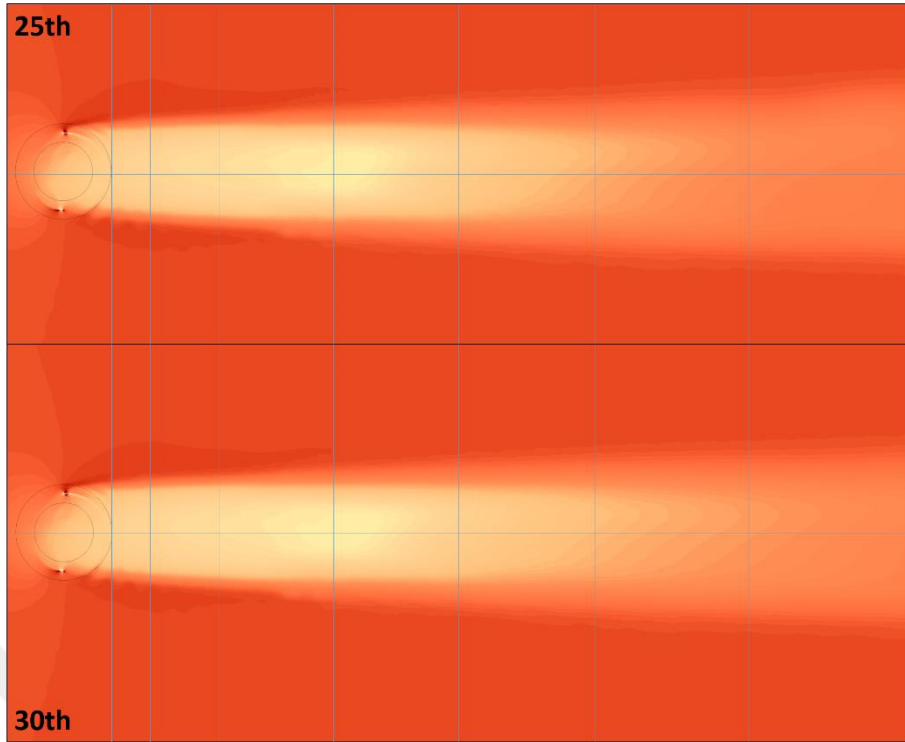


Figure 3.20 Wake characteristic of midplane of the turbine for 25th (top) and 30th (bottom) rotation of turbine (λ of 4.5) 3D CFD

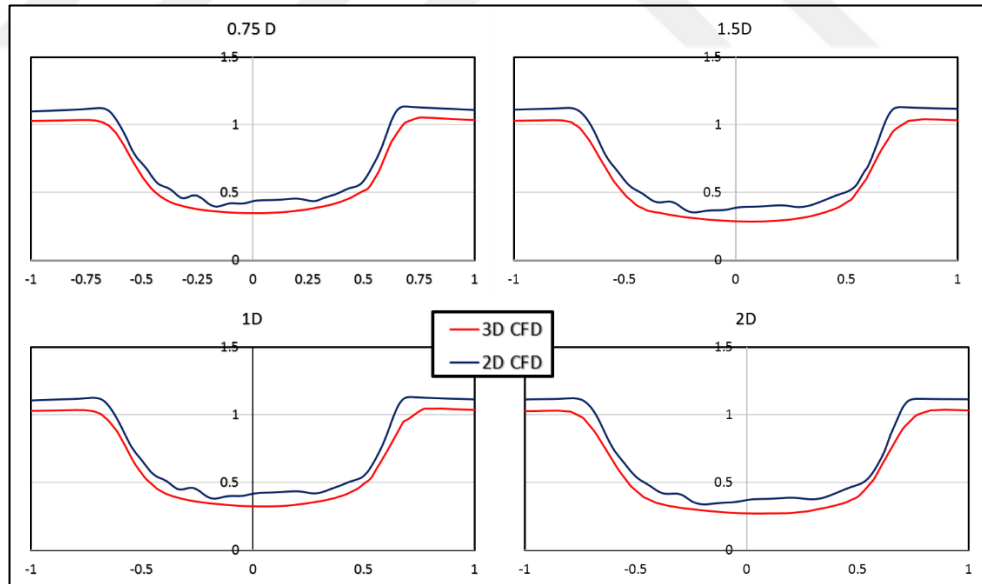


Figure 3.21 Comparison of normalized stream-wise velocity in near wake of midplane of the 3D turbine model and 2D model

3.2.2 Preliminary Results of Prototype Turbine Geometry

In this section preliminary results of 3D model of prototype turbine will be given. All of the 3D models could not reach mesh independency criteria. First two models had too basic mesh structures. As it is mentioned before 2D computations made with the mesh mentioned above. Two different blade structure compared one of them has blade concavity towards turbine center, other was in opposite direction. These two case simulated in different constant rotational speeds. Under those circumstances Reynolds number effect on a turbine shown in Figure 3.22. The aim of this study was to determine working range of prototype in simulation so data taken from rotating zone and in 10th revolution of the blade. Near wake flow on this circumstances and wake characteristics of diffirent situations show in Figure 3.23 and 3.24. Two contours in different Reynolds numbers look a like in terms of same λ .

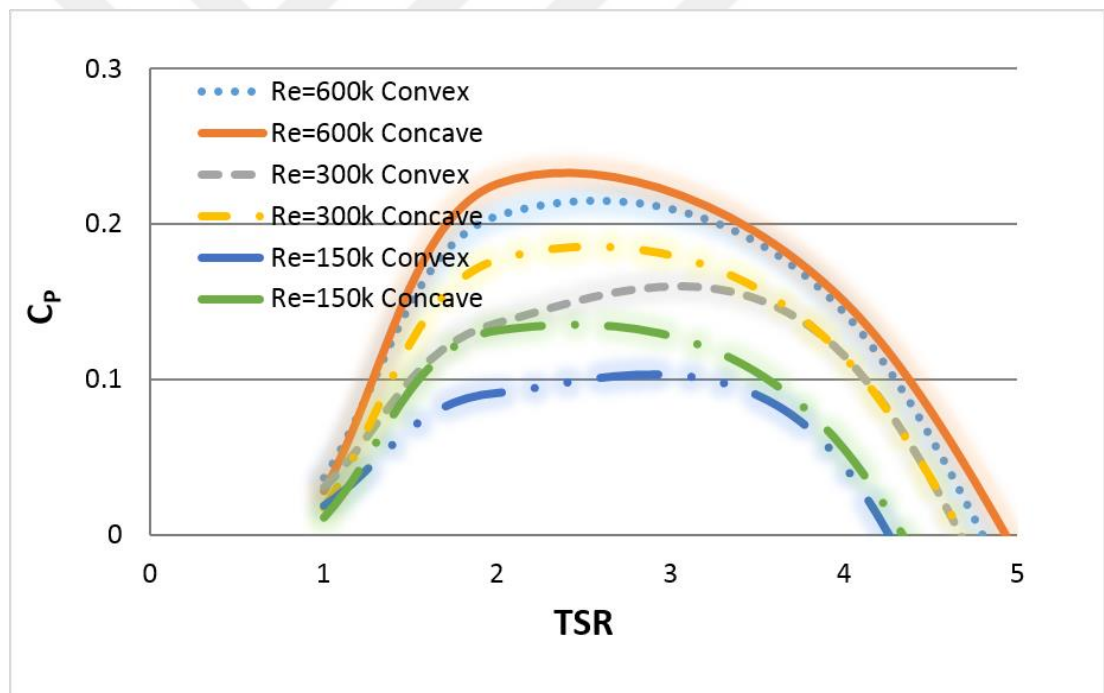


Figure 3.22 Comparison of C_p with respect to λ in $Re_C = 3 \times 10^5$ and $Re_C = 6 \times 10^5$ situation of concavity change of the blades

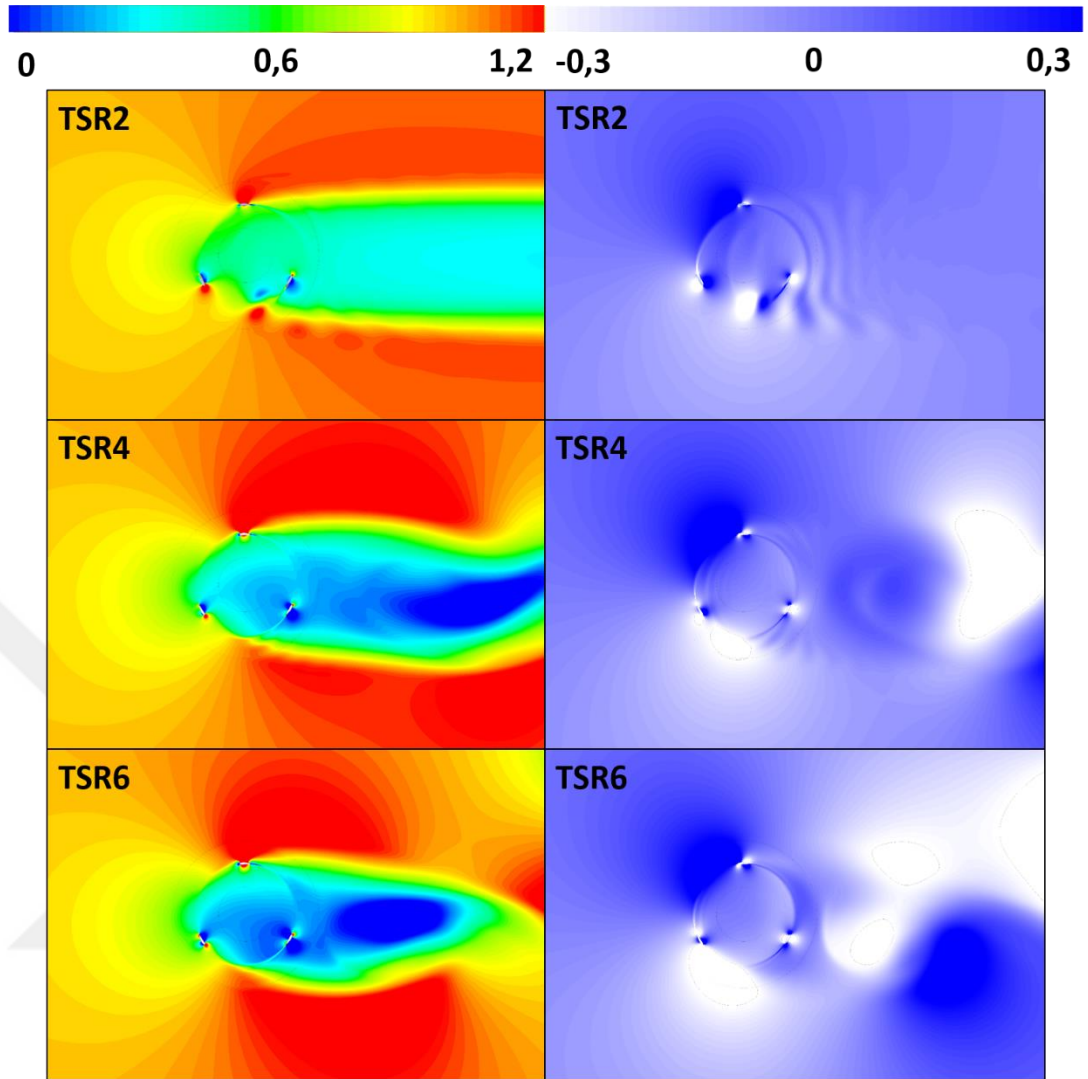


Figure 3.23 Comparison of near wake normalized stream-wise (left side) and cross-stream (right side) velocity contours at different λ 's at $Re_C = 6 \times 10^5$

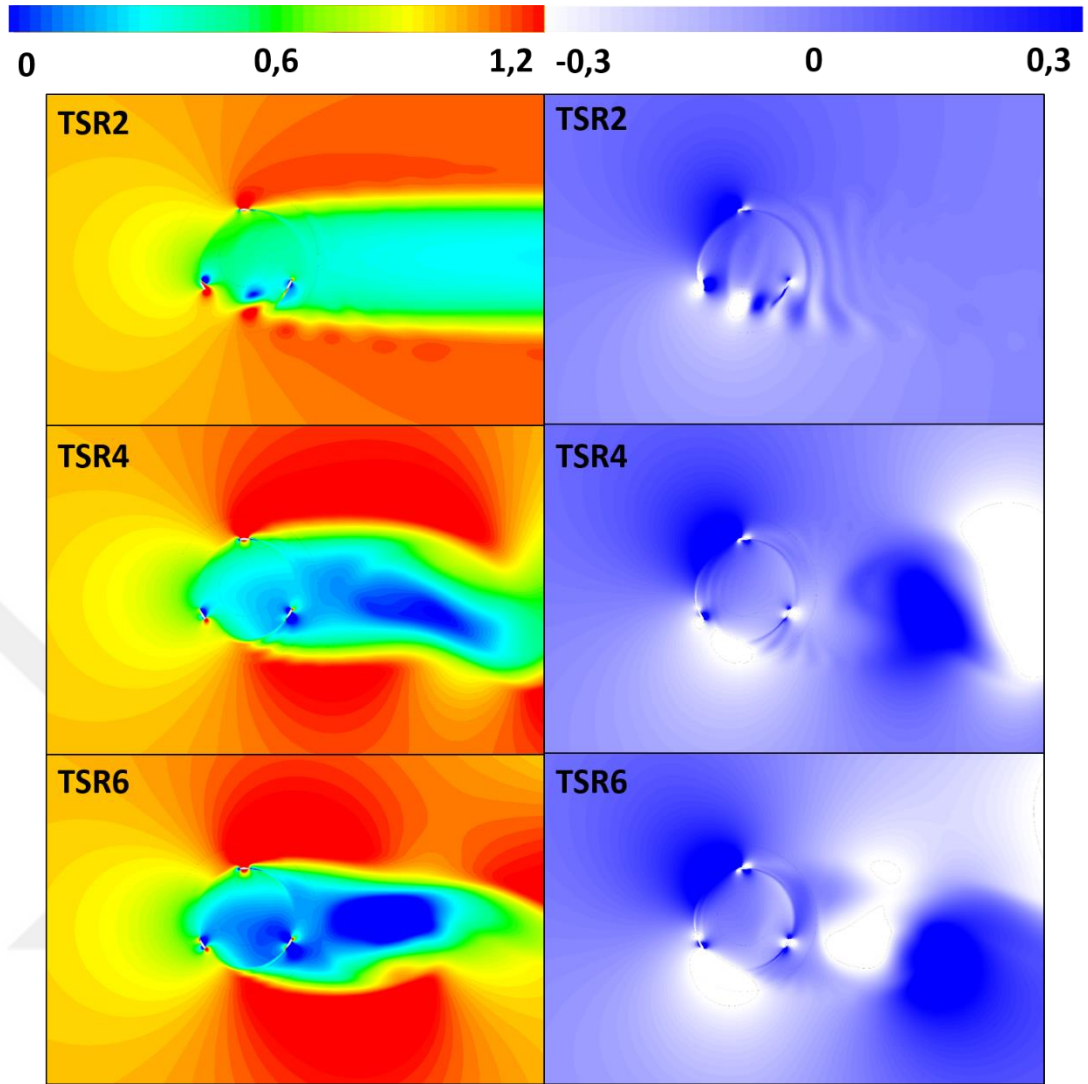


Figure 3.24 Comparison of near wake normalized stream-wise (left side) and cross-stream (right side) velocity contours at different λ 's at $Re_C = 3 \times 10^5$

CHAPTER FOUR

CONCLUSION AND FUTURE WORK

Vertical axis wind turbines draw significant interest due to new application areas and new concepts. In order to perceive turbine behavior, a lot of parameters should be taken into consideration. These parameters could be tested experimentally in wind tunnels or field. On the other hand with the help of computational analyzing produces and scientist will deal with this parameters more easily and economically. In this thesis a pattern was tried to consturct by using experimental and computational data to simulate another turbine. Mesh independency, time step size effect , and number of rotation as convergence criteria were dealt in reference 2D simulation and a prototype model was constructed for further analysis. First of all reference turbine behavior in different λ 's was examplified. As mentioned in previous studies every turbine has its optimal working range and for the reference turbine in 2D analysis it's between $\lambda=3$ and $\lambda=6$ for given Reynold number. Above this range dynamic stall occur and decrease the energy extraction, below this range revolutionary speed of the turbine makes it act like a bluff body. Between this range near sides of turbine affected positively in directional wind and negatively high turbulence.

The time-dependent Reynolds Averaged Navier Stokes equations in numerical analysis is used in the ANSYS-FLUENT packet program. Continuity and momentum equations is resolved SIMPLEC. Pre-analysis of the method to be used for solution of speed-pressure couple the convergence speed, accuracy and resolution time is determined. Turbulence model SST k- ω method is used, within the thesis in order carry out not only boundry layer interactions but also core region well.

In the scope of this thesis 2D and 3D modelling approaches is verified and compared with previous numerical and experimental studies. Furthermore, for a project which I take part, a different turbine is examined 2D and 3D in terms of performance in order to verify its working range and power coefficient.

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