

**FLOW-CONTROL OVER VERTICAL AXIS WIND
TURBINE BLADES FOR PERFORMANCE
ENHANCEMENT**

BY

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In

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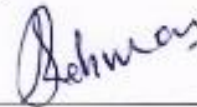
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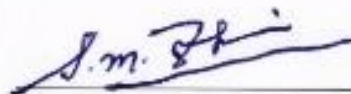
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Dedicated to the unwavering and unconditional love of my parents

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS.....	VII
LIST OF TABLES.....	X
LIST OF FIGURES.....	XI
LIST OF ABBREVIATIONS.....	XVI
ABSTRACT	XVIII
ملخص الرسالة	XX
CHAPTER 1 INTRODUCTION.....	1
1.1 Wind Turbines.....	2
1.1.1 Horizontal Axis Wind Turbines- (HAWTs).....	3
1.1.2 Vertical Axis Wind Turbines- (VAWTs)	4
1.1.3 Vortex Wind Turbines (VWTs)	6
1.2 Prospects of VAWTs	6
1.2.1 Advantages of VAWTs	7
1.2.2 Limitations of VAWTs	8
1.3 Problem Statement	9
1.3.1 Research Gap.....	10
1.3.2 Aims and Objectives	10
1.3.3 Limitations of this study	11
1.4 Thesis-Structure	12
CHAPTER 2 LITERATURE REVIEW	14
2.1 Aerodynamics of VAWT	14
2.1.1 Blade and Airfoil Nomenclature	15
2.1.2 Force and Moments on Airfoil.....	16

2.1.3	Airfoil Static Stall.....	17
2.1.4	Dynamic Stall in VAWT	18
2.2	Methods and Models Used to Analyse VAWTs	21
2.2.1	Computational Aerodynamic Models.....	22
2.2.2	Computational Fluid Dynamics.....	27
2.2.3	Experimental and Field Testing.....	35
2.3	Flow-control Techniques to Enhance Performance of VAWTs	37
2.3.1	Active Flow control Devices.....	38
2.3.2	Passive Flow-control Devices.....	40
CHAPTER 3	AERODYNAMIC DESIGN OF A VAWT.....	45
3.1	Wind Data at Dhahran	45
3.2	Wind Tunnel Testing of Airfoils	48
3.2.1	Wind Tunnel Testing Setup.....	49
3.2.2	Static Testing	52
3.2.3	Dynamic Testing	59
3.3	Preliminary Design Using Q-Blade	64
3.3.1	Airfoil Selection and its Polar Data	65
3.3.2	Performance Evaluation	67
3.4	Detailed Design Using ANSYS FLUENT	68
3.4.1	Validation of CFD Model.....	69
3.4.2	Mesh and Turbulence Model Independence.....	71
3.4.3	Wind Turbine Design Parameters.....	77
CHAPTER 4	EXPERIMENTAL TESTING OF WIND TURBINE.....	82
4.1	Manufacturing of Wind Turbine	83
4.1.1	Turbine Blades	83
4.1.2	Central Shaft and Struts.....	84
4.1.3	Generator	84
4.1.4	Wind Turbine Base.....	85
4.1.5	Wind Turbine Assembly.....	86

4.2	Experimental Setup and Data Logging	87
4.3	Experimental Results	88
4.3.1	Lab Testing with Open-Jet	89
4.3.2	Field Testing at Rooftop	92
4.4	Comparison of Analytical, Numerical, and Experimental Results	95
CHAPTER 5 POWER ENHANCEMENT USING FLOW-CONTROL.....		97
5.1	Numerical Model Validation	98
5.2	VAWT with a Leading Edge Cylinder (LEC).....	101
5.2.1	Effect of Leading Edge Cylinder Diameter	102
5.2.2	Effect of Leading Edge Cylinder Spacing.....	103
5.2.3	Optimized Leading Edge Cylinder	104
5.3	Effect of LEC on Flow Field	105
CHAPTER 6 CONCLUSION.....		112
REFERENCES.....		116
CURRICULUM VITAE.....		126

LIST OF TABLES

Table 2.1 Summary of findings on GF for VAWTs	42
Table 3.1 Uncertainty of measured quantities	52
Table 3.2 Geometric parameters of vertical-axis wind turbine.....	69
Table 3.3 Mesh characteristics for independence study	73
Table 3.4 Wind Turbine Design Space	78
Table 3.5 Final Design Parameters for the Wind Turbine	81
Table 5.1 Maximum C_p for VAWTs with LEC	104

LIST OF FIGURES

Figure 1.1 Overall contribution of Wind Power Capacity	2
Figure 1.2 a) Horizontal axis, b) Vertical-axis and c) Vortex wind turbines.....	3
Figure 1.3 a) Darrieus, b) Savonius, and c) Straight-bladed VAWT rotors [12].....	5
Figure 2.1 Airfoil a) Nomenclature and b) aerodynamic forces and moment [24]	15
Figure 2.2 Geometric parameters of a VAWT [25]	16
Figure 2.3 Static airfoil stall [27]	18
Figure 2.4 Velocity vectors for turbine blade during one revolution	19
Figure 2.5 AOA Variation with azimuthal position at various TSRs	20
Figure 2.6 Actuator disk placed in a stream tube [31]	23
Figure 2.7 Single Stream tube model for VAWT [31]	24
Figure 2.8 Multiple stream model [39]	25
Figure 2.9 Cascade Model for VAWT [42]	26
Figure 2.10 Typical CFD domain for a) 2D, b) 2.5D, and c) 3D simulation [54]	29
Figure 2.11 Comparison of 2D and 3D CFD in terms of VAWT C_p [59]	30
Figure 2.12 Comparison of 2D, 2.5D, and 3D CFD models [54]	32
Figure 2.13 low visualization of dynamic stall on a straight bladed VAWT [78]	37
Figure 2.14 Comparison of fixed and variable pitch blade orientation [70]	38
Figure 2.15 Performance of fixed pitch compared to variable pitch VAWT [70]	39
Figure 2.16 Moment coefficient of VAWT during half-revolution [102]	40
Figure 2.17 HAWT blade with micro cylinder [104]	41

Figure 2.18 a) Leading edge slot and b) its effect on HAWT performance [105].....	42
Figure 2.19 Separation delay due to gurney flap [106]	43
Figure 2.20 Leading edge serrations [110]	44
Figure 2.21 a) VAWT with J-blade, and b) its effect on turbine performance [111]	44
Figure 3.1 Wind speed (a) directional and (b) hourly averaged frequencies	46
Figure 3.2 Geographic locations of Site-A and Site-B	47
Figure 3.3 Monthly wind (a) speed and (b) power density at two locations	48
Figure 3.4 Schematic of the wind tunnel	49
Figure 3.5 NACA 0012 and NACA 0022 models during wind tunnel testing.....	50
Figure 3.6 Servo motor drive system for airfoil pitching motion control.....	51
Figure 3.7 a) Lift and b) drag coefficient for NACA 0012.....	53
Figure 3.8 Moment coefficient for NACA 0012	53
Figure 3.9 Lift (left) and Drag (right) coefficients for NACA 0022	55
Figure 3.10 Pitching moment coefficient for NACA 0022 airfoil.....	56
Figure 3.11 Lift Coefficient of NACA 0022 at different Reynold Numbers.....	58
Figure 3.12 Drag Coefficient of NACA 0022 at different Reynold Numbers.....	58
Figure 3.13 Moment Coefficient of NACA 0022 at different Reynold Numbers	58
Figure 3.14 Variation of lift (left) and drag (right) coefficients for $\alpha=10^\circ+15^\circ\sin\omega t$	60
Figure 3.15 Variation of pitching moment coefficient during oscillation	60
Figure 3.16 Lift (left) and drag (right) coefficients for $\alpha(t)= 0^\circ +15^\circ \sin\omega t$	61
Figure 3.17 Moment coefficient for $\alpha(t)= 0^\circ +15^\circ \sin\omega t$	61
Figure 3.18 Dynamic lift coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$	63

Figure 3.19 Dynamic drag coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$	63
Figure 3.20 Dynamic moment coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$	63
Figure 3.21 Five airfoils with their polars	66
Figure 3.22 Preliminary Design of Wind Turbine	66
Figure 3.23 Power and Thrust coefficient variation with TSR.....	67
Figure 3.24 a) Preliminary design and b) vortex shedding from the VAWT	68
Figure 3.25 Computational Domain and boundary conditions	70
Figure 3.26 Comparison of fine, medium and coarse mesh densities	72
Figure 3.27 Medium mesh density variation near blades	73
Figure 3.28 C_p Variation with azimuthal position for mesh independence	73
Figure 3.29 Turbulence Model Independence	75
Figure 3.30 Flow field comparison at $\lambda=4$ from CFD, PIV and current study	76
Figure 3.31 Vorticity distribution around blades at different azimuthal angle positions .	76
Figure 3.32 VAWT with Different Blade a) Radii, b) Heights, and c) Chords	78
Figure 3.33 VAWT Geometries with Different Number of Blades.....	78
Figure 3.34 Effect of a) Blade Chord and b) Rotor Radius on Power Coefficient	79
Figure 3.35 Effect of a) Number of Blades and their b) Height on Power Coefficient	80
Figure 4.1 Turbine Blade	83
Figure 4.2 Central Shaft and Support Struts	84
Figure 4.3 Three Phase 600-W Electric Generator	85
Figure 4.4 CAD Model of Turbine Base and Mounting Flange	85
Figure 4.5 Wind Turbine Assembly.....	86

Figure 4.6 Block Diagram of the Experimental Setup and its Components	88
Figure 4.7 a) Velocity Profile and b) Turbulent Intensity for Open Jet.....	90
Figure 4.8 a) Starting RPM and b) Power Production of Wind Turbine	91
Figure 4.9 Power Coefficient of VAWT at different Reynold Numbers.....	92
Figure 4.10 Wind speed and turbine power during a day with typical wind	93
Figure 4.11 Wind speed and turbine power during a day with low wind	93
Figure 4.12 Wind speed and turbine power during a day with high wind.....	94
Figure 4.13 Comparison of Different Power Prediction Techniques	95
Figure 5.1 a) 2D and b) 2.5D CFD Domains.....	99
Figure 5.2 Validation results from different CFD formulations	100
Figure 5.3 VAWT blade cross-section with a Leading Edge Cylinder	101
Figure 5.4 Mesh around the a) Blades and b) Leading Edge Cylinder	101
Figure 5.5 Effect of LEC diameter on turbine's performance	102
Figure 5.6 Effect of LEC spacing on turbine's performance.....	103
Figure 5.7 Z-vorticity around blades and LEC at 0° azimuthal angle.....	106
Figure 5.8 Z-vorticity around blades and LEC at 60° azimuthal angle.....	106
Figure 5.9 Z-vorticity around blades and LEC at 120° azimuthal angle.....	107
Figure 5.10 Z-vorticity around blades and LEC at 180° azimuthal angle.....	107
Figure 5.11 Z-vorticity around blades and LEC at 240° azimuthal angle.....	107
Figure 5.12 Z-vorticity around blades and LEC at 300° azimuthal angle.....	108
Figure 5.13 Pressure around blades and LEC at 0° azimuthal angle	109
Figure 5.14 Pressure around blades and LEC at 60° azimuthal angle	109

Figure 5.15 Pressure around blades and LEC at 120° azimuthal angle	109
Figure 5.16 Pressure around blades and LEC at 180° azimuthal angle	110
Figure 5.17 Pressure around blades and LEC at 240° azimuthal angle	110
Figure 5.18 Pressure around blades and LEC at 300° azimuthal angle	110

LIST OF ABBREVIATIONS

AOA	:	Angle of Attack
CFD	:	Computational Fluid Dynamics
COP	:	Centre of Pressure
DES	:	Detached Eddy Simulation
DMS	:	Double Multiple Streamtube
DMST	:	Double Multi Stream Tube
GF	:	Gurney Flap
HAWTs	:	Horizontal Axis Wind Turbines
ISFH	:	Institute for Solar Energy Research in Hamelin
KFUPM	:	King Fahd University of Petroleum and Minerals
LEC	:	Leading Edge Cylinder
LES	:	Large Eddy Simulation
MPPT	:	Maximum Power Point Tracking
NI	:	National Instruments

PIV	:	Particle Image Velocimetry
RANS	:	Reynolds Averaged Navier Stokes
RSM	:	Reynolds Stress Model
SA	:	Spalart Allmaras
SIMPLE	:	Semi Implicit Method for Pressure Linked Equations
S-PIV	:	Stereoscopic PIV
SST	:	Shear Stress Transport
SST LRe	:	SST with number correction
TEV	:	Trailing Edge Vortex
TI	:	Turbulence Intensity
TSR	:	Tip Speed Ratio
URANS	:	Unsteady RANS
VAWT	:	Vertical Axis Wind Turbine
VIV	:	vortex induced vibration
VWTs	:	Vortex Wind Turbines

ABSTRACT

Full Name : Zakria Ghazanfar Toor

Thesis Title : Flow-control Over Vertical Axis Wind Turbine Blades for Performance Enhancement

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Formidable renewable energy source like wind energy are essential to reduce our reliance on fossil fuels and mitigate the threat of carbon emissions to the environment. However, Vertical Axis Wind Turbines (VAWTs) have traditionally been less efficient than Horizontal Axis Wind Turbines (HAWTs). This thesis presents a novel flow-control device to improve the efficiency of VAWTs. In addition, a comprehensive roadmap for designing an efficient VAWT based on local wind conditions is also developed. The aerodynamics of VAWT blade were analyzed using analytical, numerical, and experimental methods to propose a passive flow-control device for enhancing their performance. An accurate knowledge of the aerodynamic behavior of the blade section is necessary to design efficient VAWT blades. The aerodynamic polars of the NACA 0022 airfoil were obtained through static and dynamic wind tunnel testing, which showed it to be superior to other airfoils due to its better stall characteristics and higher moment. The wind turbine design process was established by analyzing the wind data for Dhahran to determine the design requirements. A preliminary design was carried out using analytical methods, and the detailed design was

performed using Computational Fluid Dynamics (CFD). The effect of blade height, blade chord length, number of blades, and rotor diameter were investigated, and a 3-bladed VAWT with a blade length of 1m and a chord length of 0.2m was found to be optimal for the local wind conditions. The wind turbine was fabricated and subjected to laboratory and field testing. The laboratory testing provided a performance baseline for validating numerical techniques, while the field testing evaluated the turbine's starting and operational characteristics in real-world conditions. In addition, a novel flow-control device, the Leading Edge Cylinder (LEC), was proposed and analyzed for its optimum size and placement. It was found that LECs can delay stall onset and improve the performance of VAWTs by up to 13%. The proposed comprehensive design process and passive flow-control device can be adapted to different locations and wind conditions, thus advancing the design and performance of VAWTs.

ملخص الرسالة

الاسم الكامل: زكريا غضنفرطور

عنوان الرسالة: التحكم في التدفق فوق شفرات التوربينات ذات المحور الرأسي لتحسين الأداء

التخصص: السوائل الحرارية

تاريخ الدرجة العلمية: مايو ٢٠٢٣م

يعد مصدر الطاقة المتجددة الهائل مثل طاقة الرياح ضروريا لتقليل اعتمادنا على الوقود الأحفوري والتخفيف من خطر انبعاثات الكربون على البيئة. ومع ذلك ، فإن توربينات الرياح ذات المحور الرأسي كانت تقليديا أقل كفاءة من توربينات الرياح ذات المحور الأفقي. تقدم هذه الأطروحة جهازا جديدا للتحكم في التدفق لتحسين كفاءة. بالإضافة إلى ذلك ، تم أيضا تطوير خارطة طريق شاملة لتصميم فعال يعتمد على ظروف الرياح المحلية. تم تحليل الديناميكا الهوائية لشفرة باستخدام الطرق التحليلية والرقمية والتجريبية لاقتراح جهاز تحكم سلبي في التدفق لتحسين أدائها. تعد المعرفة الدقيقة بالسلوك الديناميكي الهوائي لقسم الشفرة أمرا ضروريا لتصميم شفرات فعالة. تم الحصول على القطبين الديناميكيين الهوائي للجناح NACA 0022 من خلال اختبار نفق الرياح الثابت والديناميكي ، والذي أظهر أنه متفوق على الجنيحات الأخرى نظرا لخصائصه الأفضل في الكشف ولحظته الأعلى. تم إنشاء عملية تصميم توربينات الرياح من خلال تحليل بيانات الرياح الخاصة بالظهران لتحديد متطلبات التصميم. تم تنفيذ التصميم الأولي باستخدام الأساليب التحليلية ، وتم تنفيذ التصميم التفصيلي باستخدام ديناميكيات السوائل الحسابية. تم فحص تأثير ارتفاع الشفرة ، وطول وتر النصل ، وعدد الشفرات ، وقطر الجزء المتحرك ، ووجد أن ذات 3 شفرات بطول 1 متر وطول الوتر 0.2 متر هي الأمثل لظروف الرياح المحلية. تم تصنيع توربينات الرياح واختبارها معمليا وميدانيا. قدمت الاختبارات العملية أساسا للأداء للتحقق من صحة التقنيات العددية ، بينما قام الاختبار الميداني بتقييم خصائص بدء التوربين وتشغيله في

ظروف العالم الحقيقي. بالإضافة إلى ذلك ، تم اقتراح جهاز جديد للتحكم في التدفق ، وهو الأسطوانة الرائدة ، وتحليله لحجمه وموضعه الأمثل. تم العثور على أن LECS يمكنها تأخير بدء المماطلة وتحسين أداء VAWTs بنسبة تصل إلى 13٪. يمكن تكييف عملية التصميم الشاملة المقترحة وجهاز التحكم السلبي في التدفق مع المواقع المختلفة وظروف الرياح ، وبالتالي تطوير تصميم وأداء.

CHAPTER 1

INTRODUCTION

Carbon emission and climate change are major growing concerns and have led researchers across the globe to look for alternate and renewable energy resources [1]. Electricity with 8,000 terawatt-hours amounts to 40% of global energy use. Meanwhile also producing ten gigatonnes of carbon dioxide each year [2]. While renewable energy has a great potential to reduce carbon emissions and global dependency on depleting fossil fuel resources [3], there are still some concerns like efficiency, cost, intermittency, and stochastic characteristic [4]. Renewable resources contribute about 26.5% of global power production [2]. Among all the available renewable energy resources, including wind, solar, biomass, and ocean, wind energy has an advantage due to its round-the-clock accessibility, negligible emissions, and sustained availability [5], [6]. Wind energy contribution was approximately 4-6% of the entire energy production around the globe in 2018 [7]. Wind-based power production is expected to contribute about 20% and 35% of the world's power consumption in 2030 and 2050, respectively [8]. In 2020, the global wind power installed capacity reached 744 GW. A trend over the last decade in global wind power installed capacities is shown in Figure 1.1. 2020 saw a remarkable 14% increase in wind power production compared to 2019. Hence, the world is getting more acquainted with wind energy conversion systems for power production.

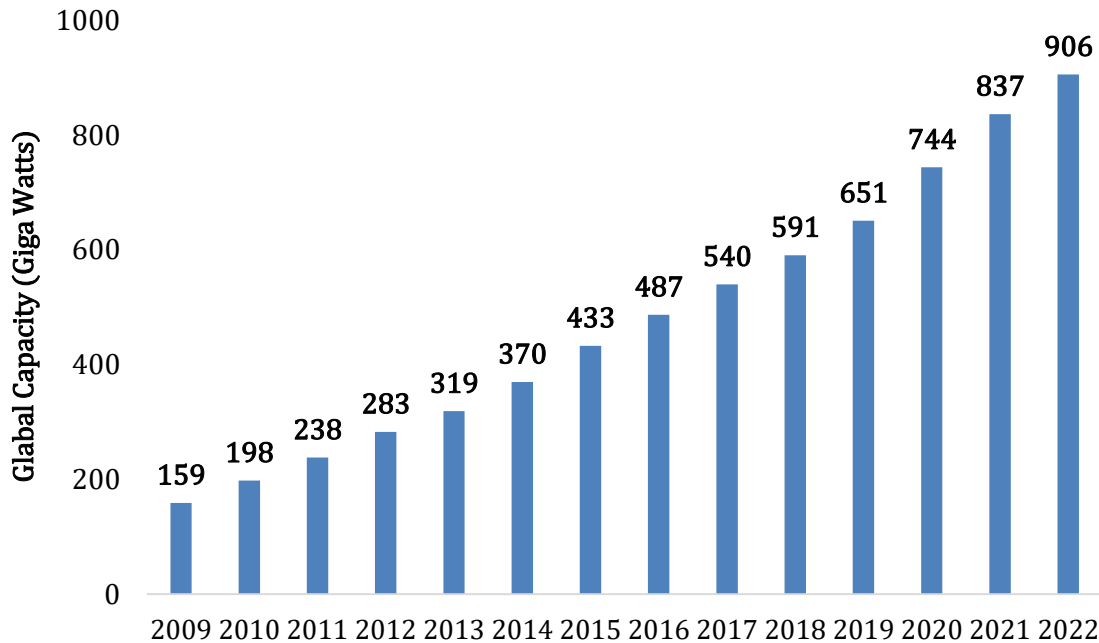


Figure 1.1 Overall contribution of Wind Power Capacity

1.1 Wind Turbines

Winds are caused due to atmospheric changes such as differentials in temperatures and pressure and the movement of the earth. The sun triggers all of these changes; hence, wind energy can be attributed as an alternate solar energy. The power contained in the wind is extracted by wind turbines in the form of mechanical rotational energy. When the wind moves over the turbine blade surfaces, flow accelerates over one side of the blade resulting in relatively lower pressure. This low-pressure region creates suction that pulls the blade and provides turbine rotation. This force, termed the lift, is greater than the wind force acting against the front of the blade called the drag. The compound effect of these forces rotates the turbine rotor. The gearbox containing a series of gears increases the rotational speed by a factor of around 100. This generated moment powers the generator to produce AC electricity. The electricity, so produced, is stepped up using transformers and then fed

to the transmission line for end users through several controls and transmission mechanisms. Wind turbines can be divided into Horizontal Axis, Vertical Axis, and Vortex Wind Turbines, as seen in Figure 1.2.

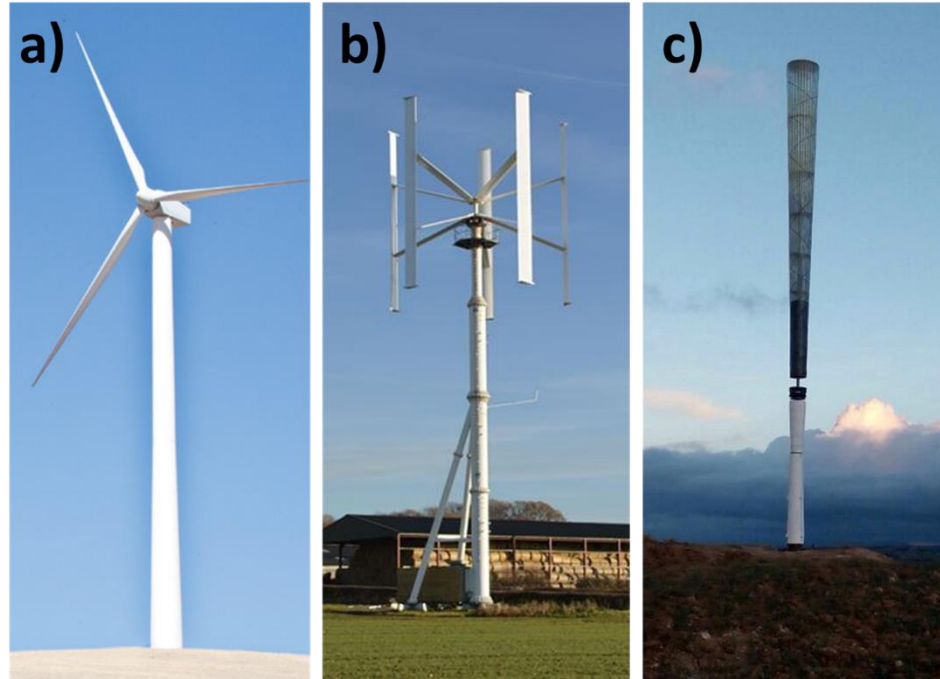


Figure 1.2 a) Horizontal axis, b) Vertical-axis and c) Vortex wind turbines

1.1.1 Horizontal Axis Wind Turbines (HAWTs)

The turbines with their rotational axis along the wind direction are called Horizontal axis wind turbines. Wind flow over the blades generates lift that turns the blade and provides a moment. HAWTs are the widely accepted choice of wind turbines for commercial projects. Their research and development have received more financial assistance [9] since it offers greater efficiency than VAWTs owing to their design allowing energy extraction through the complete rotation of the blades [9]. However, HAWT design requires the turbine direction always pointed toward the incoming wind to produce optimum power. The nature of wind in terms of its direction and velocity is stochastic which requires dedicated

mechanism to rotate and direct the wind turbine towards the incoming wind to work efficiently. Small wind turbines can solve the problem using a simple rudder-like mechanism to provide yaw control of the turbine that positions itself towards the wind direction. Commercial-scale wind turbines need a steering mechanism that accurately determines the incoming wind direction and positions the turbine towards the wind [10]. Some additional concerns pertaining to HAWTs include higher noise, complicated maintenance with a higher failure rate, and higher starting / rated wind speeds.

1.1.2 Vertical Axis Wind Turbines (VAWTs)

VAWTs are turbines whose rotational axis is set normal to the direction of the wind. The main shaft of the rotor, which is along the rotational axis drives a generator through gearboxes or in some cases, directly driven generators. This allows the gearbox and generator assembly to be placed much closer to the ground allowing ease of installation and maintenance. While many configurations are possible, the VAWTs classification can be done depending on the power extraction mechanism. These are Savonius, Darrieus, and H-type rotors shown in Figure 1.3.

Savonius turbine is a configuration where rotation is achieved by the change in momentum between incoming air and the paddle. Hence this is a drag-based turbine and generally utilizes cup-type designs to maximize the drag when facing the wind during its rotation [11]. Its operation is characterized by very low starting speeds, making it appropriate for areas with low wind speeds. However, its efficiency tends to reduce significantly with increase in wind velocity. This wind turbine is particularly useful for areas with low wind speeds and applications where wind turbine is to be installed at a lower height.

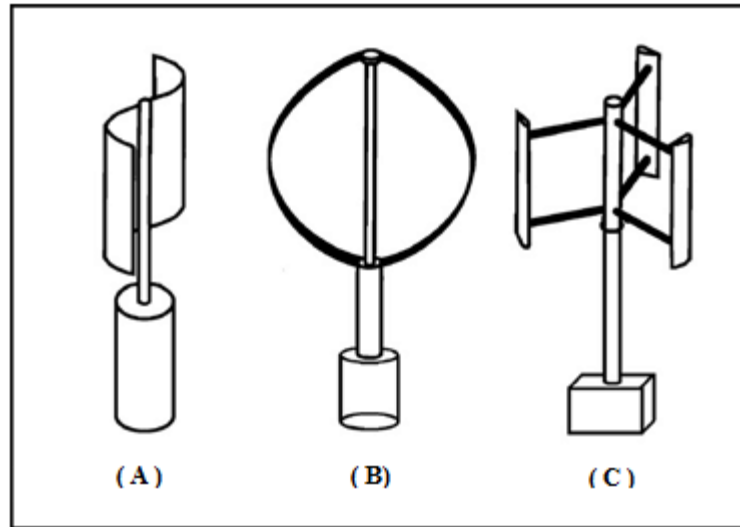


Figure 1.3 a) Darrieus, b) Savonius, and c) Straight-bladed VAWT rotors [12]

Darrieus turbine is a pressure-based configuration where rotation is achieved due to the pressure difference between the blade's upper surface and the lower surface. Hence this is a lift-based turbine with blades shaped like aircraft wing airfoils to maximize the lift [11]. Turbine blades have a curved shape that makes the blade more robust against the centrifugal load generated during rotation and minimizes the bending loads act the blade. An inherent drawback of this configuration is the decreasing diameter of the rotor blade near the ends of the wind turbine generating less aerodynamic moment due to lower blade velocity. Therefore, these turbines are appropriate for low to moderate wind speeds.

Musgrove [13] suggested that the ideal orientation for blades is straight and set perpendicularly to the wind to maximize the aerodynamic efficiency, also called straight-bladed H-type rotor configuration. Moreover, the straight-bladed turbine offers a simplistic design that is simpler and more inexpensive to manufacture than other VAWT configurations [14]. HAWTs with straight blades also assist in better self-start capability

than other VAWTs [15]. However, the blades need additional attachment, called struts, to join the blades to a central shaft, a complexity that can be improved in the Darrieus turbine.

1.1.3 Vortex Wind Turbines (VWTs)

The vortex-induced vibration and galloping of cylindrical structures served as the inspiration for the revolutionary design of the vortex wind turbine. This innovative wind turbine is known as a "bladeless vortex wind turbine" because its operation relies on vortex-induced vibration (VIV) and lacks revolving blades. This innovative wind turbine design has the distinct advantages of being light, ecologically benign, simple to maintain, free of mechanical motion, and having a compact footprint when compared to conventional horizontal- or vertical-axis wind turbines. Most importantly, by eliminating pricey mechanical components like wind turbine blades, gears, and gearboxes, the production cost is dramatically decreased. The bladeless vortex turbines are expected to ensure energy conversion efficiency of roughly 70% [16]. The fact that this device uses cutting-edge technology to capture energy from an aero-elastic oscillation movement is one of its most evident selling advantages.

1.2 Prospects of VAWTs

The versatility and scalability of VAWTs make them a viable choice for a wide range of onshore and offshore applications. Onshore, VAWTs can be used in agricultural settings to power irrigation systems or rural areas to provide off-grid power for homes or villages. They can also be installed on highways or in urban areas as streetlights, providing a sustainable energy source for lighting. Offshore, VAWTs could be an important source of

alternative energy in the future. They may be installed in deep waters and coastal areas where wind speeds are high and consistent, making them ideal for offshore wind farms. In addition, VAWTs can be used with HAWTs in large wind farms to provide a more diverse energy mix. They can also be used in small-scale offshore installations for oil rigs, providing an alternative power source and reducing reliance on fossil fuels. Another potential application for VAWTs is in disaster relief efforts. In areas affected by natural disasters, VAWTs can be deployed quickly to provide emergency power for hospitals, relief centers, and communication systems. As the technology continues to improve and become more cost-effective, we will see more VAWTs being deployed in various settings to provide sustainable energy solutions.

1.2.1 Advantages of VAWTs

A VAWT is omnidirectional and can operate against the wind from all directions, eradicating the requirement for an additional yaw control system compared to a HAWT. Hence it has a broader range of geographic locations for installation, such as areas with time-varying wind direction and speed. It makes VAWT especially useful for operation in urban environments where it can be integrated on top of existing buildings and structures [17].

At the base of the main shaft, the generator for the VAWT is located, allowing easy access for maintenance. The generator can be designed focusing on its efficiency without considering space requirements since the main shaft does not support a generator at the top. Moreover, lower generator placement provides a lower center of gravity which is more convenient in floating and off-shore applications. A generator with direct drive can also be

integrated since there is no limitation on generator size. as in the HAWT, which requires a nacelle for generator placement. These mechanical and structural design concerns allow easy access for scheduled and unscheduled [18].

Blades of a VAWT are supported using struts which can vary in number based on the turbine size. Whereas, the blade of a HAWT is supported at one end, resulting in higher deflection of the tip and makes it more susceptible to fatigue failures. Therefore, VAWTs are less prone to failure as compared to HAWTs. HAWTs can self-start, even at lower wind velocities, while VAWTs may require additional equipment and assistance to acquire their design rotational speeds. Most HAWTs employ pitch control of blades for power regulation, which is not required in Darrieus turbines. Therefore, VAWTS tend to be self-limiting regarding maximum power generation at optimal operating conditions [19].

Noise generated from a VAWT is generally lower than HAWT, due to its generator placement and lower rotational speeds. The lower operational rotational speed, lower Tip Speed Ratio (TSR) than that of a HAWT, and the lower placement of the generator near the ground allows less space for the sound to travel [20].

1.2.2 Limitations of VAWTs

Despite these advantages, the efficiency of VAWTs is lower compared to HAWTs, which remains a primary concern. Researchers across the globe are putting in concerted efforts to improve the efficiency of VAWTs, which would lower the power production cost and contribute to the broader adoption of VAWTs, in the form of individual units as well as farms, especially in an urban environment. However, the scarcity of life operational data

and robust analytical tools for vertical-axis wind turbines have slowed their mass adaption for power generation. The manufacturing facilities are limited to a few countries outside Europe, including China and USA. Even the available manufacturing capabilities are restricted to low-scale productions. The cost is expected to further reduce for VAWTs as technology improves and manufacturing shifts to a larger scale. A review of vertical-axis wind turbines by Kumar [21] concluded that technological advancement in technology and manufacturing processes of VAWTs is vital to make them a dependable and economically viable power solution for remote and low-demand areas.

1.3 Problem Statement

VAWT has numerous advantages and excellent prospects, especially in urban environments. However, the efficiency of VAWTs is an area of concern and has constrained its wide adoption for power generation across the globe. Flow-control devices have proved to improve the wind turbine efficiency. They improve the stall characteristics of the blade, and an overall improvement in the turbine's performance is achieved. During its operation, the blade encounter continuous change in Angle of Attack (AOA) that reaches values higher than its stall angle. Four stages characterize the blade's dynamic stall. Initially, the airflow is attached completely to the blade at relatively lower AOAs. As the AOA increases, the airflow separates from the surface due to development of adverse pressure gradient on the surface of the blade. As AOA further increases, the blade becomes completely stalled. Finally, when the blade moves to lower AOA values, flow reattaches to the surface. Flow-control can delay the onset of flow separation and / or assist in early flow reattachment. The flow control can be accomplished by energizing the airflow at the

blade surface. The stall delay and early flow reattachment can improve the energy generated by the vertical axis wind turbine.

1.3.1 Research Gap

VAWTs have been an area of interest for researchers and engineers due to their prospects for generating renewable energy. One approach to improve their efficiency is using passive flow-control devices, which modify the flow around the turbine. However, there lies a research gap in this area, as most prior research has pertained to Horizontal Axis Wind Turbines and their associated flow-control devices. Furthermore, there is yet to be a clear consensus on the optimal design, placement, and potential impact of flow control devices on the turbine performance needs to be investigated. Thus, there is a dire need for further investigations to explore the efficacy of passive flow control techniques, and to find their optimal integration with the turbine to achieve maximum performance. This will require a combination of experimental and numerical studies, as well as an exploration of the various design parameters that can impact the efficacy of these devices.

1.3.2 Aims and Objectives

The following objectives are aimed by the research:

- (1) To design, fabricate, and conduct experimental investigations for a small VAWT.
- (2) To study the dynamic stall of a simple VAWT blade and propose a passive flow control device which facilitates stall delay and early flow reattachment over the blade.

- (3) To integrate and optimize the modified blade design by incorporating the flow-control device into a VAWT.
- (4) To investigate the efficacy of the flow-control device.

1.3.3 Limitations of this study

There are several limitations to this research study:

- (1) The study focuses only on a small VAWT and does not explore the performance of larger or more complex VAWTs.
- (2) The examination of the dynamic stall and a flow-control device is limited to a simple straight blade design, which may be different for other VAWTs.
- (3) The integration and optimization of the modified blade design are conducted only on a small scale, and the findings may not be directly applicable to larger VAWTs.
- (4) The evaluation of the proposed flow-control device is limited to laboratory experiments, and the real-world effectiveness of the device may vary depending on wind speed, wind direction, turbulence intensity, and planetary boundary layer.
- (5) The study does not consider the economic feasibility or practical implementation of the proposed modifications to a VAWT.

1.4 Thesis Structure

The arrangement for the research and the thesis is constructed to present the study in a well-organized and coherent manner. The following chapter names and descriptions outline the thesis structure:

Chapter 1 gives an overview of the study and its significance. This chapter aims to introduce the problem statement, objectives, limitations, and background context for the study. Chapter 2 reviews the literature on VAWT aerodynamics, its analysis methods, and flow-control devices. This chapter examines the analytical, numerical, and experimental methods used for VAWT analysis and previous efforts pertaining to passive flow-control devices that enhance the power output of VAWTs.

Chapter 3 provides the design process of a VAWT using various analytical and numerical methods to determine design parameters. This chapter aims to provide a detailed design of the VAWT covering wind tunnel testing of two airfoil profiles to generate aerodynamic polars, preliminary design using analytical methods, and performance evaluation of the VAWT at various operating conditions.

Chapter 4 is aimed toward the experimental investigation of VAWT, explaining the fabrication process of the VAWT and its mounting base structure. This chapter outlines the experimental setup to measure and store the wind data, turbine RPM, and its power. The baseline performance of a simple VAWT is established in this chapter. Chapter 5 proposes and investigates power enhancement capabilities of a passive flow-control device. This

chapter aims to determine an optimal design of the flow-control device and assess its efficiency in enhancing the power coefficient of the VAWT.

Finally, Chapter 6 summarizes the essential findings and conclusions of the study. It provides a critical evaluation of the research and its implications for future studies in the field of VAWTs. This chapter also highlights the limitations of the research followed by few recommendations for prospect work.

CHAPTER 2

LITERATURE REVIEW

The idea of VAWTs was first given by Darrieus's [22] in 1927 through a patent covering any arrangement using vertically aero-foiled blades. Since then, many researchers have investigated the efficiency of VAWTs through various methods. The literature review is carried out in three parts. The foremost section focuses on the aerodynamics theory of the vertical axis wind turbine. The second part reviews various methods and models for analyzing VAWTs. Finally, previous efforts to enhance the performance of wind turbines using flow-control are summarized.

2.1 Aerodynamics of VAWT

Wind power naturally exists as kinetic energy and the total available power through an area [23], as expressed in equation 2.1.

$$P_w = \frac{1}{2} \rho A V_\infty^3 \quad (2.1)$$

Where ρ is the density of the air, A is the total swept area, and V_∞ is the velocity of the wind. The airflow interacts with the turbine blades and produces aerodynamic forces and moments. The design of wind turbine blade and its cross sectional shape is of utmost importance. The cross sectional shape of the wind turbine blade affects how wind interacts and the resulting forces produced during the interaction. Therefore, blade cross section is the fundamental shape that affects turbine's performance and determines blade shape.

2.1.1 Blade and Airfoil Nomenclature

The shape of the cross section of a VAWT blade is an airfoil, as presented in Figure 2.1a, with the following geometric nomenclature:

- Leading edge is the vertex located at the forward of the airfoil that the air encounters first.
- Trailing edge is the vertex located at the end of the airfoil that is facing away from the incoming air
- Chord length, ' c ' is the directed distance (or line) connecting the leading edge with the trailing edge. The distance between the leading edge and the trailing edge along the chord line is called chord length.
- Mean camber is the locus of mid-points of top and bottom surfaces starting from the leading edge and terminating at the airfoil trailing edge.
- Maximum camber is the maximum distance between the chord line and the camber line.
- The AOA, denoted by ' α ', is the angle formed among the chord line of the airfoil and the relative wind direction.

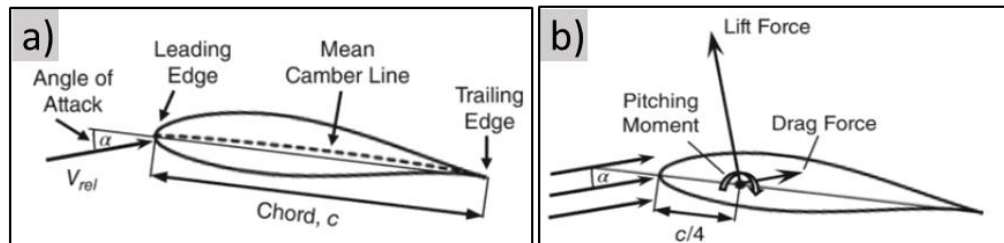


Figure 2.1 Airfoil a) Nomenclature and b) aerodynamic forces and moment [24]

The airfoil shape creates lift and drag forces along with a pitching moment, as seen in Figure 2.1b. A VAWT consists of 2 or more blades connected to a central shaft through struts, as shown in Figure 2.22.2. The distance from the shaft to the blade chord length is the radius of the rotor. Twice of rotor radius is called rotor Diameter ' D '. Blade height ' H ' is the vertical length of the blade along the rotational axis.

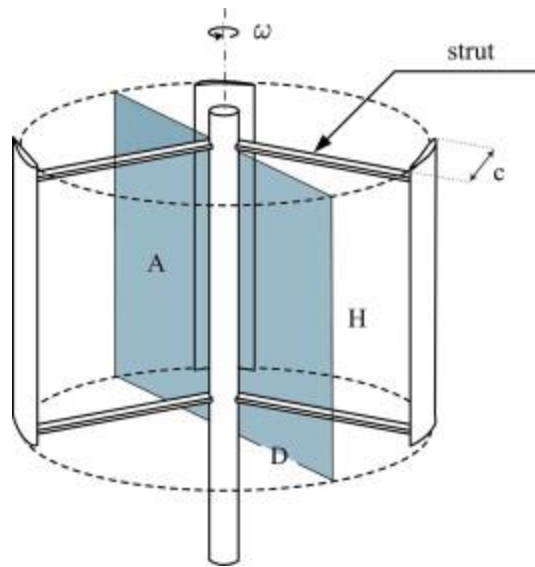


Figure 2.2 Geometric parameters of a VAWT [25]

2.1.2 Force and Moments on Airfoil

Figure 2.1b also shows the direction of lift force, drag force, and pitching moment. Airflow past an airfoil surface exerts a normal pressure and tangential shear force throughout the blade surface. The pressure and skin friction (shear) can be integrated over the blade surface contour to get the resultant vector. The factor of the resultant force normal to the wind is termed lift, L , and the factor of the resultant force parallel to the wind direction is termed drag, D . The point where this resultant force passes through the airfoil is called the Centre of Pressure (COP) and principally, airflow produces no moment about this point.

The pitching moment, C_m , is the moment produced by the resultant force at the quarter chord ($c/4$) of the blade. For aerodynamic forces and moment analysis, dimensionless coefficients for these terms are defined in equations 2.2, 2.3, and 2.4.

$$\text{Lift Coefficient:} \quad C_l = \frac{L}{\frac{1}{2}\rho V_\infty^2 S} \quad (2.2)$$

$$\text{Drag Coefficient:} \quad C_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 S} \quad (2.3)$$

$$\text{Moment Coefficient:} \quad C_m = \frac{M}{\frac{1}{2}\rho V_\infty^2 S c} \quad (2.4)$$

Here C_l , C_d and C_m represent the lift force, drag force, and pitching moment coefficients. Whereas S is the wetted area of the blade air-foiled section.

2.1.3 Airfoil Static Stall

For a given fluid and wind velocity, the aerodynamic forces (lift and drag) vary with the blade's AOA [26]. VAWTs usually use symmetric upper and lower surfaces with zero camber. These symmetric airfoils do not produce any lift at zero AOA. The lift force increase is directly proportional to the incident AOA due to the pressure difference among the upper and lower surfaces. This linear trend continues until a critical AOA, after which the boundary layer starts to separate from the upper surface, as seen in Figure 2.3. As the AOA achieves higher values from this critical value, the lift declines, and the drag increases. This loss of lift is catastrophic and is termed a stall. A typical lift variation with AOA is shown in Figure 2.3.

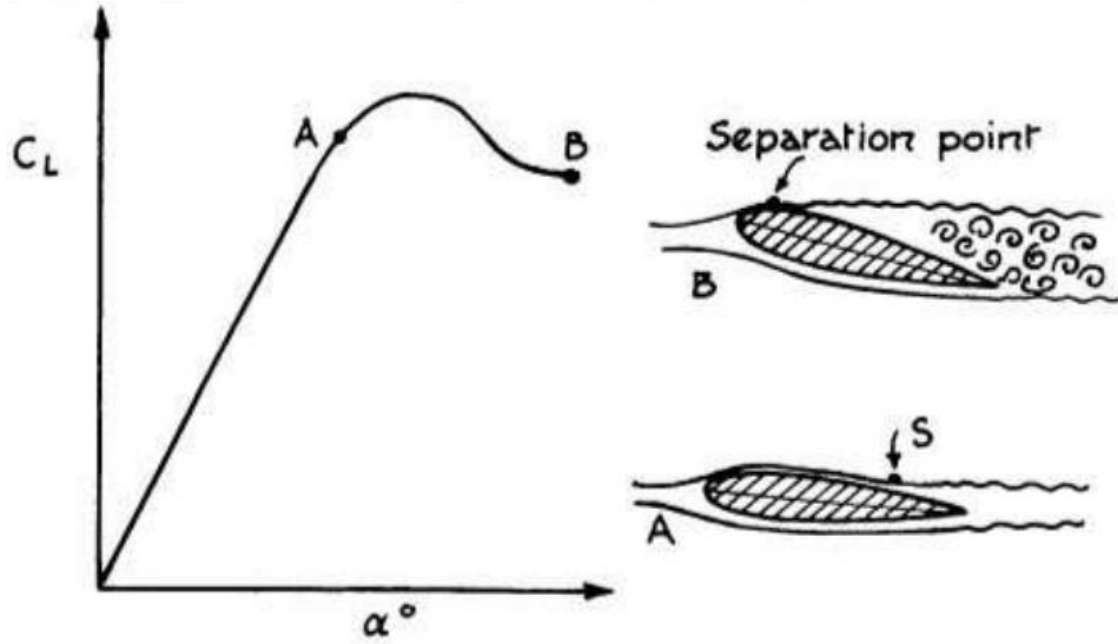


Figure 2.3 Static airfoil stall [27]

2.1.4 Dynamic Stall in VAWT

The atmospheric wind with velocity V_∞ encounters the wind turbine rotating with angular velocity ω . Both these velocities combine to form the absolute velocity experienced by the blade at any given instant. It is pertinent to highlight that the wind velocity vector also varies as the velocity field around the turbine changes. This is because the velocity field becomes considerably distorted in the wake region of the blades. However, assuming constant uni-directional free stream wind velocity, the velocity vectors at various azimuthal angles θ of the turbine are signified in Figure 2.4. It is essential to mention here that the blade toward the forward half of the wind turbine interacts with the unmodified wind conditions. However, as the wind passes over the rotating blade, vortices are generated that significantly distort the flow behind the wind turbine. The returning blade experiences a much more complex flow field than simplified representation in Figure 2.4.

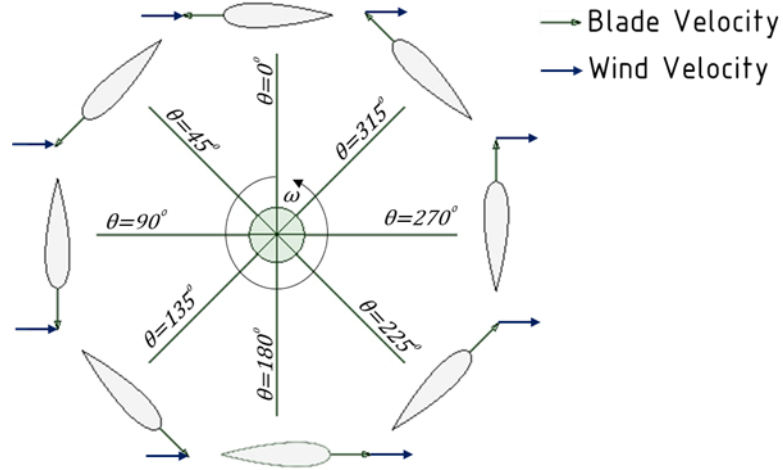


Figure 2.4 Velocity vectors for turbine blade during one revolution

Here, θ is the azimuthal angle of the blades defined as 0 at the top of the domain when the leading edge is facing toward the incoming free stream wind and the blade chord is in-line with the wind velocity vector. The ratio between blade velocity and wind velocity is called Tip Speed Ratio (TSR), λ .

$$\lambda = \frac{R\omega}{V_{\infty}} \quad (2.5)$$

Expressing the relative velocity, V_R in terms of Tip Speed Ratio (TSR) λ , we get:

$$V_R = V_{\infty} \sqrt{1 + 2\lambda \cos \theta + \lambda^2} \quad (2.6)$$

From geometry, the local AOA α seen by the blade changes with the blade position, and it is specified by:

$$\alpha = \tan^{-1} \frac{\sin \theta}{\cos \theta + \lambda} \quad (2.7)$$

As seen in equation 2.7, local AOA becomes a function of azimuthal position and TSR only. Variation of AOA with azimuthal blade position for one revolution is shown in Figure 2.5 for various TSRs.

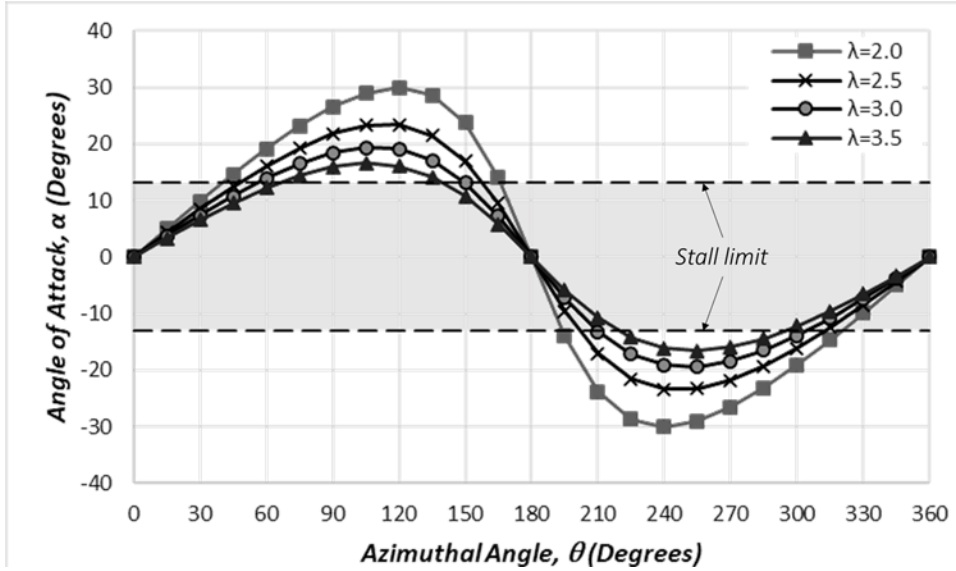


Figure 2.5 AOA Variation with azimuthal position at various TSRs

Turbine blade interaction with the wind results in aerodynamic forces acting on the turbine blades. These forces can be represented in terms of normal component and tangential component defined as:

$$C_T = \frac{F_T}{\frac{1}{2}\rho c H V_R^2} \quad (2.8)$$

$$C_N = \frac{F_N}{\frac{1}{2}\rho c H V_R^2} \quad (2.9)$$

Where F_T and F_N are tangential component and normal components of the forces acting on the turbine blades, and ρ, c, H , and V_R represent the fluid density, chord length of the

blade, the blade height, and relative velocity experienced by the blade at any instant, respectively. The tangential and normal forces are defined in terms of their coefficients using C_T and C_N . The efficacy of a VAWT is defined in terms of the torque and the power produced by the rotor. Power and the torque of the turbine in coefficient forms are defined as follows:

$$C_t = \frac{T}{\rho H R^2 V_\infty^2} \quad (2.10)$$

$$C_p = \frac{T \omega}{\rho H R V_\infty^3} \quad (2.11)$$

Where T represents the torque produced by the turbine. The local AOA experienced by the blades continuously changes during the turbine rotation at different azimuthal positions. Also, for most of the λ values, the AOA values reach beyond the static stall angle. This time-varying response of the blade for angles exceeding the stall angle is called the dynamic stall phenomenon [28]. Dynamic stall is a phenomenon where cyclic flow separations and reattachments are encountered due to continuously varying AOA beyond the static stall limits. Dynamic stall significantly affects the VAWT performance. [29].

2.2 Methods and Models Used to Analyse VAWTs

The efficiency of VAWTs is traditionally measured in terms of flow energy conversion factor, torque coefficient, moment coefficient, and power coefficients at different Tip Speed Ratios (TSRs) [30]. The analysis types for VAWTs can be subdivided into 3 categories: computational aerodynamic models, numerical methods based on computational fluid dynamics, and field / experimental testing.

2.2.1 Computational Aerodynamic Models

The computational aerodynamic analysis models for VAWTs is conventionally divided into momentum, cascade, and vortex models [31].

Momentum Models

Momentum models have been utilized to calculate the aerodynamics and efficiency of all kinds of wind turbines. Currently, three momentum models are used, and they are founded on the examination of the aerodynamic forces acting on the turbine blade by means of a control volume calculations approach. The mass, linear momentum, and angular momentum remains conserved within the control volume. Hence it can be used to estimate power generation from the turbine based on its blade geometry [32].

The actuator disk model is one of the simplest wind turbines analysis method. This model considers the rotor as a disk that is placed in a stream tube as presented in Figure 2.6 [33]. The disk creates a pressure discontinuity within the tube which can be estimated using Bernoulli's equation. The theory utilizes a number of simplifying assumption, including those applicable for the Bernoulli's equation, which are as follows: [32]:

- Incompressible, steady flow with homogeneous properties of the fluid;
- Inviscid flow;
- Number of blades is infinite;
- Whole rotor area contributes equally with constant thrust distribution;
- Irrotational flow;
- and the upstream and downstream conditions are ambient.

The power estimation from actuator disk theory can be computed using equation 2.12. Extracted power can be expressed in terms of non-dimensional coefficient of power by taking its ratio to available wind power (equation 2.13) which is conventionally used parameter to characterize wind turbine performance.

Power:
$$P = 2\rho Aa(1-a)^2V_\infty^3 \quad (2.12)$$

Power Coefficient:
$$C_p = \frac{P}{P_{wind}} = \frac{2\rho Aa(1-a)^2V_\infty^3}{\frac{1}{2}\rho AV_\infty^3} = 4a(1-a)^2 \quad (2.13)$$

Where, ‘ a ’ is called the induction (interference) factor in axial direction and mathematically defined as

$$a = 1 - \frac{V_{avg}}{V_\infty} \quad (2.14)$$

Here V_{avg} is the average velocity at the stream tube inlet and outlet as shown in Figure 2.6.

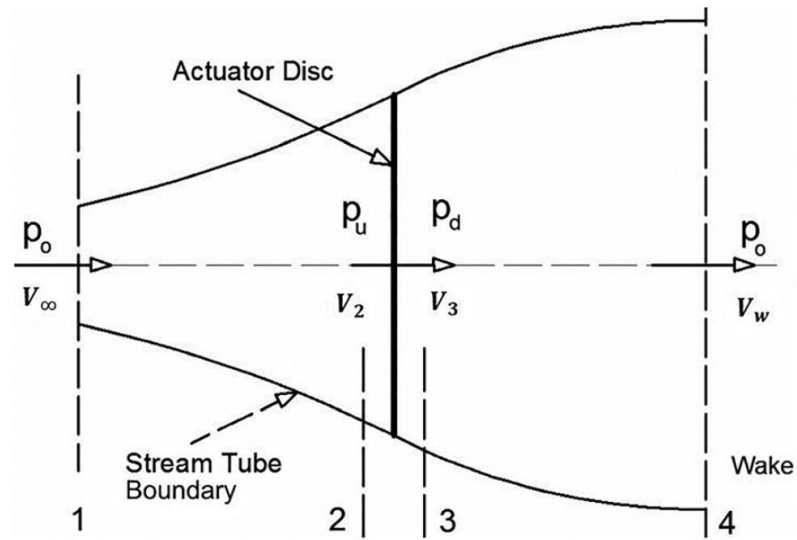


Figure 2.6 Actuator disk placed in a stream tube [31]

Equation 2.13 can be used to find the maximum power that a wind turbine can produce, by varying axial induction factor, and is known as ‘Betz Limit’. Maximum power occurs at $a=0.33$ with $C_{p,max}=0.5926$.

Single stream tube model was first introduced by Templin [34] in 1974, which is one of the first and simplest method to estimate performance of VAWTs. This approach assumes that the complete turbine rotor lies inside a single tube as illustrated in Figure 2.7. The model assumes constant axial velocity throughout the disk and found by estimating momentum change which is equal to the drag force. This model also considers airfoil performance characteristics including stall. The performance is calculated for one blade having a chord length equal to the chord of one blade times total number of blades.

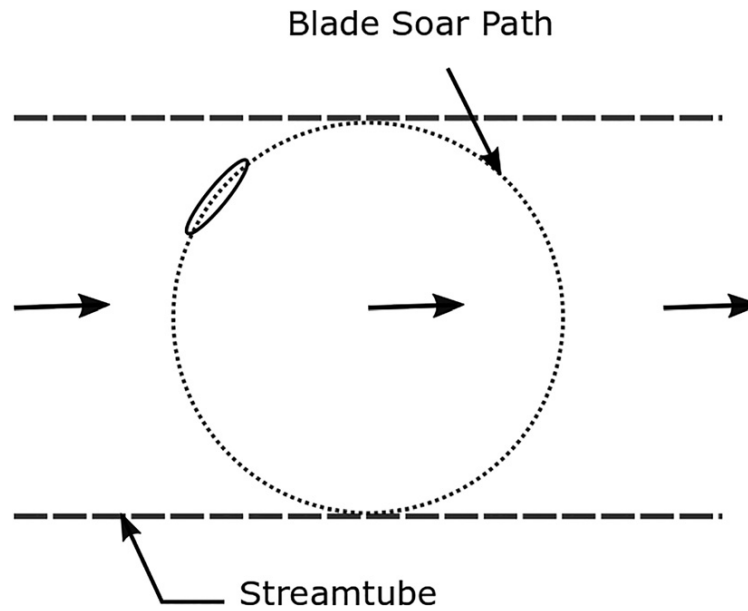


Figure 2.7 Single Stream tube model for VAWT [31]

In 1980, Noll and Ham [35] came up with an analytical technique to assess performance estimation of a periodically pitching VAWT using the single stream tube model which

included the effect of shed vortices, strut and dynamic stall. Patel [36] used this model for hydrodynamic analysis of the VAWT and reported that the model accuracy reduced significantly at higher TSR values.

Single stream tube model assumes constant velocity within the stream tube, however, the turbine interaction with airflow affects flow behavior downstream of the turbine. Lapin [37] improved the model by dividing the stream tube in upstream and downstream segments with different velocities, called double stream model. Further improvement to single stream tube model was proposed by Wilson [38] whereby the single stream was divided into multiple parallel tube sections which were unconstrained aerodynamically as shown in Figure 2.8.

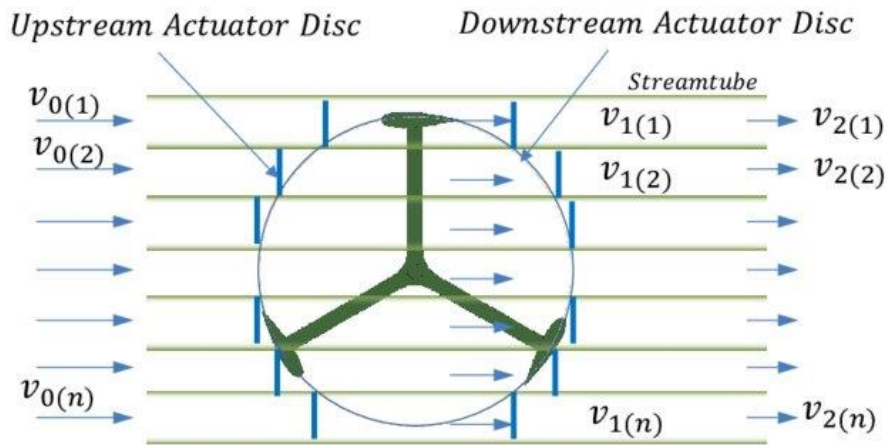


Figure 2.8 Multiple stream model [39]

Cascade Models

The cascade model is traditionally used to analyze turbomachinery and Hirsch and Mandal [40] used it to analyze VAWTs. In this approach, the turbine blades are staggered in a plane (called cascade) and the inter blade distance is set equivalent to the cumulative distance

among all the turbine blades as seen in Figure 2.9. Burton [41] further improved the cascade model by integrating the dynamic stall and blade wake within the model. Although this model is applied in limited studies, it is reported that this model can reasonably predict turbine performance. However, the method's accuracy is exclusively dependent on empirical models of the parameters [42]. Hand [43], [44] developed a tool for design and analysis of straight bladed VAWTs based on cascade model including the empirical parameters.

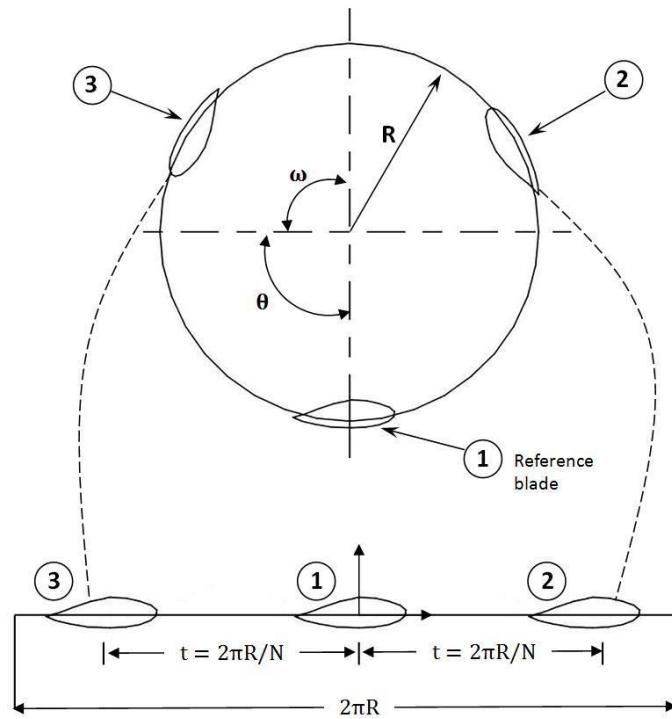


Figure 2.9 Cascade Model for VAWT [42]

Vortex Models

Potential flow based vortex models study the velocity and pressure variations around the blades through the vortex behind each blade. The blades are modeled as lifting-line or bound vortices [45]. The model assumes inviscid flow far away from the blades including

the turbine wake, whereas, viscosity effects within boundary layer are integrated through empirical correlations. Vortex method was first applied to VAWT by Larsen [46]. Earlier models [38], [46], [47] did not account for blade stall. Strickland [48] extended the model to explain the 3D turbine effects, dynamic stall and free wakes. Cardona [49] further improved the model by integrating effects of flow curvature within the rotor. The results were reported to compare fine with the experimental outcomes [50].

2.2.2 Computational Fluid Dynamics

The computational aerodynamics models covered in section 2.2.1 use airfoil data that is already available, do not account for wake formation, and partially use semi-empirical correlations to account for tip vortices and dynamic stall. These restrictions can significantly reduce the accuracy of the results, particularly for modified airfoils for which there is no prior data. A different approach that analyzes the effectiveness of VAWTs with greater accuracy and design flexibility is computational fluid dynamics (CFD). CFD solves the Navier Stoke equations numerically over the specified geometry. Generally, the RANS formulation is used with appropriate turbulence modeling. CFD can be done using in-house developed codes or commercially available software. CFD has been widely used for the design and analysis of VAWTs over the past ten years. However, the time and computational resources needed to achieve this accuracy come at a cost. In the preliminary design phase, designers frequently use simplified models (2D with a coarse mesh and a lower order turbulence model), and they only use high fidelity CFD models for final design adjustments. This section first discusses and contrasts the turbulence models, after which it reviews the 2D and 3D CFD studies carried out for VAWTs.

2D CFD

2D CFD provides remarkable reduction in computational domain to analyze VAWTs but tends to be less accurate. A typical 2D computational domain is depicted in Figure 2.10a. VAWT is enclosed in a circular inner rotating domain that is coupled to the outer domain through a sliding interface. This allows for turbine rotation without the need of re-meshing after each time step. The blades may or may not be enclosed in their respective blade sub-domain. This sub-domain become more useful if the blades have independent pitch control in case of a variable pitch turbine. The top and bottom sides are modelled as symmetry to allow for zero shear and zero normal velocity across the boundary. In a case where domain is created to validate wind tunnel testing, these boundaries may be modelled as no-slip walls to achieve similar conditions as those of wind tunnel testing. Velocity inlet and pressure outlets are set at the opposite ends. The distance of velocity inlet and pressure outlet from the turbine may be set at $10D$ and $15D$ (D being rotor diameter) from turbine center as suggested by Ferreira [51]. These boundaries and domains are consistently extended to 2.5D and 3D simulations hence remaining same across all these techniques.

Danao [52], [53] performed 2D CFD of a small VAWT and matched it to the experimental results. He found that 2D CFD tends to over predict the turbine power coefficient since the tip vortices are not captured. This over-prediction of power for VAWTs is analogous to over-prediction of lift coefficient by 2D airfoils. However, the variation with experimental results remain consistent and follows similar trend. Hence the turbine behavior can be predicted successfully using 2D simulations [55]. Wekesa [56] performed 2D CFD of the same turbine had similar findings.

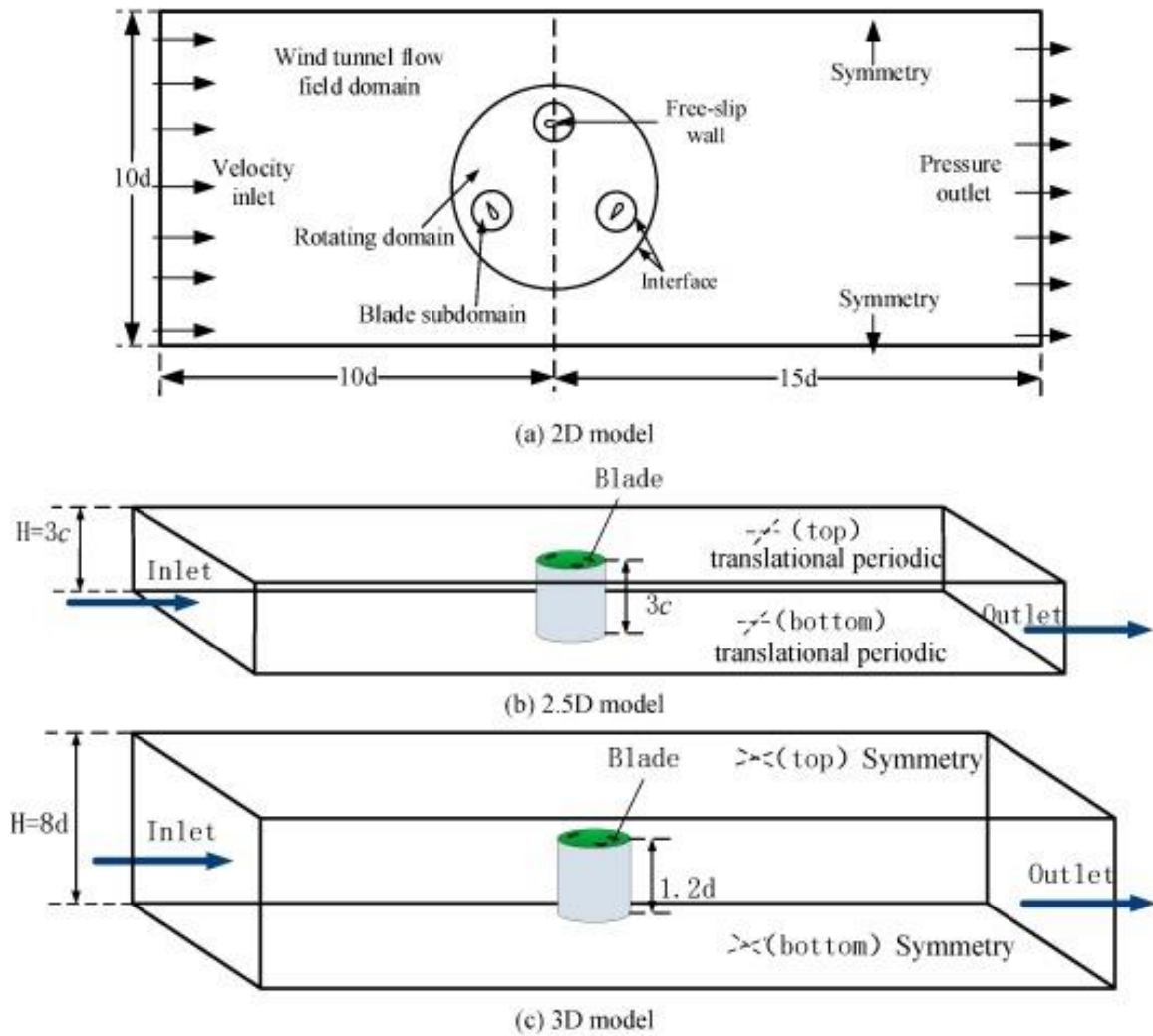


Figure 2.10 Typical CFD domain for a) 2D, b) 2.5D, and c) 3D simulation [54]

3D CFD

3D CFD is the most accurate numerical method, but it has highest computational cost. With the advancement in the processing power technology, 3D CFD is getting widely adopted. A typical 3D simulation domain is shown in Figure 2.10c. 3D CFD model uses the actual CAD model of the turbine with actual dimensions. Recommended height of the simulation domain is 8 times the rotor diameter, with symmetry boundary conditions for

the walls above and below the turbine [55]. VAWT is enclosed in a cylindrical rotating inner volume that connects to outer stationary volume through sliding interface.

Howell [56] investigated the accuracy of 3D CFD of a VAWT by comparing its findings to 2D and experimental results. It was observed results from 3D simulation were closer and in better agreement with experimental observations as compare to 2D results. Alaimo [57] studied straight bladed and helical bladed VAWTs using 3D CFD. In particular, influence of mesh density, time step and turbine angular velocity were investigated. Bachant [58] performed experimental studies to evaluate Reynolds number effect on the efficacy of wind turbine. Mannion et al. [59] performed 2D and CFD studies of the same turbine. A comparative analysis of 2D CFD, 3D CFD and experimental results is presented in Figure 2.11. It is seen that for major part of the operational range of the turbine, 3D CFD simulation results are comparable to experimental results.

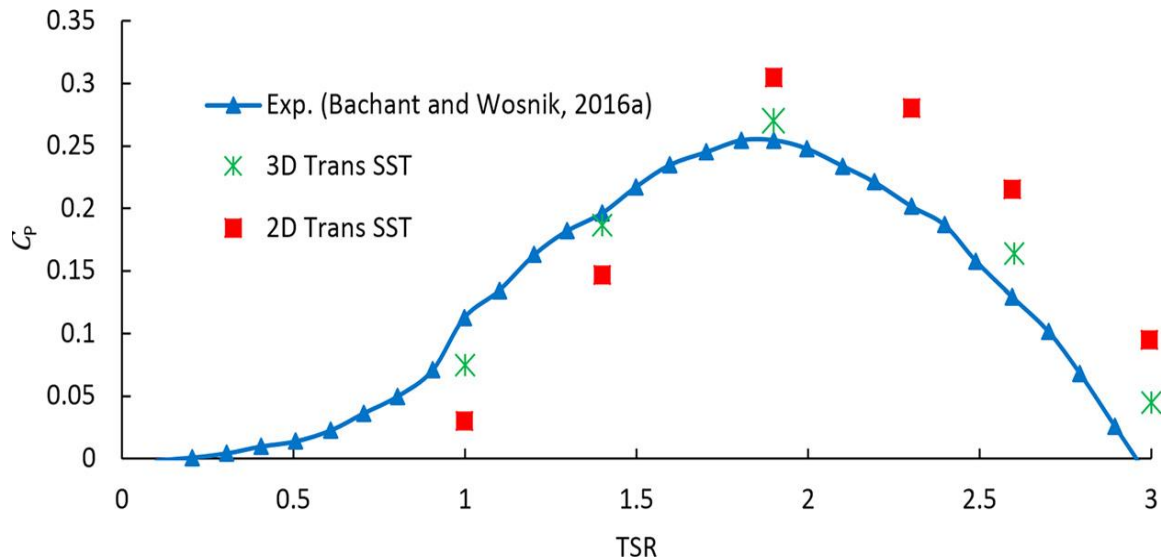


Figure 2.11 Assessment of 2D and 3D CFD in terms of VAWT C_p [59]

2.5D CFD

Another computational method uses a 2.5D model, which extrudes the 2D domain to a predetermined length in the span wise direction. Actual blade length is shorter than this measurement. In Figure 2.10b, a typical 2.5D CFD domain is displayed. With the exception of tip end effects, this enables the inclusion of 3D effects. This method is particularly useful for blades with repeating sections that cannot be modeled in two dimensions, such as dimples or vortex generators. Bertagnolio [60] proposed the span wise length which is thrice the chord length, with translational periodic boundary condition for walls above and below the turbine.

He et al. [54] compared 2D Unsteady RANS, 2.5D Unsteady RANS, 3D Unsteady RANS, 2.5D LES, and 3D LES with experimental results and their findings are shown in Figure 2.12. It was found that all these CFD models correctly replicated the power coefficient variation trend, where the C_p increased with the increasing TSR until the maximum power coefficient was achieved, and then it decreased with further increase in TSR. It was also observed that both 2D and 2.5D Reynolds Averaged Navier Stokes (RANS) approaches overestimated the turbine C_p . Whereas, LES (2D and 3D) and 3D Unsteady RANS (URANS) provided better results as compared to experimental data.

It is conventional to analyze the CFD code with various turbulence models and modeling techniques before finalizing the CFD model for further investigations and analyses. In addition to turbulence model selection, mesh size can significantly affect the results. A finer mesh is generally more accurate but requires more computational power. Hence a compromise between accuracy and computational time is sought.

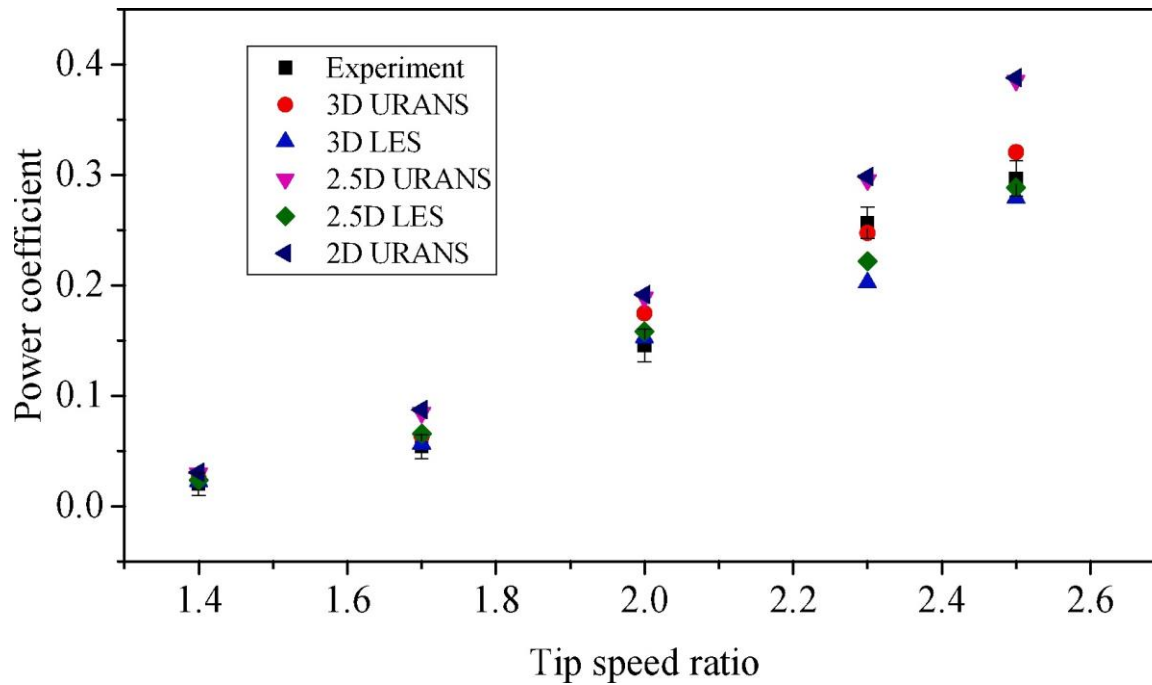


Figure 2.12 Comparison of 2D, 2.5D, and 3D CFD [54]

Turbulence Model and Related Studies

Precision of CFD models is greatly reliant on the mesh characteristics and the turbulence model selection. The flow about the turbine is inherently turbulent. In addition to this, wake from each blade, support struts, and the central shaft further introduces unsteadiness in the flow. Moreover, the dynamic stall of the blade also contributes to the turbulence. For highly turbulent flows the selection of turbulence model is imperative. Lower order models are seldom used for analysis of VAWTs.

The $k-\epsilon$ turbulence model is more robust and hence widely used for variety of flows with high turbulence in aerodynamics and heat transfer studies. Daroczy et al. [61] evaluated and compared various turbulence models to assess their precision to estimate VAWT performance. CFD results were contrasted to four experimental results and results showed that for 2D simulations, the $k-\omega$ SST and Realizable $k-\epsilon$ turbulence models

were more accurate. Castelli [62] also performed CFD using 2D domain with Realizable k -epsilon turbulence model and reported that the peak moment was generated during the forward half of the turbine rotation (up-wind direction) where the blades experience higher AOAs as compared to down-wind half of the rotation. It was also observed that the instantaneous power produced by a single blade surpassed the Betz's limit, which may be attributed to sudden pressure coefficient drop. Howell [63] studied the k -epsilon turbulence model (RNG) for 2D and 3D CFD, which once again indicated that the predictions from 3D CFD were closer to the experimental observations, whereas, 2D CFD over-predicted the turbine performance.

The k -omega Shear Stress Transport (SST) is a two equation model. This turbulence model is based on eddy viscosity modelling that combines the two k -epsilon and k -omega equations [40]. Modified eddy viscosity takes into account turbulent shear stress transport effect, inherently prevalent phenomenon in boundary layer separation and flow reversal due to adverse pressure gradient [64]. A comparative study by McNaughton [65] compared baseline k -omega SST with modified k -omega SST turbulence model with Reynolds number correction (k -omega SST LRe) and reported that the k -omega SST LRe model correctly captured leading edge vortices as observed experimentally through Particle Image Velocimetry (PIV). Comparing blade performance in terms of lift coefficient showed that the results from k - ω SST was nearest to the experimental results and the vortex development during dynamic stall was also well captured.

The SST transition turbulence model couples the k -omega (SST) formulation with 2 additional equations for the momentum thickness (Re based) and the intermittency [64]. It

results in a reliable model that can efficiently solve adverse pressure gradient flows. Lam [66] investigated development of wake in a 3D turbine using SST model, which showed that the turbine produced an asymmetric wake in the horizontal plane parallel to the ground. In contrast, the 2D model either under-predicted or over-predicted the flow velocity in the wake due to absence of vortices in the infinite blade and central shaft. McLaren et al. [67] used SST model to analyze a high solidity turbine, which revealed that flow field around turbine and that experienced by the blade was much complex than an isolated pitching blade. Vortex shedding and separation bubbles from the blades resulted in flow reversal over the blades. Flow separation was also reported in regions with positive thrust generation, which was not accurately predicted by earlier discussed Double Multi Stream Tube (DMST) analytical model.

Large Eddy Simulation (LES) is an expensive model, compared to previously stated turbulence models, based on computational resources and time required for simulations. LES directly resolves the larger scales containing more energy, whereas the smaller scales of turbulence are spatially filtered out by means of sub-grid scale models [68]. Li [69] used the LES model to assess VAWR performance, which showed that the vortex generated from the turbine blades and its subsequent diffusivity the wake was more realistic, and hence were able to better estimate the turbine's performance. RANS degraded accuracy is mainly attributed to its ability to capture small scale phenomenon and its formulation to capture these small eddies and vortices. Elkhoury et al. [70] used LES to investigate the effects of blade shape, its pitch angle, wind speed, and turbulence intensity on a VAWT, and the findings matched well with the experimental results endorsing LES accuracy for

VAWT analysis. Patil [71] studied blade dynamic stall using LES and compared the computed flow field to actual flow field captured using PIV. The simulations accurately captured generation of 6 vortices' pairs generated from leading edge and trailing of the blades during one rotation.

2.2.3 Experimental and Field Testing

Experimental measurements and field testing form the basis of all analytical and numerical studies by providing the data sets to validate these models and assess their accuracy. Experimental studies for VAWTs have been primarily focused towards wind tunnel testing rather than field testing [72]. Unlike HAWTs, the application of VAWT is more suited towards small scale urban environment with more chaotic and unique wind characteristics. Recently researchers have started generating these wind profiles in the wind tunnel testing. A detailed review of the methods employed to generate these profiles has been provided by Mankowski [73].

Wind Tunnel Testing

Earlier wind tunnel testing for VAWTs were limited to obtain turbine's performance curves under steady wind condition. However, later studies have expanded to include other effects as well. Bianchini et al. [74] performed the wind tunnel testing of a VAWT with NACA 0021 blades to assess its efficacy and wake structure. Eboibi et al. [75] performed testing to analyze effect of solidity, varying from 1.2 to 2.1, on turbine's performance. Armstrong et al. conducted several tests to study the flow separation performance of a straight bladed VAWT. Greenblatt et al. [76] conducted wind tunnel testing for a VAWT

with plasma actuators fitted on the blade leading edges. Du et al. [77] studied variation of VAWT starting and operational performance by varying its geometric parameters.

Optical Measurements and Visualization

Particle Image Velocimetry (PIV) is a specialized measurement method where the entire flow field velocity can be simultaneously measured optically. The field measurement is a major difference and inherent advantage from conventional measurement methods (like anemometry) that use sensors to find the velocity of a single point. PIV provides a physical (velocity) and visual (contours) insight into the flow field variables like velocity field, pressure field, turbulence, eddy formation and vortex generation. Fujisawa et al. [78] used PIV in his wind tunnel experiments on a straight bladed VAWT to observe its dynamic stall as shown in Figure 2.13. It was observed from optical measurements that the dynamic stall resulted from a cyclic mechanism due to flow separation on the surface followed by a separation bubble and roll-up vortex. Vortex structure within turbine wake was studied by Posa et al. [79] and it was revealed that at higher Re numbers, wake was greatly affected by the turbine's TSR. Ferreira et al [51] performed wind tunnel testing and extracted planar PIV data to visualize flow field development around the blade during dynamic stall. This data set serves as baseline to various numerical studies for validation purposes. A similar three-dimensional data was extracted by Tescione et al. [80] which validated the existence of asymmetric wake in both, horizontal and vertical planes. Rolin [84] used Stereoscopic PIV (S-PIV) and discovered that two vortices at the wake edge with counter rotating directions were developed. This phenomenon was captured and compared using numerical studies by Buchner [81] with k-omega SST turbulence model.

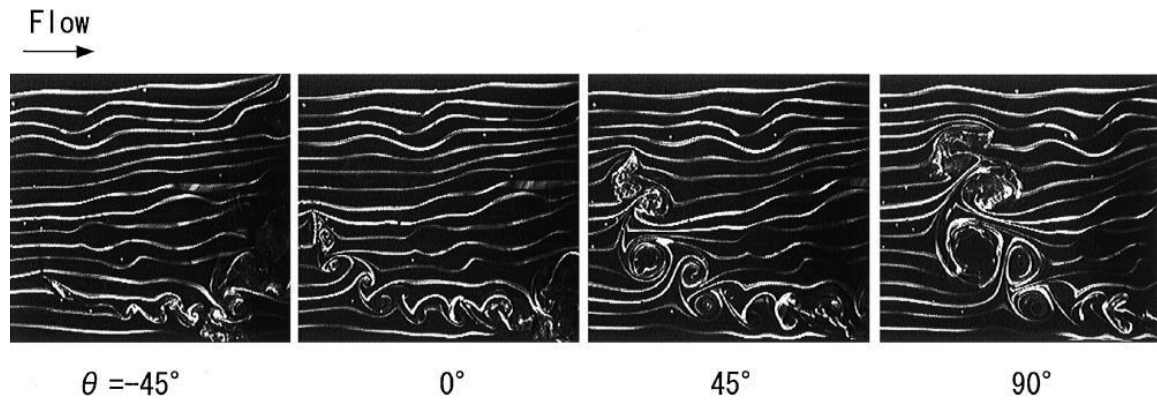


Figure 2.13 low visualization of dynamic stall on a straight bladed VAWT [78]

2.3 Flow-control Techniques to Enhance Performance of VAWTs

Dynamic stall in a VAWT can be subdivided into four stages as follows [82]:

- (1) Low AOAs, where flow remains attached to the surface;
- (2) Vortex develops at the leading edge as AOA increases;
- (3) Leading edge vortex shedding resulting in complete stall;
- (4) As AOA is reduced, the flow re-attaches to the blade.

Flow-control over the surface attempts to energize the flow by introducing the turbulence. It can help delay the stall and assist early flow attachment. An airfoil with delayed stall can contribute to power generated by the blade for a longer duration during the turbine operation. Even a slight delay by each blade can significantly improve the overall power generated by the wind turbine. As a result, the moment contribution from the blades can be increased resulting in overall increase in power generation capability of the VAWT. Flow-control methods can be segregated into active methods; that require a control system, and passive methods; that are integrated into the geometry and do not need any additional controller or control mechanism, which control the airfoil surface or flow injection.

2.3.1 Active Flow control Devices

Active flow control methods could be pre-determined or reactive. A pre-determined control has the desired output stored in a micro controller which are triggered at pre-determined position or time. A reactive technique employs a feedback control system to sense the trigger and subsequently command the output. The most common active flow-control methods that improve the power conversion efficacy of VAWTs include blowing / suction and pitch control.

Variable Pitch

Variable pitch control allows changing the pitching angle of the blade at predetermined azimuthal positions. This allows to change the blade AOA, which can be reduced to avoid blade stall. A fixed and variable pitching blade is displayed in Figure 2.14.

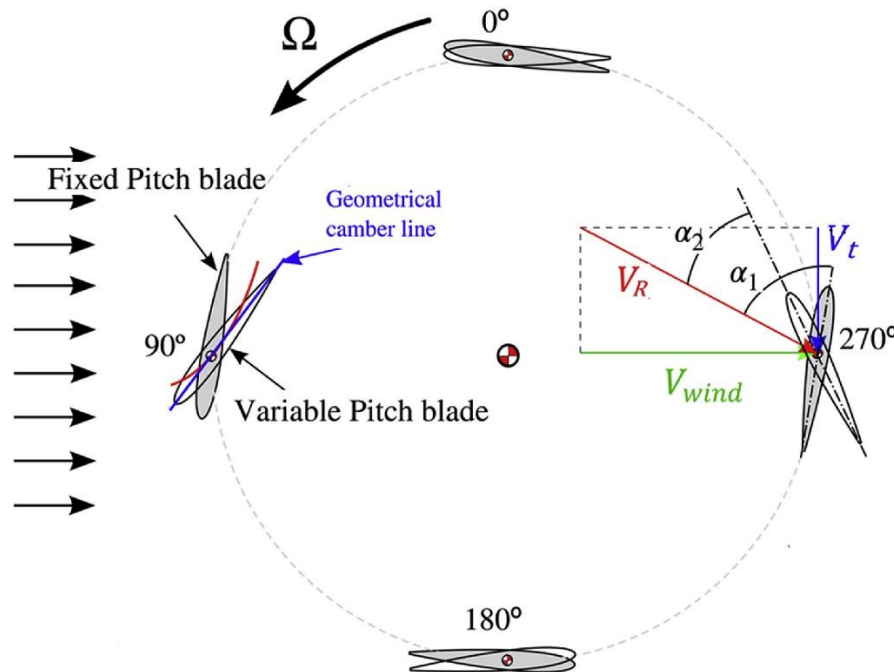


Figure 2.14 Comparison of fixed and variable pitch blade orientation [70]

Numerous studies [83]–[97] have been performed to evaluate effect of variable pitch and investigate optimum pitching profile to extract maximum energy from the wind. Elkhoury [70] investigated, through experiments and numerical analyses, the effect of variable pitch on the VAWT performance. The results shown in Figure 2.15 reveal that the C_p of the VAWT with variable pitch is greater than the C_p of VAWT with fixed-pitch. Moreover, the maximum C_p occurs earlier for variable pitch VAWT, however, the power coefficient of variable pitch turbine tends to reach lower values at higher TSRs.

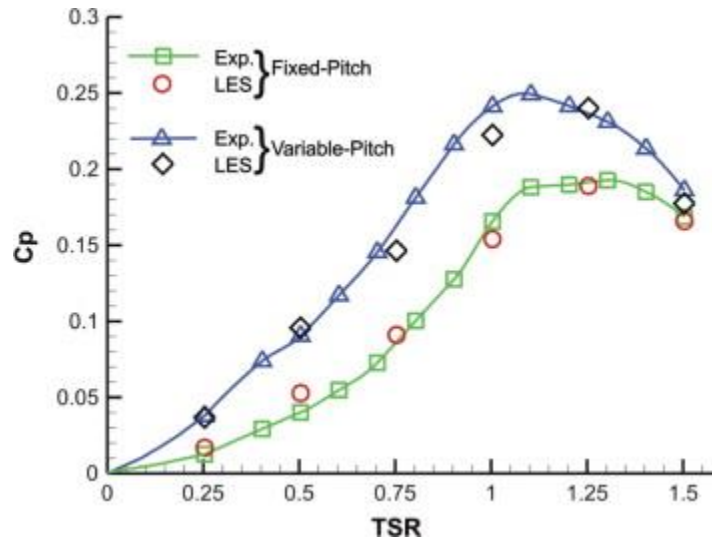


Figure 2.15 Performance of fixed pitch compared to variable pitch VAWT [70]

Blowing / suction

Boundary layer suction is a technique used in both, external and internal flows, to control flow separations [98]–[101]. It creates a suction on the surface that not only reattaches the flow, but also delays the separation and pushes the separation point downstream. Rezaeiha [102] studied the influence of suction on the blade of a VAWT. When comparing suction ON and suction OFF cases, it was found that the power generation from suction ON blade

was more for longer part of the blade rotation. A plot of moment generated by the turbine blade corresponding to its azimuthal position is compared in Figure 2.16 for both, suction ON and suction OFF cases.

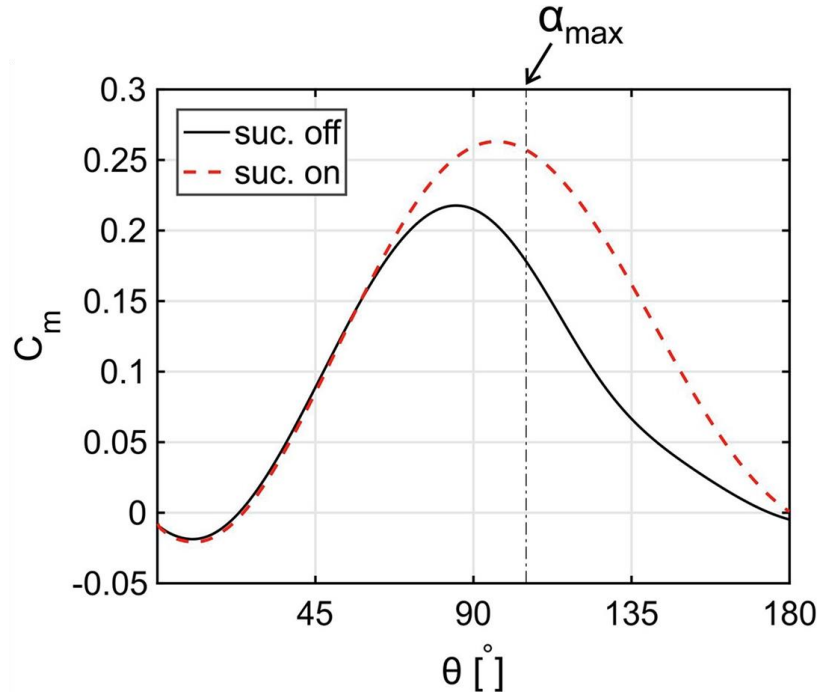


Figure 2.16 Moment coefficient of VAWT during half-revolution [102]

2.3.2 Passive Flow-control Devices

The techniques for passive flow control have an advantage that they do not require any controller or sensor for its operation. However, the blades with a passive flow-control integrated in its design are generally difficult to fabricate and require precise machining. Despite that, the advantages have the potential to outweigh the manufacturing disadvantage and various passive flow-control techniques have been investigated for VAWTs and HAWTs. Some passive flow control techniques are more complex to manufacture than others, and the simpler to manufacture designs are always preferred.

Leading Edge Cylinder

Wang [103] proposed attaching a micro-cylinder slightly ahead of the turbine blades, as presented in Figure 2.17, and investigated its effects experimentally and numerically (CFD using $k-\omega$ SST). It was found that the micro-cylinder was successful in achieving a deferment in the boundary layer separation on the surface with minimal effect on wind turbine stability. Results showed a 27.3 % improvement in HAWT's torque coefficient with optimal micro cylinder. Application of such micro cylinder to VAWT is still an area to be investigated.

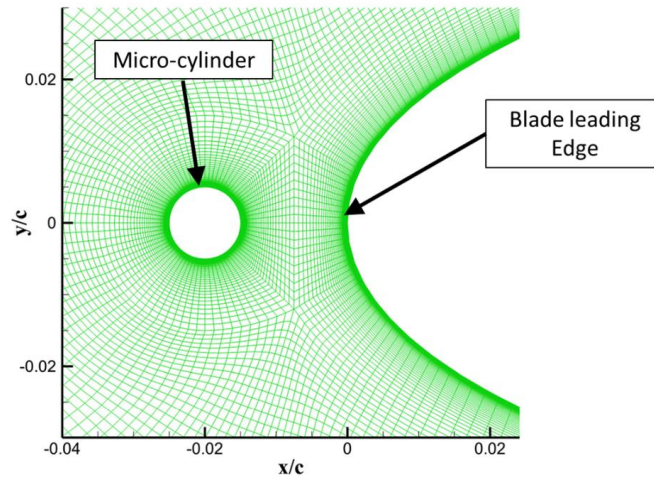


Figure 2.17 HAWT blade with micro cylinder [104]

Leading edge slots

Leading edge slots provide an opening to the high pressure flow at the bottom surface of the airfoil and introduce this extracted air to be introduced directly in the boundary layer of the top surface. Tariq [105] carries out a numerical investigation to determine the optimum angle for leading edge slot for a VAWT as shown in Figure 2.18a. It was observed, from the comparison of VAWT with and without leading edge slot, that the slot

increases the power coefficient of the VAWT by 15% as presented in Figure 2.18b. It was also observed that the relative advantage of the slot reduced at higher TSR values.

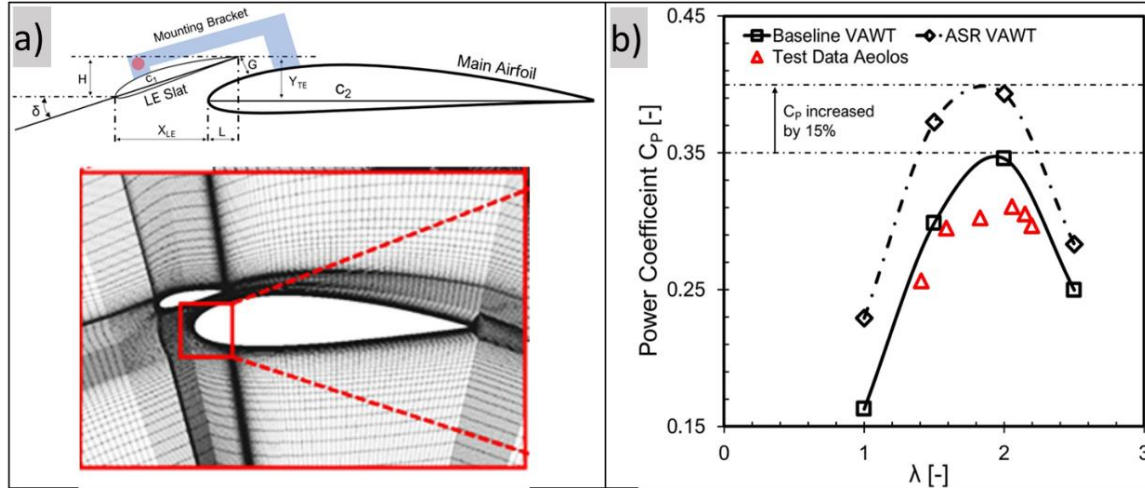


Figure 2.18 a) Leading edge slot and b) its effect on HAWT performance [105]

Gurney Flap

Gurney flaps have recently caught attention of many researchers [106]–[109] who have investigated effect of a gurney flap on a straight bladed VAWT performance. Gurney flaps are small tabs that are placed perpendicularly on the pressure side adjacent to the trailing edge of airfoils as shown in Figure 2.19. Vortex generated from the lower surface do not interact with the upper surface and delay the inception of boundary layer separation. A summary of the turbines investigated with the percentage improvement in their performance is summarized in Table 2.1.

Table 2.1 Summary of GF for VAWTs

Author	Blade Profile	Solidity	Rotor Diameter	GF Height in %chord	Improvement in Turbine C_p
Bianchini[106]	NACA0021	0.249	0.5150	2.0, 3.0	23.1% with 2% GF
Zhu[107]	NACA 0021	0.18	0.75	0.75, 1.0, 1.25, 1.5, 1.75	22.03% with 1.75 % GF
Ni[109]	NACA 0021	0.25	1.03	2.0	25.3% with 2% GF

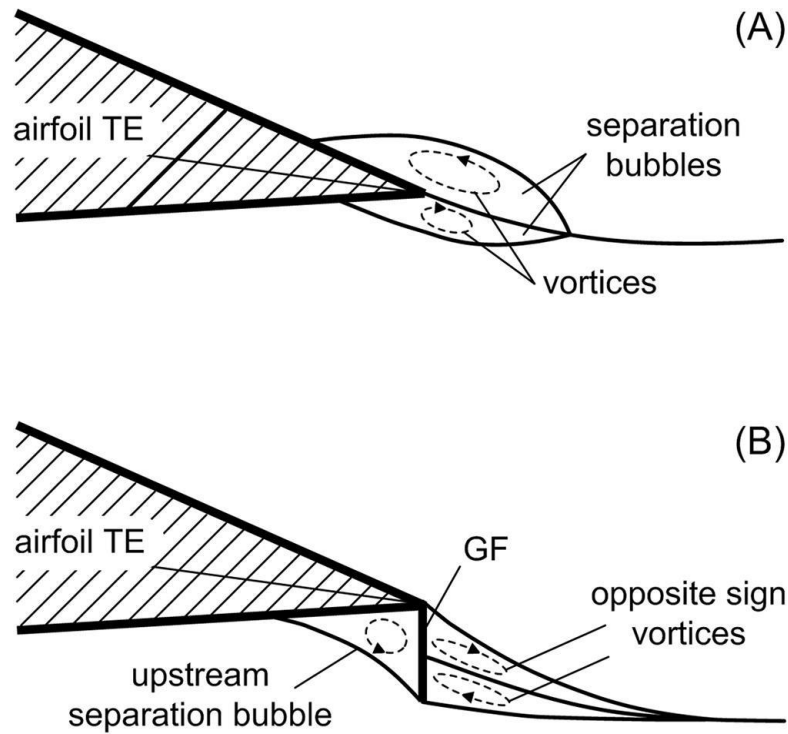


Figure 2.19 Separation delay due to gurney flap [106]

Serrated blade

Leading edge serrations are sinusoidal profile at the leading edge of the blade, as seen in Figure 2.20, that can energize the flow by adding vorticity that can delay the inception of flow separation on the blade at higher AOA. Wang [110] conducted numerical study to investigate effects of serrated leading edges with varying amplitude and height. Best turbine performance was achieved with wave length of $0.33c$ and amplitude of $0.025c$ (c being blade chord length), where the turbine power coefficient improved by 18.7% at $TSR = 2.0$. However, the blade design is significantly complex and its effects on structural life of the wind turbine still need to be evaluated.

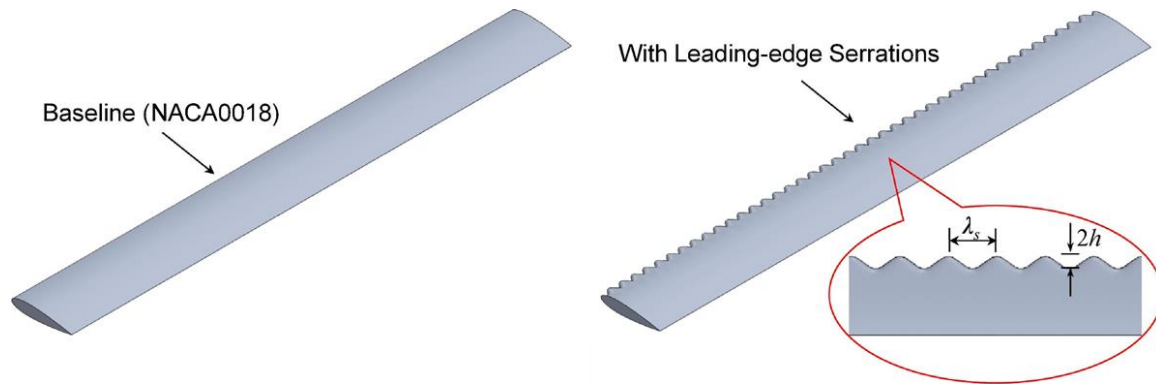


Figure 2.20 Leading edge serrations [110]

J-airfoil

Zamani [111] investigate effects of J-shaped airfoils on the performance and efficiency of straight bladed VAWT. A J-shaped airfoil is designed by partly removing the airfoil pressure side from its trailing edge as visible in Figure 2.21a. VAWT with for blades was analyzed and its performance was seen to have improved at every TSR values excluding $TSR = 1.8$. Improvement in turbine power amplitude of $h = 0.025c$ coefficient with TSR is shown in Figure 2.21b. In addition to power improvement, the starting speed of the wind turbine also increases, since the J-section provides higher drag of the blade moving with the direction of the wind.

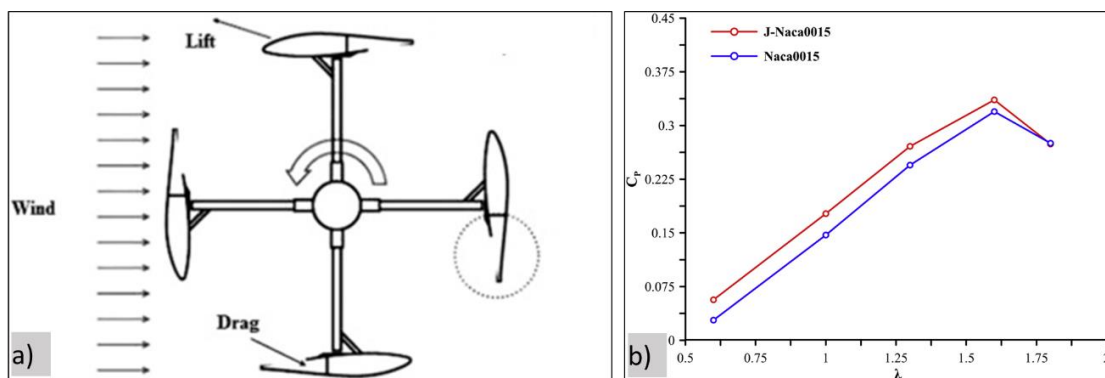


Figure 2.21 a) VAWT with J-blade, and b) its effect on turbine performance [111]

CHAPTER 3

AERODYNAMIC DESIGN OF A VAWT

The aerodynamic design of a VAWT is vital to achieve an optimal design that can produce maximum efficiency, which depends on various geometric factors and operating conditions. This chapter details the design process of a VAWT, which involves finding the optimal geometric factors and operating conditions for the turbine. The design wind speed is determined using local wind data. The preliminary design is carried out using analytical methods in QBLADE software, and the detailed design is conducted using CFD through Fluent software. The airfoil selection is the most important parameters in the wind turbine design, which is made during the preliminary design phase. The preliminary design requires the aerodynamic polars of the airfoil, which were generated using wind tunnel testing of two airfoils (NACA 0012 and NACA 0022). Other design constraints, such as blade chord, height, turbine radius, and the number of blades, are optimized using CFD. The following sections provide a comprehensive outline of the design process of a VAWT, including the selection of optimal geometric parameters, operating conditions, and airfoil selection.

3.1 Wind Data at Dhahran

For accurate wind power potential assessment, as a rule of thumb, the data is required for at least one entire year. For the current study, wind speed and direction data were collected for 24 months. Wind and other meteorological parameters are measured at the top of RI

building located in King Fahd University of Petroleum and Minerals (KFUPM) using a wind mast. The data was sensed every second, and hourly mean, least, and maximum values along with the standard deviation were recorded by the logger. During the years 2019 and 2020, the directional plot for hourly averaged wind speed frequency is displayed in Figure 3.1(a), whereas the histogram of hourly averaged wind speed frequency is presented in Figure 3.1(b).

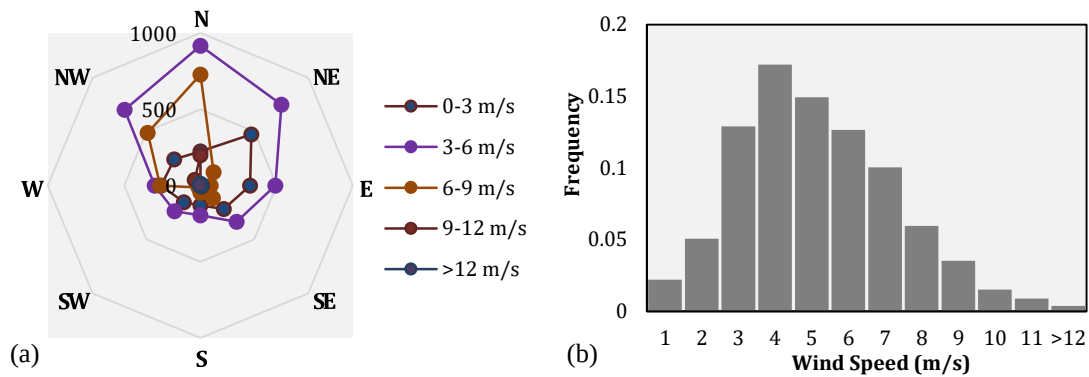


Figure 3.1 Wind speed (a) directional and (b) hourly averaged frequencies

It is observed that the wind direction is predominantly from the north, and the speed remains between 3-6 m/s for most of the duration. It also shows that wind direction variation is significant. Hence VAWT is more suited since it is not dependent on wind direction. A horizontal axis wind turbine at this location would require a yaw control mechanism to warrant that the turbine is always directed towards the approaching wind. The average wind speed during these two years was 4.6 m/s. It is also found that the hourly averaged wind speed was more than three m/s for approximately 92% of the time. This information is critical during the turbine selection process and defines the wind turbine cut-in speed criterion.

In addition to the measured wind data at KFUPM, another wind data set was utilized for the current study. This data set is from the ground weather station of NASA installed at Dhahran and was obtained through RETScreen software. The RETScreen Climate Database includes the solar resource and meteorological data collected by NASA over the years. The NASA weather station in Dhahran is referred to as Site-A and the weather station at KFUPM as Site-B in this study. The geographic locations of these sites are shown in the map presented in Figure 3.2.



Figure 3.2 Geographic locations of Site-A and Site-B

Wind data from both the sites were analyzed to calculate monthly averaged wind speeds and available wind power density. A comparison of the wind speeds at these two locations is shown in Figure 3.3 (a), whereas the available wind power density for these sites is shown in Figure 3.3 (b). Annual average wind speeds were found to be 4.4 m/s and 4.6 m/s

at the NASA ground station and KFUPM, respectively. Although there is a minor difference in the annual average wind speed at these two sites, their behavior is quite different during different months. However, certain similarities are still observed when these data sets are compared. The highest wind speeds are experienced during June and July and the lowest in September and October.

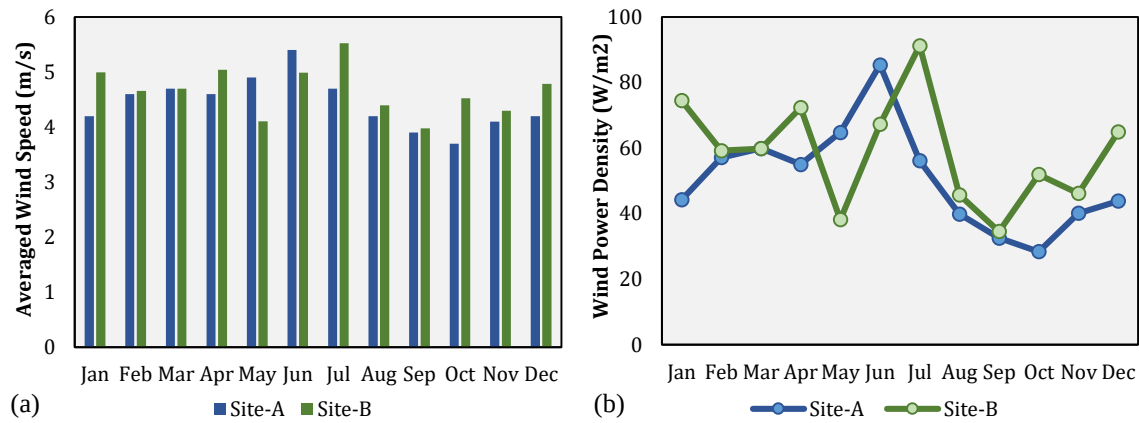


Figure 3.3 Monthly wind (a) speed and (b) power density at two locations

The efficiency of a blade designed specifically for higher wind speeds is drastically reduced when operated at lower wind speeds. Similarly, a blade designed for lower speeds has reduced efficiency at higher speeds. Dhahran experiences moderate wind speeds with a mean of 4.6 and remains above 7 m/s for 95% of the time. Hence the turbine blade is designed for 4-7 m/s.

3.2 Wind Tunnel Testing of Airfoils

An experimental investigation of NACA 0022 is conducted using wind tunnel testing. The wind tunnel measurements are first validated by analyzing NACA 0012 airfoil section and comparing it to published results. The validation study is performed for steady and

unsteady conditions. In addition, uncertainty in force and airflow speed measurements are also evaluated. After the validation study, wind tunnel testing is performed for a NACA 0022 airfoil section. The static testing is performed to determine lift, drag, and moment variations of the NACA 0022 section across the Angles of Attacks (AOAs) ranging from 0° to 180° in coefficient form. These polars are generated at the Reynolds numbers of 75k, 100k, and 150k. In addition to this, the dynamic response of the NACA 0022 airfoil in sinusoidal pitch is also evaluated at the reduced frequencies of 0.1, 0.05, and 0.025. Variation of mean AOA was kept at 0° , and its variation was deemed unnecessary for VAWT application since the blade operates with 0° mean AOA during turbine operation.

3.2.1 Wind Tunnel Testing Setup

The experimental facility consists of an open circuit suction type subsonic wind tunnel having a test section having a cross sectional area of 600 mm by 600 mm and a length of 1200 mm. Airflow is generated using a variable-speed axial fan installed downstream of the test section. The wind tunnel has a three component weighing scale to measure the airfoil's lift, drag, and pitching moment. A Schematic representation of the open-type wind tunnel to test the NACA 0022 airfoil experimentally is shown in Figure 3.4.

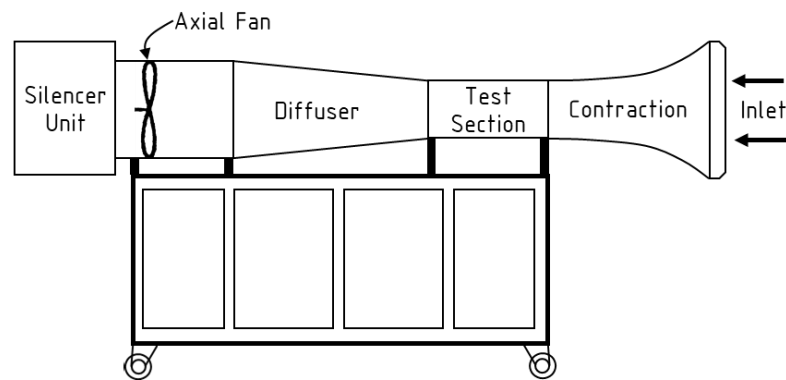


Figure 3.4 Diagram of the wind tunnel

The NACA 0022 model spans 300 mm with a chord of 150 mm. The NACA 0022 model is 3D printed using F-123 Stratasys 3D printer using ABS material. The surface of the 3D printed model is finished using 240 grit sandpaper followed by 320 grit sandpaper in orthogonal sanding stroke direction. The airfoil model is attached to a three-component balance through a 12 mm diameter steel mounting stem having a length of 220 mm. Figure 3.5 shows NACA 0012 airfoil model used for wind tunnel testing. The mounted stem is attached at the quarter chord position of the symmetric airfoil.

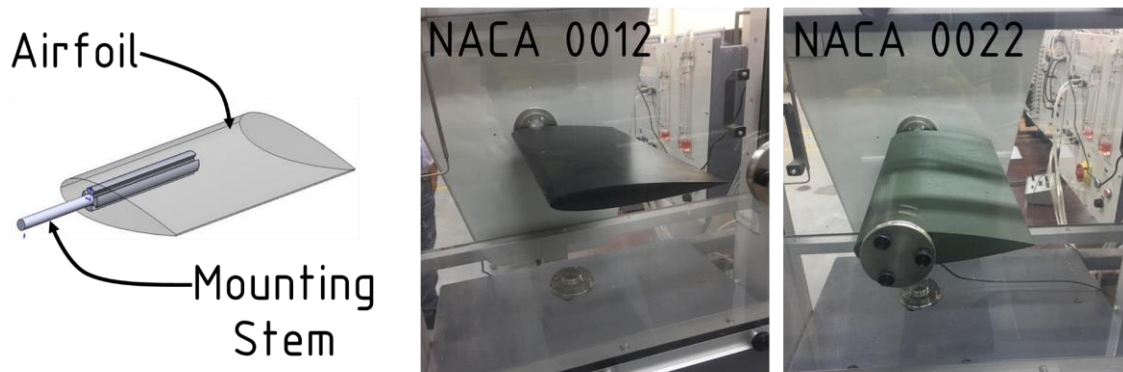


Figure 3.5 NACA 0012 and NACA 0022 models during wind tunnel testing

The weight of the airfoil and torque required for oscillatory motion is used to estimate the size of the motor. The Oscillation rig consists of a DC servo motor driven by a servo motor drive. The controller is connected to the LabVIEW software through a National Instruments (NI) motor drive module. The oscillation motion input is provided through LabVIEW software that generates the necessary voltage using the motor drive module. The servo motor drive provides the current to the motor. The control system for airfoil pitching motion is shown in Figure 3.6. The servo motor drive system can be given different oscillation signals through the LabVIEW software.

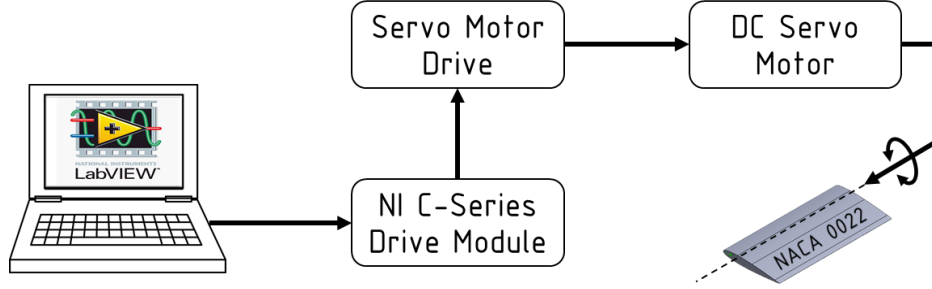


Figure 3.6 Servo motor drive system for airfoil pitching motion control

The static wind tunnel testing is done by moving the airfoil to the designated AOA and recording data after a 1-second delay to achieve steady flow conditions. The data for aerodynamic forces and pitching moment is recorded at a sampling rate of 10 kHz. Five thousand readings are recorded, and the data is subjected to time-based averaging at each AOA. Dynamic wind tunnel testing continuously records the aerodynamic forces and moment data while the airfoil oscillates between the maximum and minimum AOAs. The oscillatory motion is categorized by reduced frequency ‘ k ’, defined by equation 3.1.

$$k = \frac{\omega}{V_{\infty}} \frac{c}{2} = \frac{\pi f c}{V_{\infty}} \quad (3.1)$$

Where ‘ ω ’ is the angular frequency, ‘ c ’ is the chord length, ‘ V_{∞} ’ is the freestream wind velocity, and ‘ f ’ is the oscillation frequency. The dynamic response of the NACA 0022 airfoil in sinusoidal pitch is evaluated at the reduced frequencies of 0.025, 0.05, and 0.1, representing quasi-steady, unsteady, and highly unsteady flow conditions.

The Sensors and environmental factors are responsible for the uncertainties in the experimental results that have been presented. The ranges and accuracies of every sensor and piece of equipment differ, which has an immediate impact on the measured values.

The Kline and McClintock method is used to calculate the overall uncertainty of the experimental setup. Equation 2 is used to determine the fractional uncertainty for each measured variable. Equation 3 is used to calculate the overall uncertainty of the experimental setup.

$$u_c = \frac{\Delta C}{C} \quad (3.2)$$

$$u_{overall} = \sqrt{\sum_{i=1}^n \left(\frac{\Delta C_i}{C_i}\right)^2} \quad (3.3)$$

Where C is a quantity that has been measured, ΔC is its absolute uncertainty, u_c is its fractional uncertainty, and $u_{overall}$ is the overall uncertainty of the experimental setup. Table 3.1 displays the precision and degree of uncertainty for each quantity measured during the steady testing.

Table 3.1 Uncertainty of experimental setup

Measured Quantity	Units	Accuracy	Uncertainty
Normal Force (F_N)	lbf	± 0.001	0.0073
Axial Force (F_A)	lbf	± 0.001	0.0091
Pitching Moment (M_z)	lbf-in	$\pm 3\%$	0.0271
Wind Speed (V_∞)	ft/s	$\pm 1\%$	0.0251
Overall Uncertainty			0.0686

3.2.2 Static Testing

The static wind tunnel testing measures the aerodynamic coefficients of the airfoil at discrete AOAs. This type of testing provided valuable information about the airfoil's lift, drag, and pitching moment characteristics at different AOAs. The aerodynamic coefficient polars generated during the static testing are used during analytical modeling of the VAWT. The static wind tunnel testing of the NACA 0012 airfoil at a Reynolds number of

1.35×10^5 was conducted by varying the AOA from 0 to 16 degrees with a step size of 0.2 degrees. Zero-degree AOA was calibrated at the position where the airfoil produced zero lift. At each AOA, the readings of the aerodynamic forces and pitching moment were taken 1000 times at 10,000 Hz, and represented in their non-dimensional coefficient form using equations 2.2-2.4. The results of the current investigation are compared to the results of Gerontakos [112] and Sharma [113]. The variation of lift and drag coefficient with AOA is illustrated in Figure 3.7, whereas the moment coefficient results are seen in Figure 3.8.

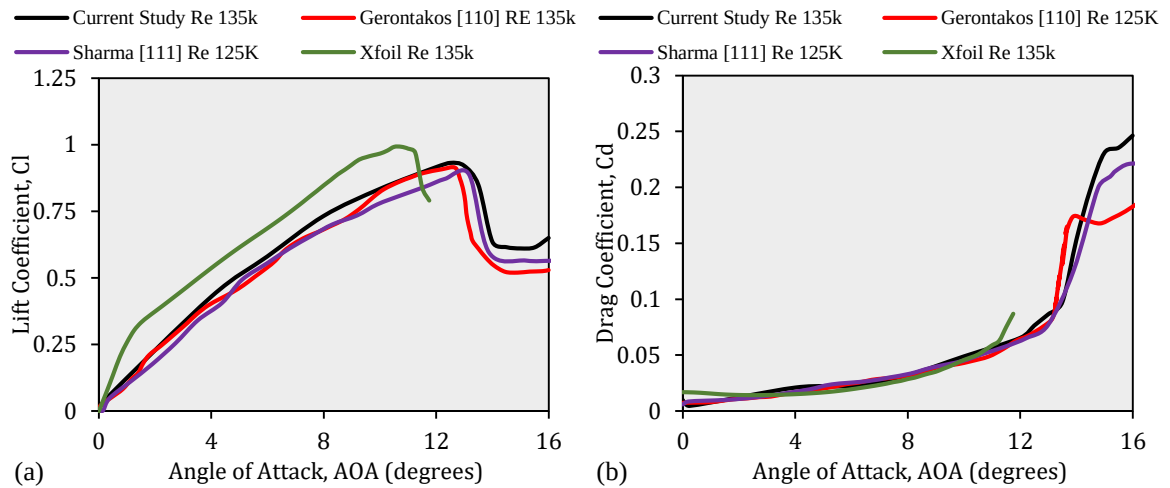


Figure 3.7 a) Lift and b) drag coefficient for NACA 0012

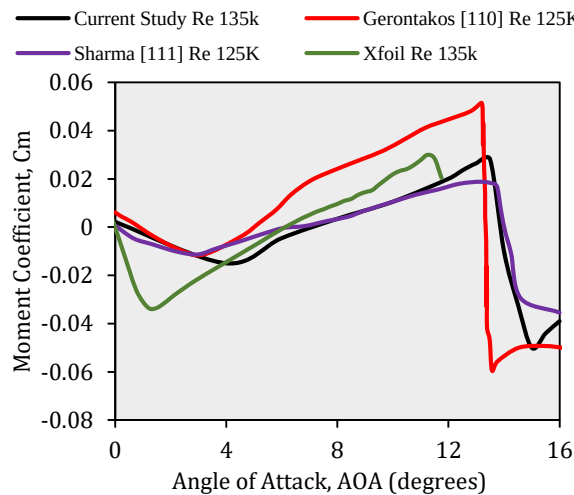


Figure 3.8 Moment coefficient for NACA 0012

Comparing the experimental values to the previously published results shows that the slope of the lift curve is comparable to previous results. However, xfoil predicts higher values than experimental results. The current testing shows a slight change in the lift curve slope after 4 degrees AOA. This effect is also depicted in the results reported by Sharma [113]. Before the stall, as the AOA rises, the flow over the wing becomes more turbulent, which creates vortices that disturb the smooth flow of air over the wing. These vortices cause the effective AOA on different parts of the wing to become uneven, which in turn causes the lift curve slope to decrease. This effect is known as the "pre-stall" regime, characterized by a slight decrease in the lift curve slope [114]. Moreover, the stall angle and the maximum lift coefficient also agree with the previously reported results. Similarly, the drag coefficient curve is similar to previous pre-stall regime results. However, the drag rise after the stall is slightly over-predicted in the current results, which are consistent with the lift results. Finally, the pitching moment variation of NACA 0012 with AOA measured during the wind tunnel testing is comparable to previous results. It is observed that the results from Gerontakos [112] show a steeper and more sudden stall compared to Sharma [113] and the current study. This effect also results in a vertical drop in the moment coefficient value. The current study shows a gradual stall and drop in moment coefficient, indicating that the stall was not uniform across the airfoil surface.

The static wind tunnel testing of the NACA 0022 section at a Reynolds number of 0.75×10^5 was conducted by varying the AOA from 0 to 180 degrees with a step size of 0.25 degrees. Zero-degree AOA was calibrated at the position where the airfoil produced zero lift. At each AOA, the readings of the aerodynamic forces and pitching moment were taken 2000 times

at 10,000 Hz to ensure accurate results. The deviation of the lift and drag coefficients with AOA is depicted in Figure 3.9. The range of values at each angle is represented by error bars with their magnitude variation with AOA at the top of each plot.

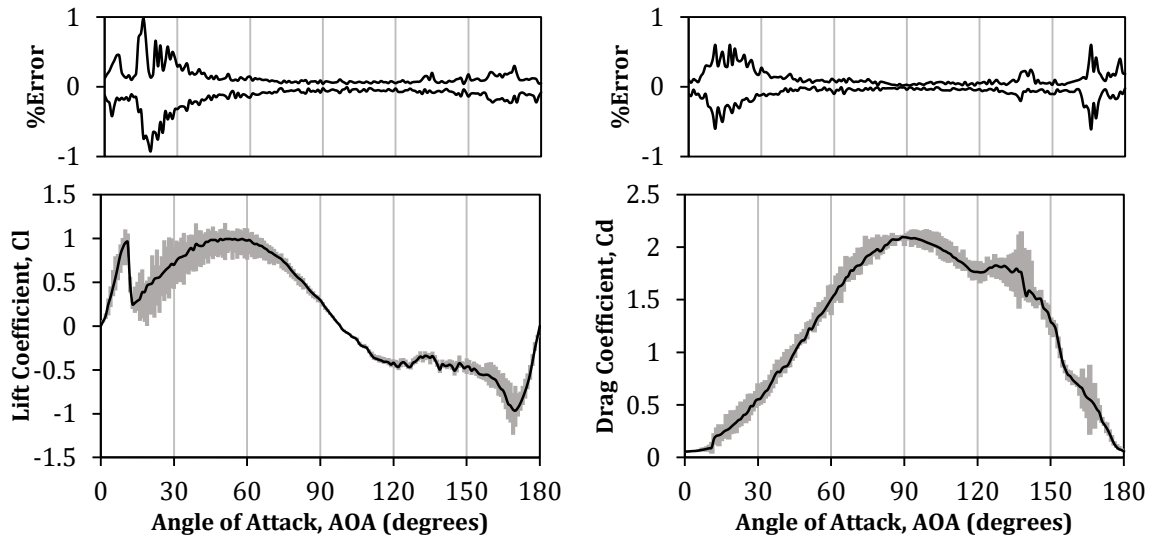


Figure 3.9 Lift (left) and Drag (right) coefficients for NACA 0022

The airflow accelerates over the upper surface compared to the lower surface of NACA 0022 at lower angles of attack. This creates a pressure difference which generates lift that increases with the AOA. The lift of the NACA 0022 section rises linearly and then drops suddenly when the airfoil experiences a stall. As the AOA rises further, the airflow on the upper surface can no longer shadow the curvature of the airfoil and begins to separate from the surface. This is known as flow separation, which results in higher drag and lower lift. The error magnitude is also greater near the stall and post-stall range which gradually reduces as the airfoil AOA increases. The airflow is highly turbulent and unsteady at post-stall AOA's, which is described by the formation of a leading edge vortex traveling over the airfoil surface. This results in unsteady pressure distribution over the surface resulting in higher variance. The variance increases again at higher AOA's, between 140 and 170,

indicating flow unsteadiness. The reattachment process occurs as the pressure gradient on the airfoil surface becomes favorable again, which means that the pressure increases in the airflow direction. This creates a favorable pressure gradient that encourages the separated flow to reattach to the surface. During the reattachment phase, the flow is highly unsteady, resulting in higher recorded values variance. The deviation of the moment coefficient with AOA is shown in Figure 3.10. The range of values measured at each angle is represented by error bars with their magnitude variation with AOA shown at the top of Figure 3.10. Wind tunnel tests have shown that the moment coefficient of the NACA 0022 airfoil follows a characteristic curve as the AOA is varied. This curve typically shows a linear increase in the moment coefficient at low AOAs, followed by a rapid increase as the AOA moves towards the stall angle. Beyond the stall angle, the moment coefficient decreases rapidly due to the separation of the airflow over the airfoil.

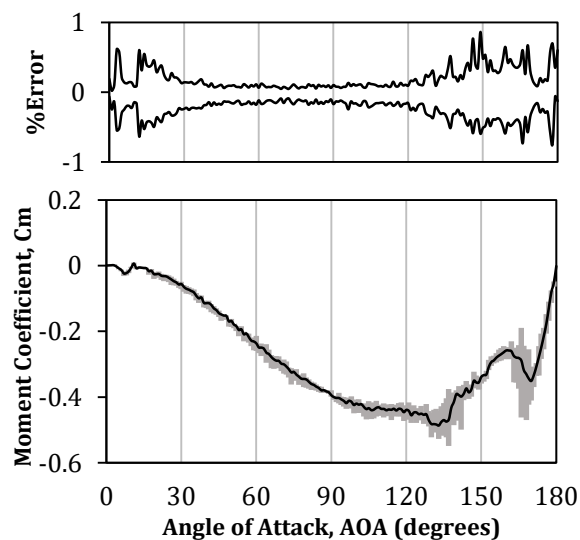


Figure 3.10 Pitching moment coefficient for NACA 0022 airfoil

Wind tunnel testing for the NACA 0022 airfoil was done at three various Reynolds numbers to investigate airfoil performance under different flow conditions. The Reynolds

number of the flow over the airfoil was varied by changing the wind tunnel velocity. The flow is typically laminar and smooth at low Reynolds numbers, and the airfoil's performance may be dominated by viscous effects such as skin friction. Conversely, the airflow becomes more turbulent as the Reynolds number increases, and the performance of the airfoil may be dominated by aerodynamic effects such as pressure gradients and vortex shedding. Wind tunnel testing at different Reynolds numbers provides valuable insights into the efficacy of the airfoil over a wide range of operating conditions and sizes of VAWTs. The values measured for lift, drag, and moment from the wind tunnel testing at different Reynolds numbers are equated in Figures 3.11, 3.12, and 3.13, respectively. The plot is zoomed-in for lower AOA values and shown in the inset to better compare the near-stall behavior of the airfoil at each Reynolds number.

The lift curve behavior is similar for low (75,000), intermediate (100,000), and high (150,000) Reynolds numbers at pre-stall AOAs. The maximum lift coefficient and stall angle increase slightly as the Reynolds number increases. The flow is more turbulent at a higher Reynolds number, which energizes the boundary layer and delays the onset of boundary layer separation on the airfoil surface. Hence the stall angle shifts to 14° at a higher Reynolds number compared to 11° for the low Reynolds number and 12° for the intermediate Reynolds number. The same behavior is evident when comparing the drag coefficients at the pre-stall AOA regime shown in figure 11. The drag increases drastically when the airfoil stalls and the stall angle shifts to a higher value with an increasing Reynolds number. However, at very high AOAs, all three curves lie very close to each other and they remain overlapped for most of the AOA range.

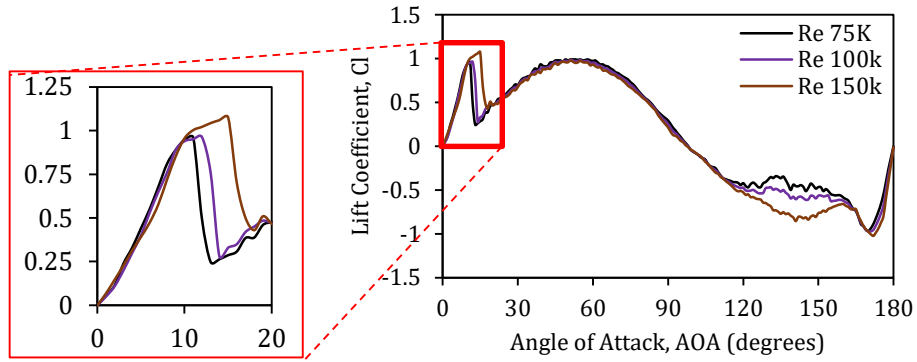


Figure 3.11 Lift Coefficient of NACA 0022 at different Reynold Numbers

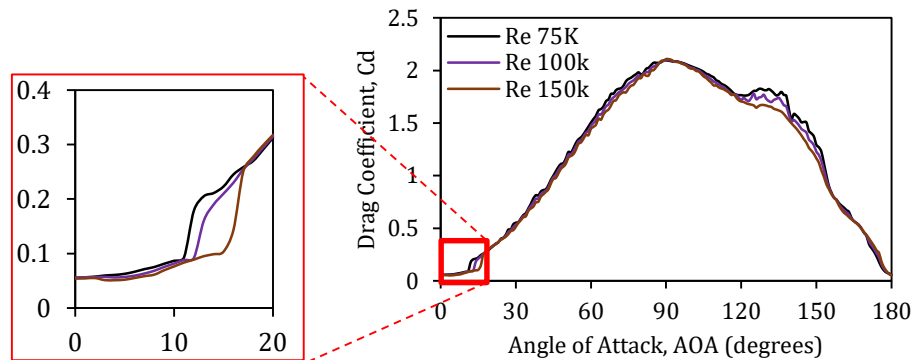


Figure 3.12 Drag Coefficient of NACA 0022 at different Reynold Numbers

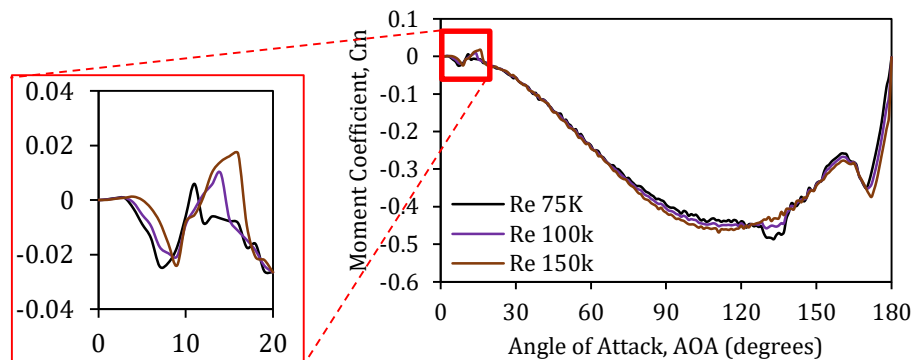


Figure 3.13 Moment Coefficient of NACA 0022 at different Reynold Numbers

The lift and drag coefficients remain somewhat similar at post stall AOA's until the early signs of the reattachment process. Similarly, the moment coefficient also follows a similar trend giving slightly higher values of the moment coefficient at a higher Reynolds number. The data shows some fluctuations in the aerodynamic forces and moment coefficients

between 135 to 165 degrees. This can be attributed to the presence of vortices and turbulent flow structure in the test environment. These complex flow phenomena can cause variations in the turbulent intensity of the airflow, leading to fluctuating results at different angles. Interestingly, this phenomenon has also been previously reported by Holst [115]. These fluctuations are also more distinct at lower Reynolds numbers and tend to diminish at higher Reynolds numbers.

3.2.3 Dynamic Testing

After static testing, the NACA 0012 airfoil was subjected to dynamic testing to validate the pitch control system. The NACA 0012 section oscillated around a mean AOA of 10 degrees and changing the amplitude by 15 degrees. The airfoil AOA was oscillated using the sine function given by equation 3.4.

$$\alpha(t) = 10 + 15\sin\omega t \quad (3.4)$$

Here α is the instantaneous AOA in degrees, ω is the oscillation frequency, and “ t ” is time. The validation is performed at a reduced frequency of 0.1, and the oscillation frequency is calculated using equation 3.1. Dynamic wind tunnel testing is also performed at a Reynolds number of 135,000 based on airfoil chord length. The variation of lift and drag coefficients during the oscillatory airfoil motion with AOA is shown in Figure 3.14, whereas Figure 3.15 shows the variation of the pitching moment coefficient. The solid lines represent the aerodynamic coefficient value during the pitch-up stroke (marked $\alpha\uparrow$ in the legend), and dotted lines indicate the pitch-down stroke (marked $\alpha\downarrow$ in the legend) during the oscillatory motion of the airfoil. The plots also include the results from static testing for comparison.

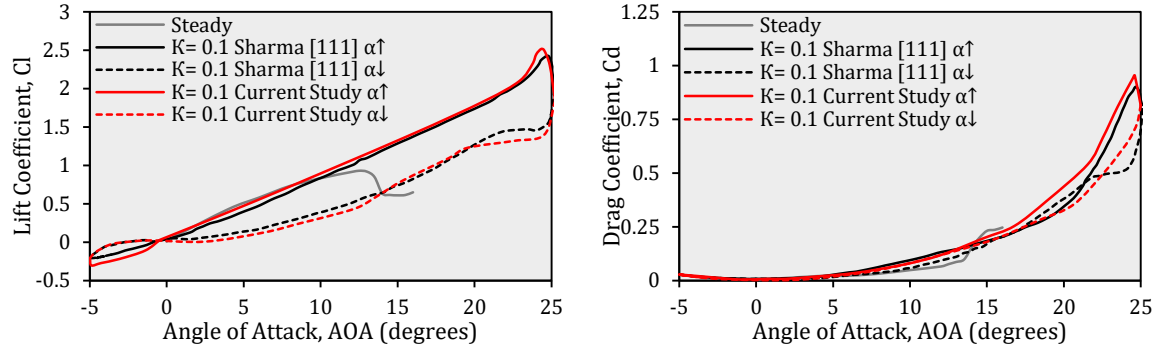


Figure 3.14 Variation of lift (left) and drag (right) coefficients for $\alpha=10^\circ+15^\circ\sin\omega t$

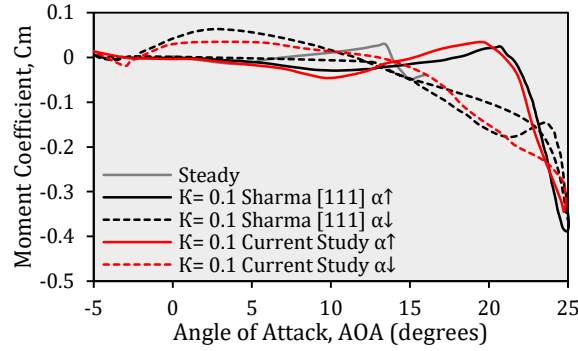


Figure 3.15 Variation of pitching moment coefficient during oscillation

It is observed that similar to static tests, the lift and drag values are slightly higher for current results than previously reported ones. However, the lift loss and drag increase near the static stall AOA is not observed during the pitch-up motion. Instead, the lift and drag continue to increase without any change in slope. This behavior is attributed to the airfoil surface moving upwards as the flow tends to move away from the surface. Initially, the boundary layer is completely attached as the upstroke portion of the cycle begins. As the AOA increases, adverse pressure gradient is formed resulting in flow reversal, and the attached turbulent boundary layer breaks down, forming a vortex in the leading edge region. This vortex grows and travels along the surface until it is shed into small vortices around the maximum AOA, causing the boundary layer to completely disconnect from the surface of the airfoil. During the downstroke motion, the boundary layer remains detached

until reattachment begins gradually downstream with decreased incidence. The results are consistent with the dynamic stall behavior of oscillating airfoils explained by McAlister [116] and McCroskey [117]. The pitching moment is also affected by the generation of the vortices. The comparison reveals that the NACA 0012 airfoil stalled earlier than the tests performed by Sharma [113]. The results also indicate signs of late reattachment of the flow. This difference can be caused by different turbulence levels and surface finishes. Dynamic wind tunnel testing for NACA 0022 is performed at a Reynolds number of 75,000 at a reduced frequency of 0.1. The deviation of lift and drag coefficients throughout the oscillatory airfoil motion with AOA is shown in Figure 3.16, whereas Figure 3.17 shows the variation of the pitching moment coefficient.

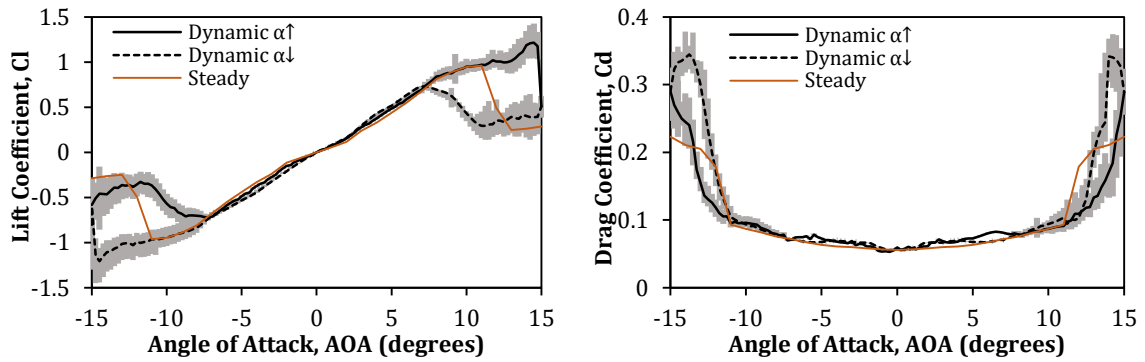


Figure 3.16 Lift (left) and drag (right) coefficients for $\alpha(t) = 0^\circ + 15^\circ \sin \omega t$

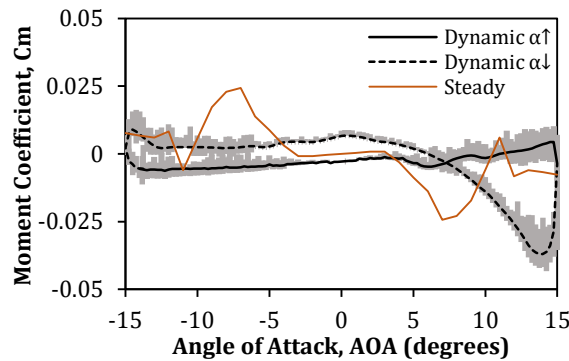


Figure 3.17 Moment coefficient for $\alpha(t) = 0^\circ + 15^\circ \sin \omega t$

The aerodynamic coefficients are similar for static and dynamic tests at pre-stall shallow AOAs. However, the dynamic testing shows a hysteresis loop indicating a non-linear correlation between the aerodynamic coefficient and AOA at the post-stall AOA range, whereby the aerodynamic coefficients follow a different path during the up-stroke and down-stroke of the oscillation. At high AOAs, the appearance of non-unique aerodynamic coefficient magnitudes that depend on the flow history (flow history pertains to whether the AOA was decreasing or increasing when the aerodynamic coefficient was recorded) results in a hysteresis loop. It is also observed that the maximum lift coefficient and the stall angle increased during the dynamic testing. The clockwise hysteresis loop detected for the lift coefficient is due to the separation bubble that migrates and reduces in the streamwise direction. The flow over the airfoil remains turbulent from the separation bubble to the trailing edge. Eventually, the bubble bursts at an AOA slightly above the static stall angle ensuing in a large-scale separated flow [35]. The airfoil stalls, and the lift coefficient reduces drastically. The airflow is highly separated when the pitch-down motion starts. After the initiation of the pitch down stroke, the lift coefficient increases and continues to rise until it meets the static stall values around 7 degrees AOA. This increase in lift coefficient specifies that the flow has reattached to the surface, and the separation region is shrinking with decreasing AOA [36]. The hysteresis loop is similar at negative AOAs with slight deviations in stall angle and analogous maximum lift coefficient values. The drag coefficient also shows a hysteresis loop which is significantly different at positive and negative AOAs. The stall delay also results in a delayed drag rise during the upstroke, and the drag values reduce as the flow starts to reattach during the downstroke. The moment

coefficient remains relatively constant during the entire pitch-up stroke of the oscillation and drops significantly as the airfoil stalls. The moment coefficient also increases as the flow reattached to the blade.

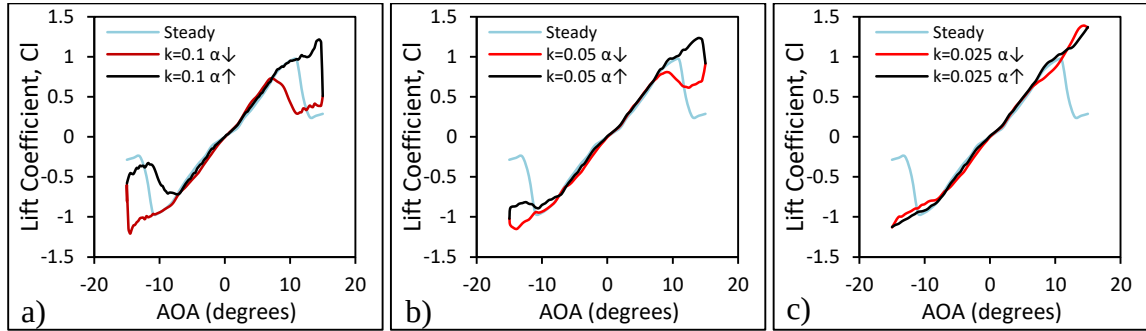


Figure 3.18 Dynamic lift coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$

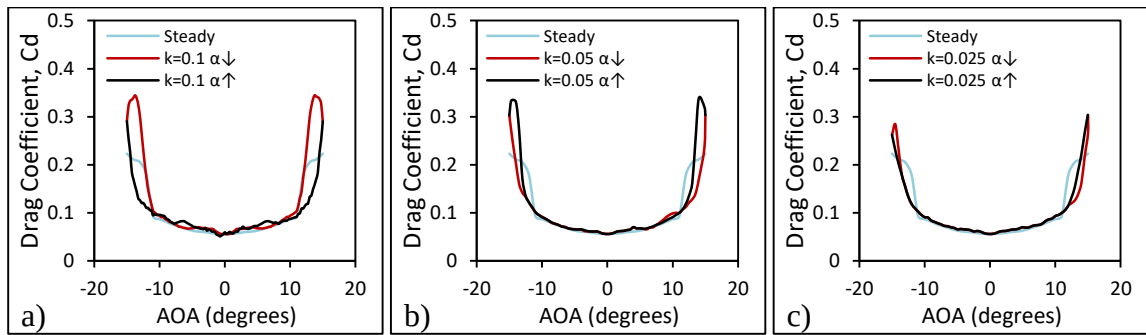


Figure 3.19 Dynamic drag coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$

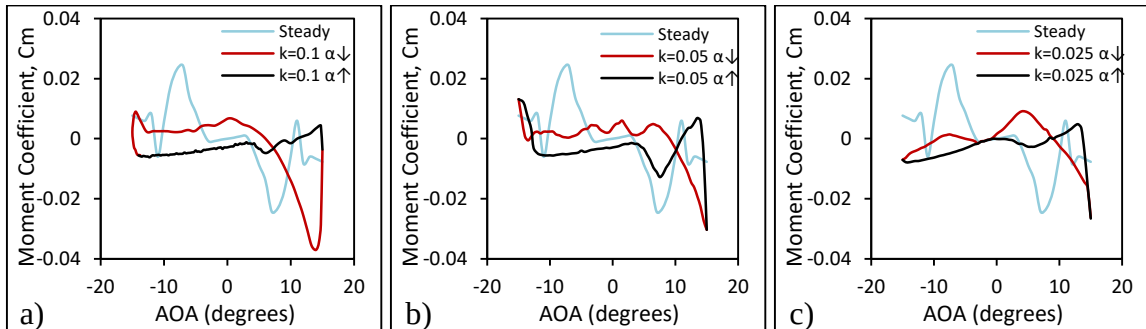


Figure 3.20 Dynamic moment coefficient at a) $k=0.1$, b) $k=0.05$, and c) $k=0.025$

The dynamic wind tunnel testing of the NACA 0022 airfoil in pitch oscillations was performed at different oscillation frequencies. The reduced frequencies for the wind tunnel

tests were 0.1, 0.05, and 0.025, corresponding to highly unsteady, unsteady, and quasi-steady oscillatory conditions. The mean AOA and AOA amplitude was kept at zero and fifteen degrees. The lift coefficient, drag coefficient, and moment coefficient for the three cases with different reduced frequencies are shown in Figures 3.18, 3.19, and 3.20, respectively. In addition, the results from static tests are included for a better comparison.

The lift coefficient shows a hysteresis loop that reduces in intensity as the reduced frequency decreases. It is also found that the direction of the hysteresis loop also changes from clockwise for $k=0.1$ to counter-clockwise for $k=0.025$. The counter-clockwise hysteresis loop allows the airfoil to achieve a higher C_l max value, whereas the counter-clockwise hysteresis loop is associated with a significant drop in C_l . The change in the hysteresis loop direction is also observed in the drag coefficients. The stall is delayed for the test having a reduced frequency of 0.05, and the separation does not occur for the case with a reduced frequency of 0.025. Hence the lift and drag coefficients overlap the steady test values. When the moment coefficient variation for the three reduced frequencies is compared, it is observed that there is a abrupt reduction in the moment coefficient at maximum AOA, which starts to increase with the pitch-up stroke. However, the increase is very sudden at $k=0.025$ compared to $k=0.1$. This behavior is attributed to the fact that when the airfoil oscillates with a lower frequency, it allows more time for the flow field to stabilize.

3.3 Preliminary Design Using Q-Blade

The preliminary design of the wind turbine is done using QBlade simulation software. QBlade is a free and open source software tool for designing and analyzing wind turbines

developed by the Institute for Solar Energy Research in Hamelin (ISFH) and the University of Hanover in Germany. QBlade uses the Double Multiple Streamtube (DMS) method for the numerical analysis of VAWTs that divides the turbine rotor into several blade elements, which are then analyzed individually. The aerodynamic forces on each blade element are calculated depending on the local wind speed, blade angle, and airfoil aerodynamic properties. QBlade includes a large library of airfoil data from various sources, including wind tunnel measurements and CFD simulations. QBlade uses mathematical models and extrapolation techniques to estimate the lift and drag for the NACA 0022 section based on the available data. However, inaccuracies in the mathematical model affect the performance prediction of the turbine rotor. The BEM method also takes into account the rotational velocity of the rotor, which affects the local wind speed and the AOA of the blade element. The induced velocity caused by the rotation of the turbine rotor is also considered. QBlade software is used for preliminary wind turbine design its performance estimation.

3.3.1 Airfoil Selection and its Polar Data

The design process started with the selection of the section. The simulations are carried out for NACA 0012, 0015, 0018, 0022 and 0025 airfoils. The aerodynamic polar data for NACA 0012 and NACA 0022 generated during the wind tunnel testing was imported into QBlade. Whereas, the QBlade inbuilt functions were used to generate the polars for remaining airfoils. Qblade uses the xfoil data at low AOAs and extrapolates the values from complete 180 degree using Montgomery method. The airfoils sections with 360 degrees polars are shown in Figure 3.21.

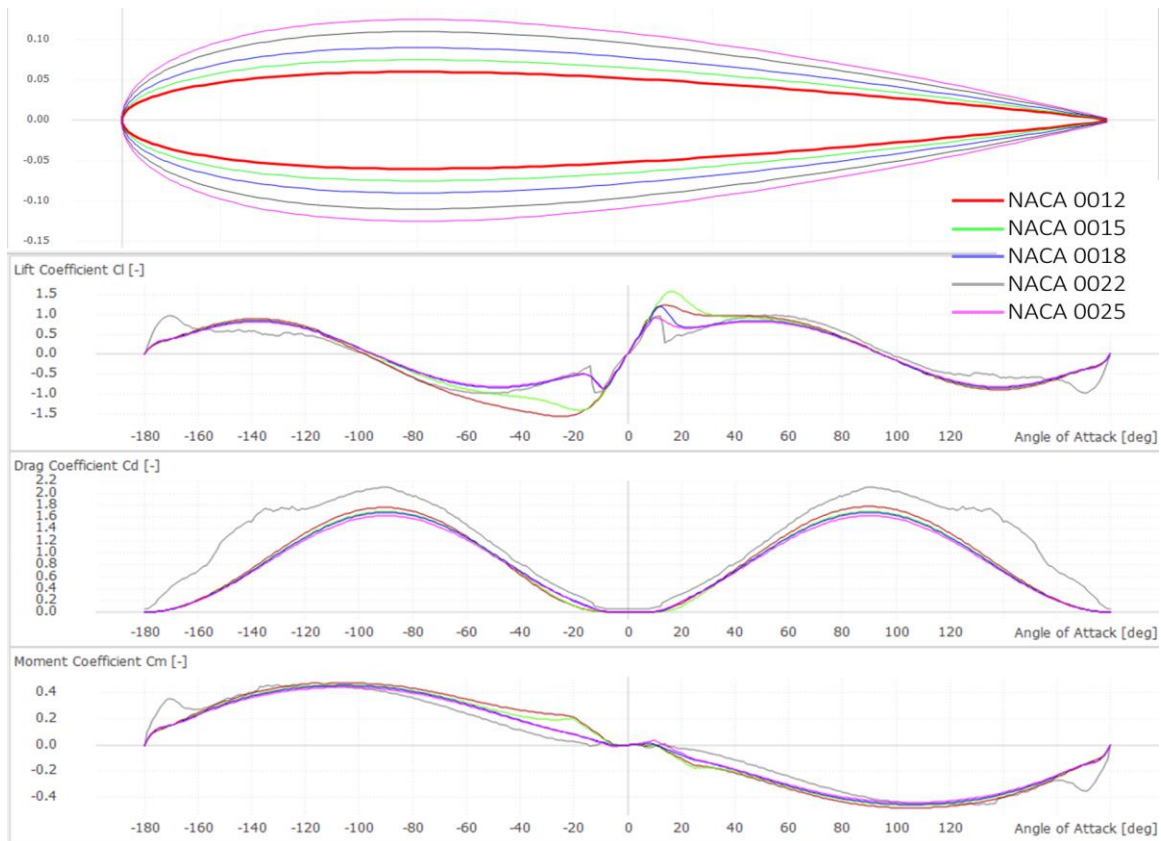


Figure 3.21 Five airfoils with their polars

The turbines were designed with three straight blades with different airfoil sections. The blades had a chord of 0.25 meters and height of 1 meter. The turbine diameter was set at 1 meter. The wind turbine for NACA 0022 is shown in the Figure 3.22.

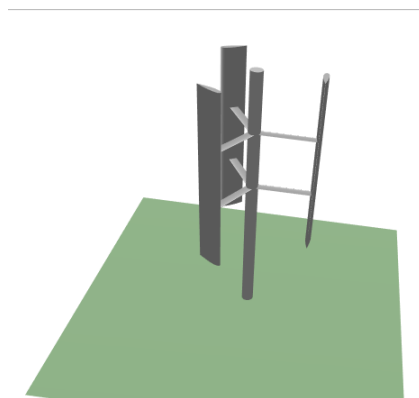


Figure 3.22 Preliminary Design of Wind Turbine

3.3.2 Performance Evaluation

After the wind turbine has been modelled, it was subjected to performance analysis using QBlade where, the balance of momentum is combined with the forces of the blades, so the flowing air pass through the rotor against the wind once and with the direction of the wind once. The simulation is analyzed at various TSRs to evaluate power coefficient and thrust coefficient produced by the turbine as shown in Figure 3.23.

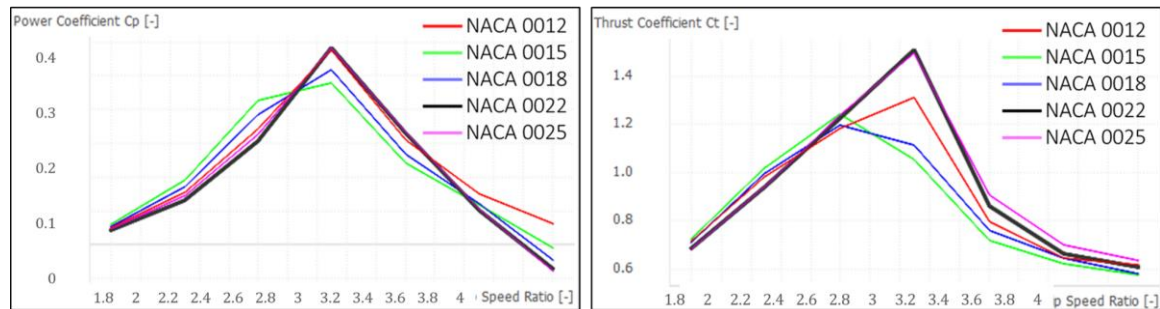


Figure 3.23 Power and Thrust coefficient variation with TSR

The results from the analysis revealed that the NACA 0022 and 0025 airfoils gave the highest c_p values, with both airfoils achieving a c_p of around 0.56 at optimum TSR of 2.5. The other airfoils had maximum c_p values ranging from 0.42 to 0.51 at. However, the NACA 0022 airfoil gave the highest c_t , with a value of 1.52 Nm, compared to 128 Nm for the NACA 0025 airfoil. The other airfoils had much lower torque values at optimum TSR. The NACA 0022 airfoil has a thickness to chord ratio of 22%, which makes it relatively thicker than the other airfoils tested in the analysis. This thicker airfoil generates more lift, which allows for a greater volume of air to be deflected by the blade, which contributes to the higher power coefficient and torque values. In contrast, the NACA 0025 airfoil is even thicker than the NACA 0022 airfoil, with a thickness to chord ratio of 25%. However, the higher thickness also results in increased drag, which reduces the overall efficacy of the

VAWT. The increased drag is due to a larger cross-sectional area of the blade, which increases the surface area of the blade exposed to the airflow and hence increases the frictional resistance of the blade. The final VAWT geometry with NACA 0022 airfoil and the trailing vortices behind the turbine are shown in Figure 3.24.

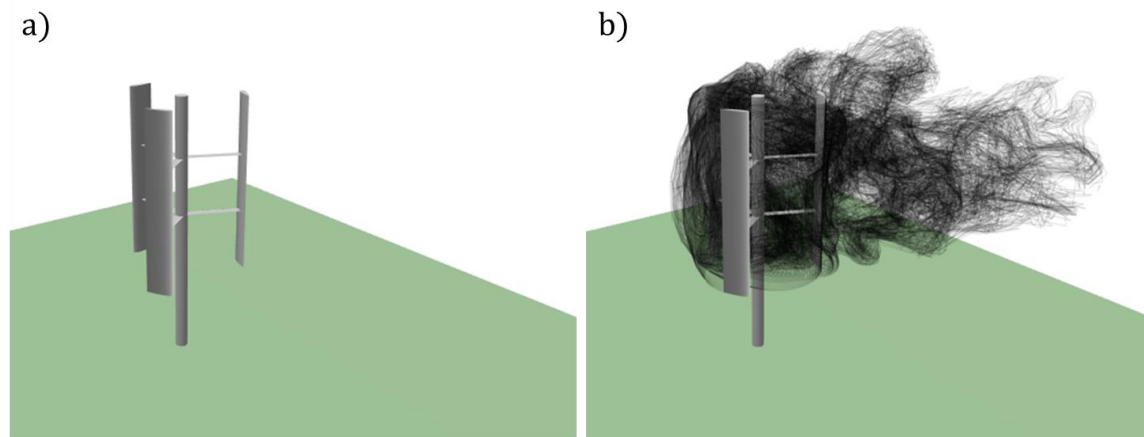


Figure 3.24 a) Preliminary design and b) vortex shedding from the VAWT

In summary, the thicker airfoil (NACA 0022) provides a balance between lift and drag, resulting in higher C_P and torque values compared to the other airfoils tested. On the other hand, the thicker and higher drag airfoil (NACA 0025) resulted in reduced performance compared to the NACA 0022 airfoil, despite its higher thickness. The results of the preliminary design analysis suggest that the NACA 0022 airfoil gives the best overall performance for the VAWT, and this airfoil would be considered for use in the detailed design process.

3.4 Detailed Design Using ANSYS FLUENT

The detailed design process for the VAWT involves using CFD simulations in ANSYS FLUENT to analyze the effect of different design factors on the efficacy of the turbine.

The design parameters include blade height, number of blades, blade chord length, and rotor diameter. The objective of the design process is to maximize the VAWT efficiency by selecting the most appropriate values for these design parameters. The CFD model is first validated by evaluating the simulation results with the experiments to ensure that the simulation model is accurately predicting the VAWT performance. The validation process helps to establish confidence in the precision of the simulation model, which is important for the subsequent detailed design process.

3.4.1 Validation of CFD Model

The baseline model chosen for validation is based on the experimental investigation performed by Danao [52]. The turbine consists of 03 H-configuration straight blades with symmetric profile of NACA 0021 section. Each blade has a chord length of 40 mm. Central shaft has a diameter of 25 mm and the rotor diameter is 700 mm. The values of these constraints of the wind turbine model are presented in Table 3.2.

Table 3.2 Geometric parameters of vertical-axis wind turbine

Turbine Parameter	Symbol	Value
Type	-	Vertical Axis
Blades type	-	Straight H-bladed
Number of blades	N	03
Blade profile	-	NACA 0022
Chord length	c	40 mm
Rotor diameter	D	700 mm
Solidity ratio	σ	0.17
Central shaft diameter	D_{shaft}	25 mm

The computational domains for 2D and 2.5D CFD analysis are shown in Figure 3.25. Computational domain is sub divided into a stationary and a rotary region. Inner region is

circular in shape and houses the turbine. Inner region rotates with the turbine and it is connected to the outer region through rotating interface. The speed of the turbine rotor is controlled through the rotation speed of the inner domain. Grid size of the inner region is kept much finer than the outer region. This allows for improved resolution of flow field variables around the blade and the wind turbine in both upstream and downstream regions. Outer domain is rectangular in shape and contains velocity inlet and outlets at two opposing ends. Remaining sides of the outer mesh domain are fixed as walls so that the computational boundary conditions are consistent with the experimental conditions of wind tunnel testing for the validation case.

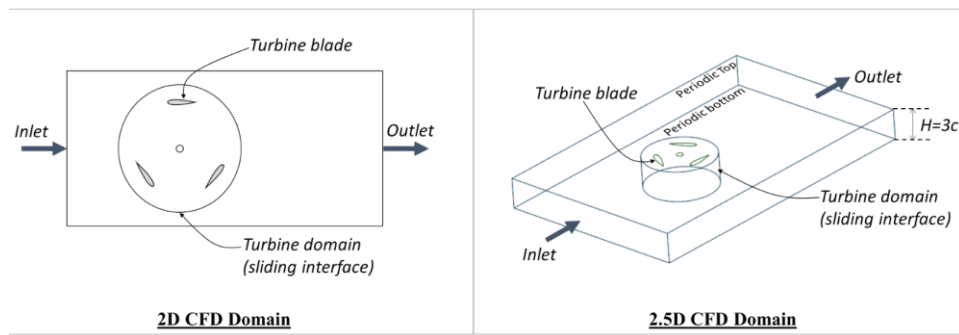


Figure 3.25 Computational Domain and boundary conditions

The numerical analysis is carried out using a 3D double precision pressure based solver of ANSYS Fluent. The calculations are carried out with the “Semi Implicit Method for Pressure Linked Equations (SIMPLE)” coupling algorithm. Time step for each run is calculated based on the rotational velocity of the turbine. Time step is selected such that the turbine rotates one degree for each time step. A total of 100 iterations are run for each time step to minimize the residuals and achieve better convergence at each time step. A residual convergence criterion of 10^{-6} is set for individual variable i.e. velocity, continuity, turbulent kinetic energy and the dissipation factor. However, instead of monitoring the

conventional lift, drag and energy parameters, a different criterion was used. Since the problem under consideration involves a rotating wind turbine, the resultant moment of the turbine is expected to demonstrate an oscillating behaviour repeating after each 120° rotation. On the other hand, one blade would have an oscillating moment repeating after complete rotation of the turbine. It was therefore considered more appropriate to monitor the moment contributed by the three blades together and a single blade. The convergence is believed to be attained when the variation of momentum appears to be periodic with a constant amplitude and frequency. The steady solution is considered converged after five full cycles that show less than 5% differences in amplitude. Hence the results from the first 5 rotations are not included in the averaged results.

3.4.2 Mesh and Turbulence Model Independence

The accuracy and reliability of the results is considerably affected by mesh resolution, the boundary conditions, and the turbulence models used to represent the turbulent flow. To ensure the accuracy and reliability of the CFD results, it is important to implement mesh independence and turbulence model independence tests. The validation simulations were first performed to conduct the mesh independence followed by turbulence model independence. In order to perform mesh independence, CFD analysis is performed using three mesh sizes. A triangular mesh was created, with mesh size increasing as we move away from the turbine. The inner domain acts as a density region where the mesh growth function is kept at lower value than the outer domain. Mesh independence is performed at TSR of 4, which is the optimum operating TSR for this wind turbine from the experimental

results. The mid-plane mesh density of the complete computational domain and the internal domain for coarse, medium, and fine mesh are shown in Figure 3.26.

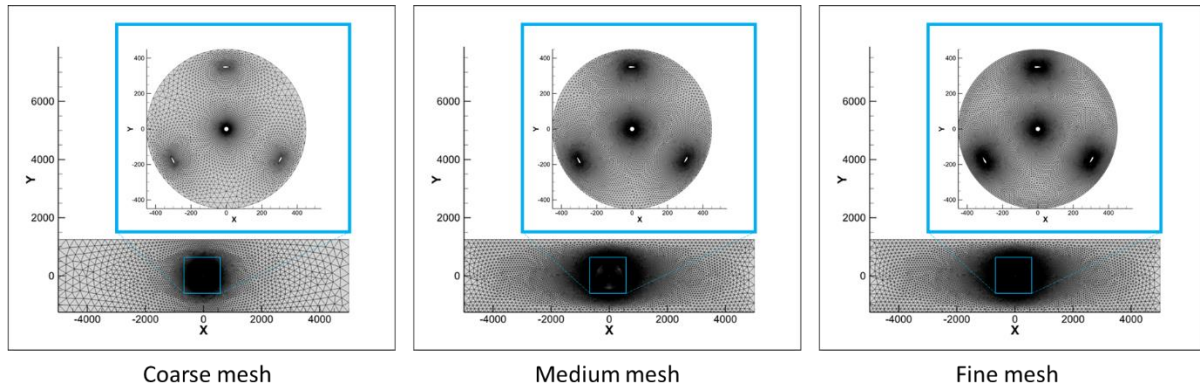


Figure 3.26 Comparison of fine, medium and coarse mesh densities

A 5-layer prism is also incorporated in mesh to capture the viscous effects near the wall better. The mesh size increases progressively away from the surface of blades and the central shaft. A geometric mesh size function of 1.05 was used with maximum mesh size limit of 10 at the interface. Since the computational domain uses a rotating inner zone interfaced to a stationary outside zone, the mesh size at the interface was kept constant. A zoomed-in view of mesh variation in the proximity of the inner domain and nearby a blade is shown in Figure 3.27.

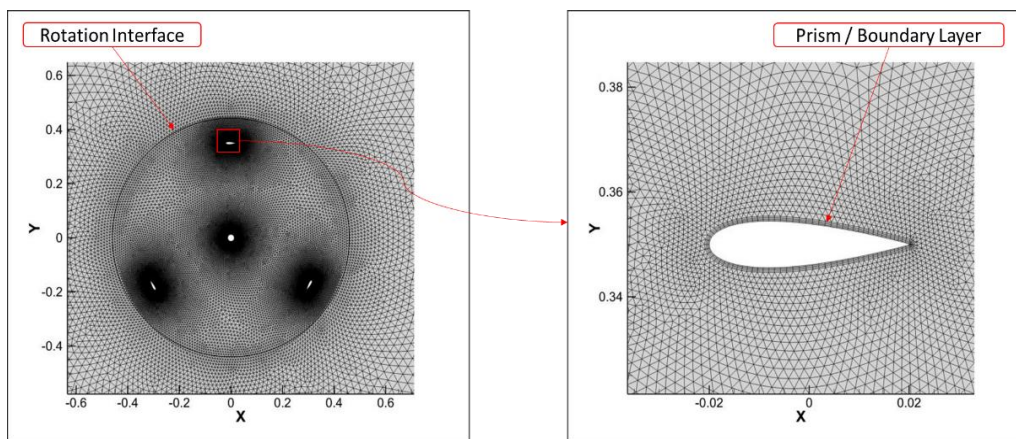


Figure 3.27 Medium mesh density variation near blades

The power coefficient results from three meshes are compared. All the computations are done for 10 cycles and power coefficient C_p is calculated and averaged over the last three cycles for comparison. Size and power coefficients obtained from three meshes are tabulated in Table 3.3.

Table 3.3 Mesh characteristics for independence study

Mesh Size	Mesh size at blades	Total number of cells	Power Coefficient (C_p)
Coarse	4×10^{-4} m	17 K	0.27632
Medium	2×10^{-4} m	34 K	0.26043
Fine	1×10^{-4} m	68 K	0.26030

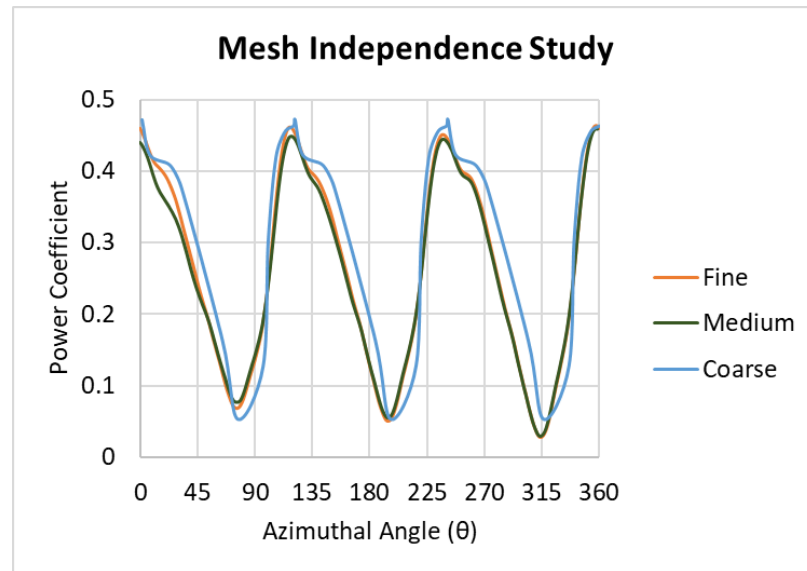


Figure 3.28 C_p Variation with azimuthal position for mesh independence

It is observed that average power coefficient from fine and medium meshes are in close agreement to each other. C_p variation during one cycle from three meshes is also compared. The variation of turbine C_p with azimuthal angle, for 10th rotation of the turbine, is plotted

in Figure 3.28. It is observed that once again medium and fine mesh have very similar results. Hence, medium mesh is used for all further investigations.

After completing the mesh independence study, the next step was to perform turbulence model independence study. In this study, different turbulence models were evaluated to determine their influence on the precision of the CFD simulations. The aim was to identify the turbulence model that produces the most accurate results for the VAWT simulations. A review of previous studies revealed that numerous turbulence models have been used by researchers with varying level of accuracy. Hence it was deemed appropriate to analyze different turbulence models and select the best one based on comparative analysis.

The following turbulence models were considered in the turbulence model independence study:

Spalart Allmaras (SA) model: This turbulence model is built on the one equation eddy viscosity model and is suitable for simulating turbulent boundary layers, separated flows, and other complex flow configurations. It is computationally efficient and is often used for industrial applications.

k- ω SST model: This two-equations eddy viscosity based turbulence model is suitable for simulating both attached and separated flows. It provides accurate predictions of flow separation and reattachment.

Reynolds Stress Model (RSM): This turbulence model is built on the Reynolds averaged Navier Stokes equations and is appropriate for simulating complex turbulent flows with

large-scale fluctuations. It accounts for anisotropy and turbulent shear stresses, making it ideal for simulations of highly turbulent flows.

Detached Eddy Simulation (DES) model: This turbulence model is a hybrid technique that utilizes both RANS and Large Eddy Simulation (LES) methods. It is suitable for simulating flows with both attached and separated regions, and is particularly useful for simulating vortex shedding and wake dynamics.

The results from these turbulence models are shown in Figure 3.29. Based on the results achieved from the turbulence model independence study, the DES and $k-\omega$ SST turbulence models provided the most accurate predictions of the VAWT performance, with the lowest discrepancies between the simulated results and the testing data. The DES model was therefore used for the subsequent detailed design process to analyze the influence of different design parameters on the VAWT power output.

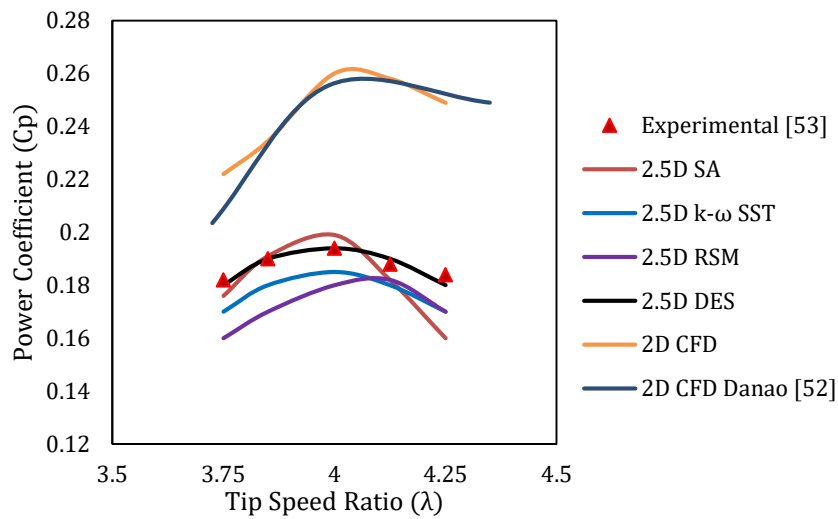


Figure 3.29 Turbulence Model Independence

In addition to overall power coefficient, flow field around the blade is also compared to experimental and numerical results presented by Danao [52] in Figure 3.30.

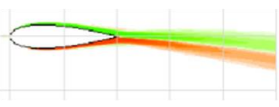
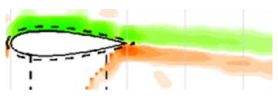
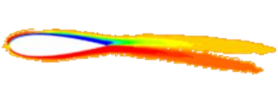
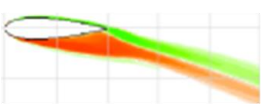
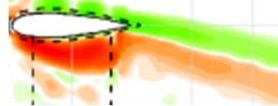
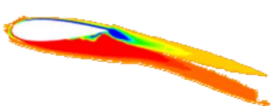
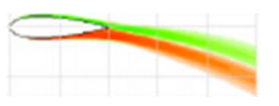
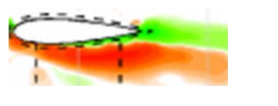
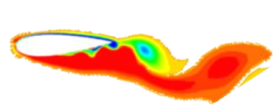
Angle	2D CFD by Danao [52]	PIV [52]	Current study
10°			
70°			
130°			

Figure 3.30 Flow field comparison at $\lambda=4$ from CFD, PIV and current study

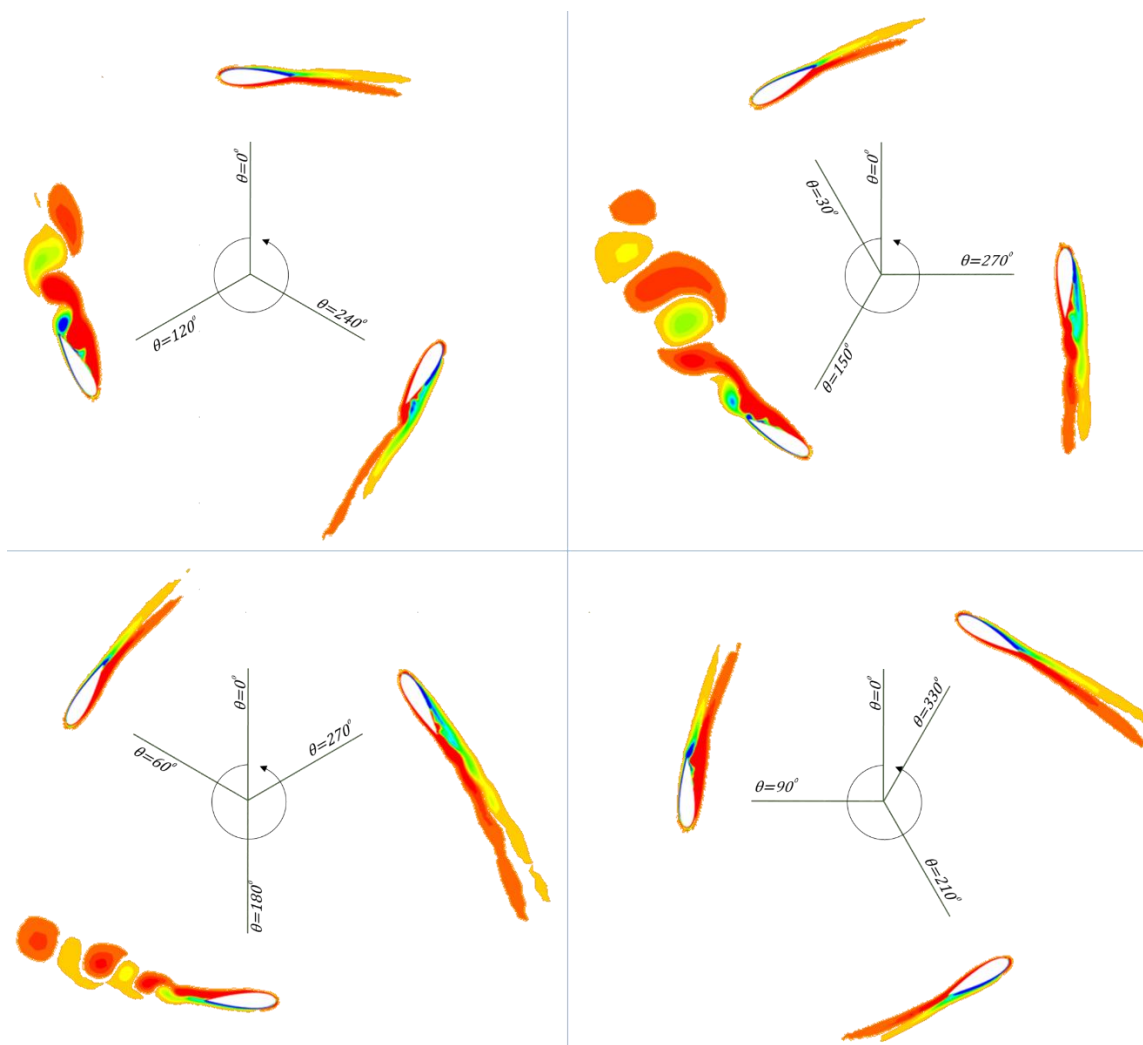


Figure 3.31 Vorticity distribution around blades at different azimuthal angle positions

A detailed view of vorticity distribution around blades at different azimuthal angle positions during the turbine rotation are shown in Figure 3.31. Figure 3.30 provides a comparison of flow field around mid-span of the blade at a tip speed ratio of 4.0. It is observed that the flow field prediction by current CFD model is comparable with the published CFD results as well as the PIV captured flow field. Airflow remains attached to the blade surface at lower AOAs. This results in stream lined flow field as observed at 10° from PIV as well as CFD. At higher AOA, higher pressure region develops below the blade and a lower pressure at upper surface is created. This region grows gradually as the AOA is increased, which can be observed by comparing relative flow fields around the blade at 70° and 130° . Hence, careful examination of flow field and comparison of numerical and experimental results revealed that the 2.5D DES can predict the turbine performance and flow field characteristics with considerable accuracy.

3.4.3 Wind Turbine Design Parameters

After completing the validation of the numerical model, the next step was to investigate the effect of different design parameters on the power coefficient of the wind turbine. These design parameters included number of blades, turbine rotor diameter, blade height, and blade chord length. All four parameters were varied to five different values, called levels, resulting in a total of 20 turbine configurations. Each configuration was analyzed using CFD simulations to identify the optimal turbine design. The minimum and maximum value of these design parameters defines the design space. These values were chosen based on practical considerations and previous research to ensure that a wide range of designs were

analyzed, while also ensuring that the designs were feasible and realistic. The chosen values for each design parameter are given in Table 3.4.

Table 3.4 Wind Turbine Design Space

Parameter	Symbol	Level				
		I	II	III	IV	V
Blade Height	H (mm)	500	750	1000	1250	1500
Blade chord length	c (mm)	100	150	200	250	300
Rotor radius	R (mm)	350	400	450	500	550
No. of blades	n	2	3	4	5	6

The turbine geometries generated with different blade heights, rotor radii, and blade chord lengths are shown in Figure 3.32. Whereas, the wind turbine configurations with different number of blades is illustrated in Figure 3.33.

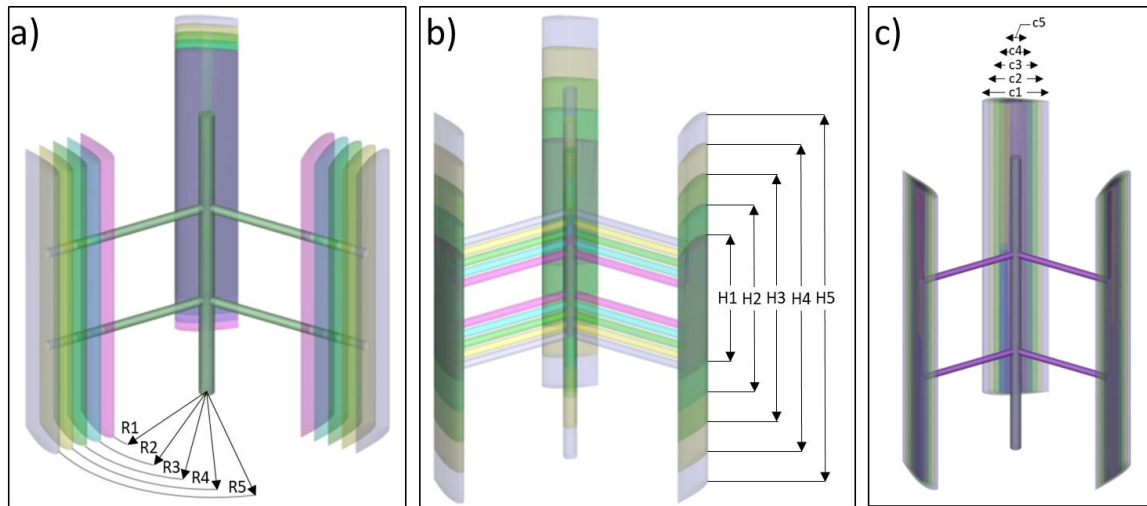


Figure 3.32 VAWT with Different Blade a) Radii, b) Heights, and c) Chords

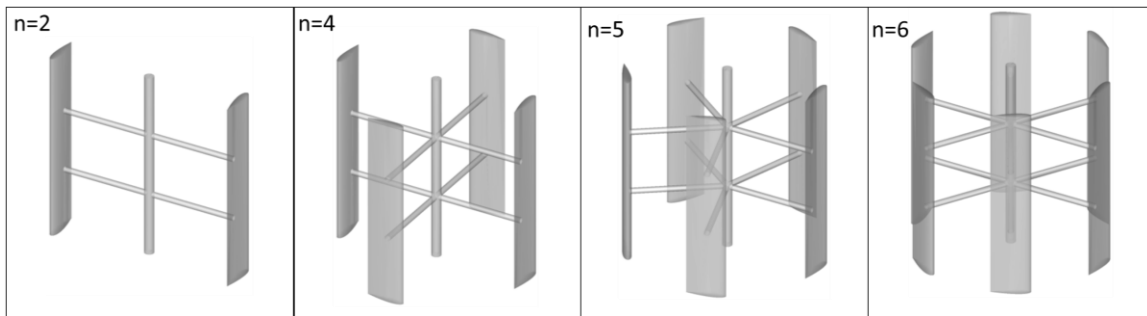


Figure 3.33 VAWT Geometries with Different Number of Blades

All these geometries were analyzed to investigate the effect of each parameter. Hence, only one parameter was varied keeping all other parameters constant to evaluate effect of each design parameter on the power output of VAWTs. For each geometry, the turbine performance was simulated at different TSR values. The range of TSR values varied for each geometry depending upon the TSR value corresponding to peak power coefficient. The effect of chord length of the blade and the rotor radius on the power output of the turbine at various TSRs is shown in Figure 3.34.

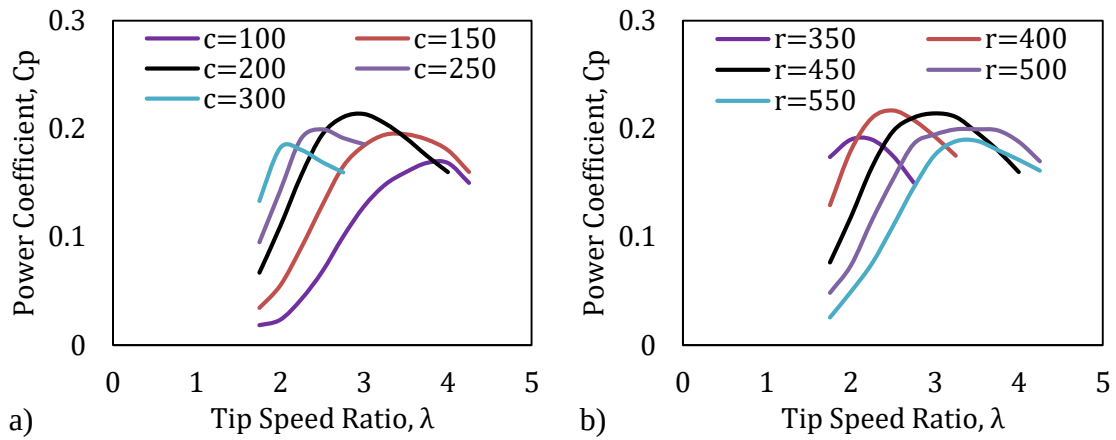


Figure 3.34 Effect of a) Blade Chord and b) Rotor Radius on Power Coefficient

It is observed that increasing the blade chord length increases the turbine power coefficient at lower TSRs. The maximum power coefficient is also achieved at a higher TSR. However, the larger chord results in larger solidity ratio and increased drag as the TSR increases. As a result, a larger chord length turbine is desirable for wind turbines operating at higher TSRs. Similarly, as the rotor diameter of a VAWT increases while maintaining a constant chord length of the blade, the optimal TSR also increases. However, the behavior of the maximum power coefficient of the turbine follows the typical pattern of initially

increasing and then decreasing, despite these changes. Based on these results, the blade chord of 200 mm and a rotor radius of 400 mm is selected for final wind turbine.

The effect of number of blades and blade height on the performance of the turbine at various TSRs is shown in Figure 3.35a and 3.35b, respectively. The study is performed at different TSRs for each turbine configuration.

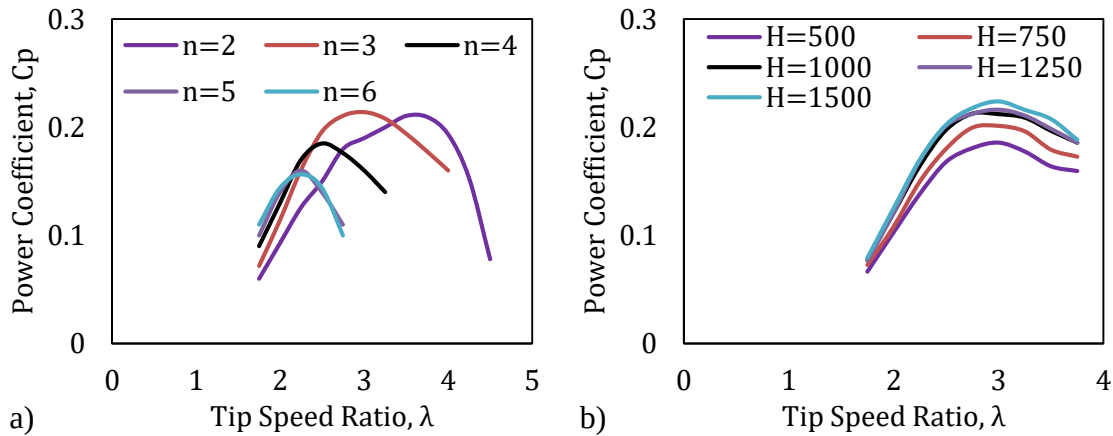


Figure 3.35 Effect of a) Number of Blades and their b) Height on Power Coefficient

The number of blades in a VAWT significantly affects its performance and aerodynamics. Based on the analysis of the five VAWTs with different numbers of blades, it is perceived that turbine solidity increases with the number of blades. Solidity is the ratio of the projected area of the blade to the frontal area swept by the rotor, and a higher value of solidity results in higher drag, lower blade efficiency, and lower power output. Hence, VAWTs with fewer blades tend to have lower solidity, and therefore, higher power coefficients at higher TSRs. Furthermore, the results show that the two bladed turbine has a higher C_p at greater TSR values but lower C_p at lower TSR values. In contrast, turbines with higher number of blades had better performance at lower TSRs. This difference in

performance can be attributed to the aerodynamic interference between the blades. In general, fewer blades lead to less interference between the blades and lower losses due to tip vortices. However, this also results in higher cyclic loading on the blades, which can reduce the turbine's durability. On the other hand, more blades lead to better stability and lower cyclic loading, but at the expense of higher losses due to wake interference. The blade height is found to be least significant parameter and results in similar efficacy of the wind turbine. The blade length can be used for wind turbine scaling based on the power requirements of the wind turbine.

Based on the detailed analysis using CFD, the wind turbine has three NACA 0022 straight blades which are 1000 mm in height having a 200 mm chord length. The turbine rotor has a radius of 400 mm. The design parameters for the wind turbine's final geometry are shown in Table 3.5.

Table 3.5 Final Design Parameters for the Wind Turbine

Parameter	Symbol	Value
Type	--	Vertical Axis wind Turbine
Blades type	--	Straight blades (H-type)
Number of blades	n	03
Blade Height	H	1000 mm
Blade profile	--	NACA 0022
Blade Height	H	1000 mm
Chord	c	200 mm
Rotor radius	r	400 mm
Central Shaft diameter	d	40 mm
Support arms	n_s	02 per blade
Support arm profile	--	Flat Plate
Average Support Arm chord	c_s	25 mm
Location of Support arms on blade	--	0.33H and 0.66 H

CHAPTER 4

EXPERIMENTAL TESTING OF WIND TURBINE

In the preceding chapters, the design of a VAWT(VAWT) was developed and optimized through computational analyses. However, in order to fully comprehend and confirm the performance of the turbine, experimental testing is necessary. This chapter emphasizes on the experimental testing of the VAWT, including the manufacturing process, experimental setup, data logging, and testing results.

The manufacturing process involved various components of the turbine including the turbine blades, generator, turbine blade supports, central shaft, and the base structure on which the turbine would be mounted. The blade manufacturing process was carefully designed to ensure the blades' structural integrity and aerodynamic performance. The generator selection process involved considering factors such as power output, size, and cost. The design and fabrication of the turbine blade supports and central shaft were also optimized to ensure efficient energy conversion and durability. Additionally, the base structure was designed and manufactured to provide a stable platform for the turbine and prevent excessive vibrations during operation.

The experimental setup was designed to simulate wind turbine operation and recording the test conditions and power output of the wind turbine. Data logging systems were installed to collect various performance parameters such as power output, turbine rotational speed, and wind speed. The testing results obtained validate the computational analyses

conducted in previous chapter and provide valuable insights into the VAWT's actual performance and its potential for practical applications.

4.1 Manufacturing of Wind Turbine

The design process focused towards the aerodynamic efficacy and power produced by the wind turbine. The manufacturing process includes material selection, manufacturing, durability, and cost analyses. In this section, we will discuss the manufacturing process of a VAWT(VAWT), including a detailed design of turbine blades, the central shaft, and struts, and the selection of the generator.

4.1.1 Turbine Blades

The detailed design of the VAWT showed that the turbine blade should have a NACA 0022 blade profile with a 1-meter height and a 0.2-meter chord length. The material selected for the blades was aluminum because of its lightweight, structural strength, and corrosion resistance properties. Moreover, the blade's surface was painted white to protect it from harsh environmental conditions and improve its visibility. The manufactured blade and its airfoil profile are shown in Figure 4.1.



Figure 4.1 Turbine Blade

4.1.2 Central Shaft and Struts

Each blade of the VAWT connects to the central shaft through two struts. The design process of the struts and central shaft involved analyzing the structural loads and the aerodynamic forces produced by the turbine blades. The central shaft has a diameter of 0.025 meters and is made of aluminum due to its high strength to weight ratio. The struts were also designed to be lightweight and stiff to minimize deflection and maintain blade alignment. The struts are 0.365 m long to achieve turbine rotor diameter of 0.4. The central shaft and blade support struts are shown in Figure 4.2.



Figure 4.2 Central Shaft and Support Struts

4.1.3 Generator

The selection of the generator is crucial for achieving the desired power production from the wind turbine. In this case, an off-the-shelf 600W generator was selected based on the analysis of the VAWT's potential power output of 680W. The generator is a 48 Volt, 3-phase permanent magnet suspension motor generator. The selection of a 3-phase generator was important to minimize the torque pulsations and improve the efficiency of the energy production method. The generator selected for use on the VAWT is shown in Figure 4.3.



Figure 4.3 Three Phase 600-W Electric Generator

4.1.4 Wind Turbine Base

The wind turbine was mounted on a steel frame base to provide support and stability during its operation. The base structure consists of a square 1m x 1m steel plate with a shaft welded at its center. The shaft is held in place using four angle iron bars welded to the shaft at one end, and welded to the base plate corners at the other end. There is a flange on top of the shaft, and the turbine is mounted on this flange as shown in Figure 4.4. Additionally, there are four wheels installed below the base plate to provide mobility to the turbine.

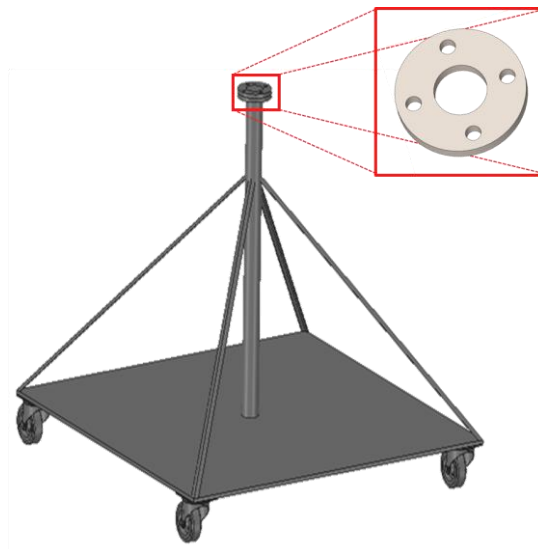


Figure 4.4 CAD Model of Turbine Base and Mounting Flange

4.1.5 Wind Turbine Assembly

After all the individual components of the wind turbine were manufactured, they were assembled into a wind turbine. First, the turbine blades were coupled to the central shaft through the struts. As mentioned earlier, each blade connects to the central shaft through two struts. The central shaft was then coupled to the electrical generator. Once the turbine and generator were assembled, they were mounted on the steel frame base through a flange on top of the central shaft. A rubber padding was placed between the flange and the turbine to mitigate the vibrations. The base provided support as well as mobility for the turbine with the help of the four installed wheels. The final assembled wind turbine is displayed in Figure 4.5, which demonstrates a complete VAWT with three aluminum blades attached to the central shaft and electrical generator mounted atop of the base.



Figure 4.5 Wind Turbine Assembly

4.2 Experimental Setup and Data Logging

The experimental setup for testing and recording wind turbine data comprises several components that are critical to accurately measure and record the data. The wind turbine, designed and manufactured as discussed earlier, rotates under the effect of wind and drives a 600-W electrical generator. The generator output is in alternating current, which is rectified using a rectifier to convert it to direct current to power the load (batteries) through a Maximum Power Point Tracking (MPPT) controller. The MPPT controller's purpose is to optimize the power produced by the turbine's generator by tracking the maximum power point of the system. The MPPT controller used in this experimental setup is a 600W 48V/60V MPPT solar charge controller. It has an operating voltage range of 48V-60V, a maximum input power of 1000W, and is equipped with an LED indicator.

There are two sensor modules employed to measure the current and voltage output of the generator. The ACS712 Current Sensor module is used to measure the current, which is a hall-effect based sensor that measures AC current with high accuracy and linearity. It has a sensitivity of 66mV/A and a range of ± 5 A. The ZMPT101B AC Voltage Sensor Module is used to measure the voltage, which is a transformer-based sensor that measures AC voltage. It has a voltage range of 0-250V AC and a linear output of 0-5V DC. These sensors are connected to an Arduino UNO, which is a microcontroller board. The Arduino UNO provides ground and 5V power to the sensors and receives the current and voltage data. It also receives wind speed and turbine RPM signals from an anemometer and tachometer, respectively. The anemometer used is a cup type anemometer with an operating range of 0-45 m/s, and the tachometer is a digital optical tachometer with a range of 2.0-99,999

RPM. The Arduino UNO is also connected to the laptop where the data is recorded and stored. The recorded data includes current, voltage, wind speed, and turbine RPM, which can be used to record the turbine power output and verify the power output calculation. The experimental setup and its components are shown in Figure 4.6.

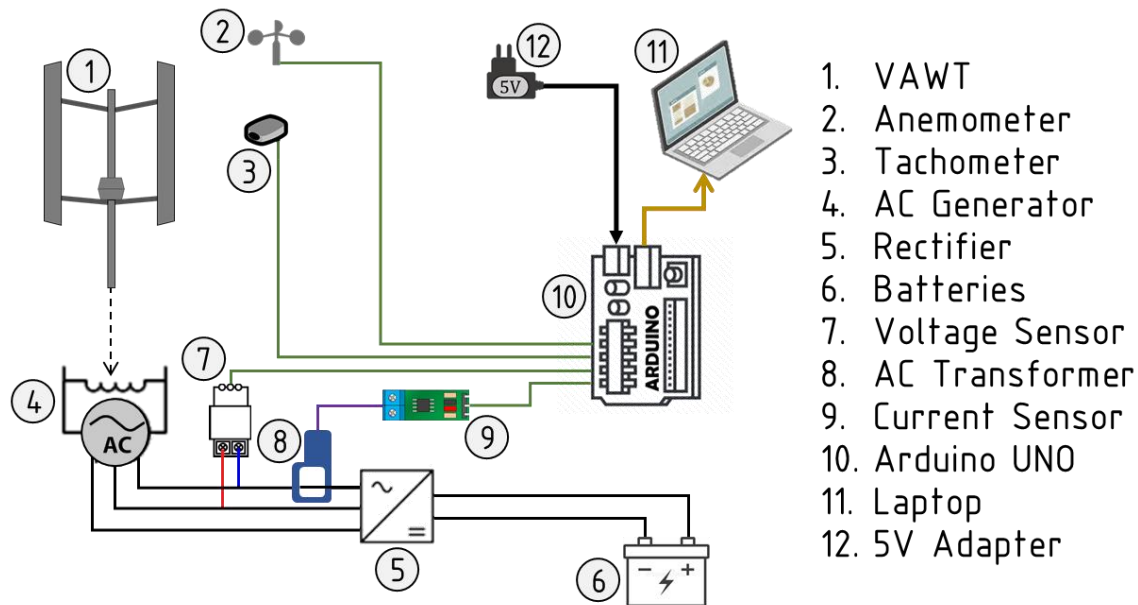


Figure 4.6 Block Diagram of the Experimental Setup and its Components

The experimental setup and data logging system allow for a thorough investigation of the wind turbine performance and validation of the previous analyses. The accuracy of the current and voltage sensors, along with the MPPT controller's ability to track the maximum power point, ensure that the data collected is reliable and can be used to increase the wind turbine's effectiveness.

4.3 Experimental Results

Wind turbine testing is a critical aspect of the development process as it helps to evaluate and optimize the performance of the turbine. In this study, two testing methods were

employed to evaluate the wind turbine performance: lab testing with open-jet and field testing at rooftop. Lab testing with open-jet allows for controlled and repeatable testing conditions, and it is possible to measure the flow velocity at various heights to evaluate flow uniformity and turbulence within the jet. However, it is limited in representing real-world wind conditions. On the other hand, field testing at rooftop provides a more realistic representation of the wind conditions but can be challenging to control and monitor the wind parameters.

4.3.1 Lab Testing with Open-Jet

The lab testing was carried out to evaluate the performance of the wind turbine under controlled conditions. The test results allowed us to identify the wind speed where the turbine starts its rotation and the maximum power output of the turbine. The data also helped to analyze the efficiency of the turbine at several wind speeds and to compare it with the theoretical predictions. The lab testing with open-jet is done by exposing the wind turbine to an open jet with fixed unidirectional velocity. The wind speed was fixed at discrete values, and the flow velocity was measured at various heights to assess flow uniformity, turbulence within the jet, and velocity deficit near the free shear layer. After that, the wind turbine was placed in the jet, and its performance was measured. The flow speed was varied to measure the turbine's starting speed and power output at different wind speeds. During the testing, the electrical power output of the turbine was recorded using a data logging system, which included sensors for measuring wind speed, turbine RPM, voltage, and current. The open jet outlet is circular in shape with 1.35m diameter at the exit. The detailed measurements of the velocity profile and turbulence intensity is carried

out to ensure that the wind turbine is within the constant velocity profile region, which leads to consistent and reliable results in the subsequent performance measurements. The radial velocity profile and Turbulence Intensity (TI) at different axial distances from the nozzle exit are shown in Figure 4.7.

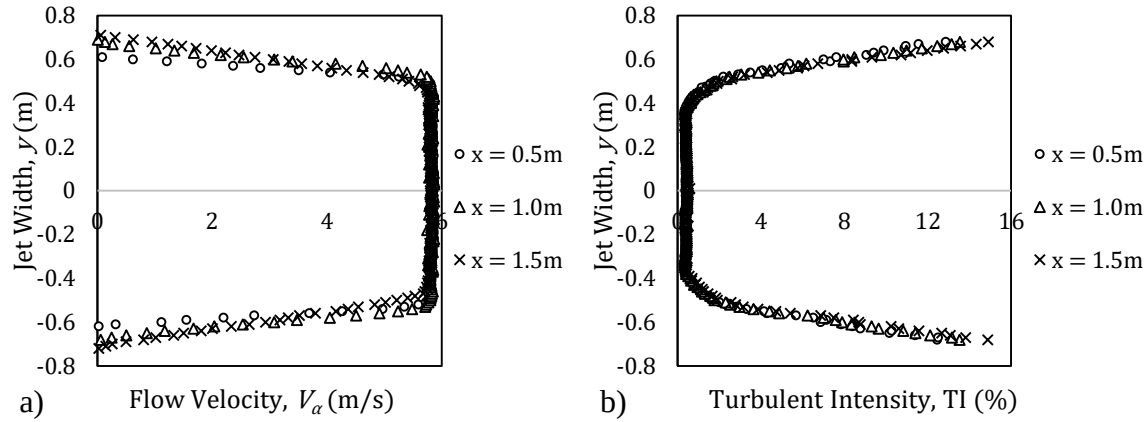


Figure 4.7 a) Velocity Profile and b) Turbulent Intensity for Open Jet

The results of the open jet velocity profiles and turbulence intensity measurements at 0.5, 1.0, and 1.5 m downstream of the nozzle exit plane are presented in Figure 4.7. The velocity profile was found to remain constant at 5.83 m/s within a range of ± 0.5 m from the centerline, when the velocity at the nozzle exit plane was maintained at 6 m/s. This indicates that the entire blade height of the wind turbine will be situated within the region of the constant velocity profile. As a result, for all further measurements, the wind turbine was positioned at a spacing of 1.0 m from the nozzle exit.

The performance of an isolated wind turbine is investigated at a wide range of wind speeds up to 14 m/s. The data was recorded for a duration of 10 minutes for each wind speed. The relationship between the power produced by the wind turbine at each wind speed is shown in Figure 4.8b. The power value at each point on the plot represents the average value

computed over a period of ten minutes. In addition to the average values, the maximum and minimum power values recorded during the testing time are depicted using error bars. To better assess the starting speed of the wind turbine, the speed change increment was reduced to 0.25 m/s for wind speeds up to 4 m/s. However, for other wind speeds, the speed change step remained at 2 m/s. The rotational speed (RPM) of the wind turbine at these lower flow speeds was also recorded and shown in Figure 4.8a. The graph illustrates that the turbine starts rotating at a wind speed of 2.25 m/s.

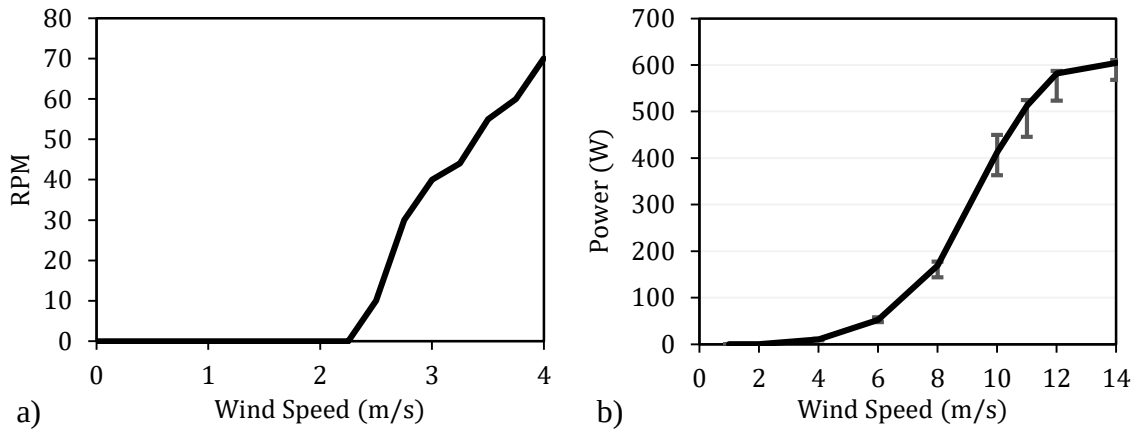


Figure 4.8 a) Starting RPM and b) Power Production of Wind Turbine

The power coefficient was measured to further understand the performance of the wind turbine at different Tip Speed Ratios (TSRs). The testing was carried out at wind speeds of 3.0, 4.5, and 6.0 m/s, which corresponded to Reynolds numbers of 35K, 53K, and 70K, respectively. These results are presented in Figure 4.9, which presents the variation of C_p with TSR for each wind speed. The results indicate that when the Reynolds number increases, the maximum C_p value also increases. This can be due to the fact that as the Reynolds number increases, the flow becomes more turbulent, which enhances the mixing of the fluid near the surface of the blade, producing a greater pressure at pressure side

compared to suction side of the blade. Consequently, the turbine can generate more power from the wind, leading to an increase in the maximum C_p value.

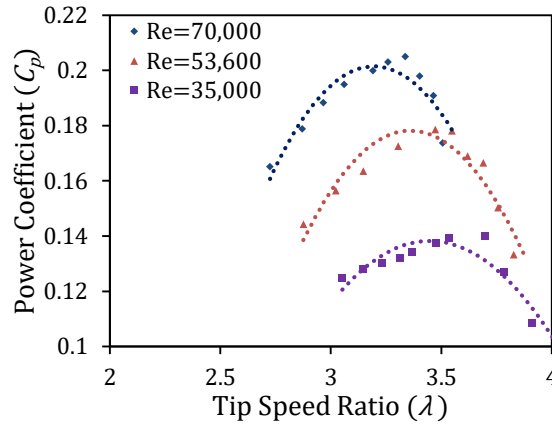


Figure 4.9 Power Coefficient of VAWT at different Reynold Numbers

4.3.2 Field Testing at Rooftop

The field testing provided valuable insights into the turbine's performance under real-world wind conditions, which helped to validate the theoretical predictions and to predict the actual turbine performance for practical applications. The field testing of the wind turbine was conducted by placing it on the rooftop of the Mechanical Engineering Department building. The rooftop location was chosen due to its accessibility and being free from obstruction. The tests were conducted under various weather conditions. MS-WS1080 weather station was installed on the rooftop close to the wind turbine to measure the wind speed, wind direction, temperature, and humidity at a frequency of 1 Hz. The power generated by the wind turbine was measured by means of the same MPPT controller and data logging system used for the laboratory testing. The system recorded the power formed by the turbine averaged every 60 seconds, along with the wind direction, wind speed, humidity, and temperature. Each field test was conducted for 24 hours to cover different

wind and gust conditions. The wind speed and the electric power produced by the generator for days with average, lower than average, and higher than average wind speeds are shown in Figures 4.10, 4.11, and 4.12, respectively.

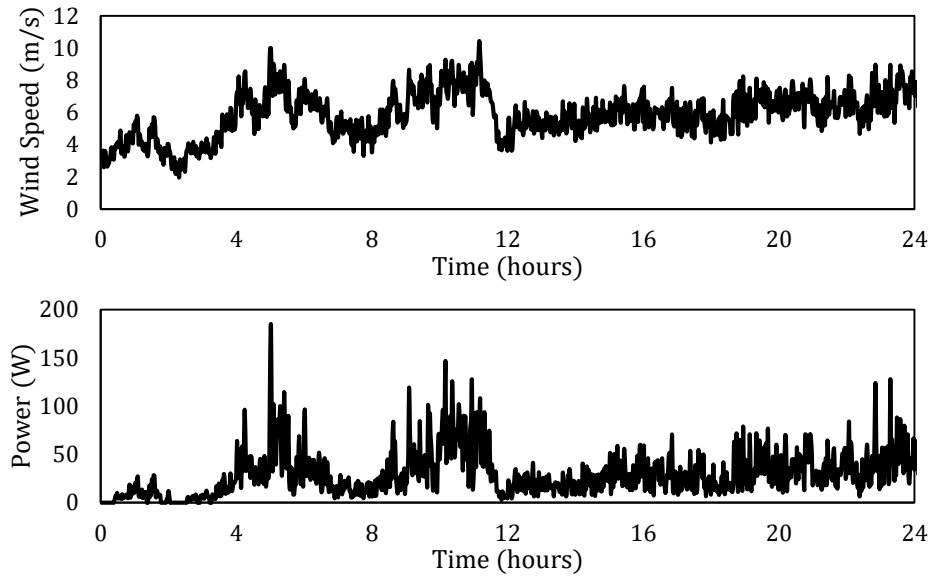


Figure 4.10 Wind speed and turbine power during a day with typical wind

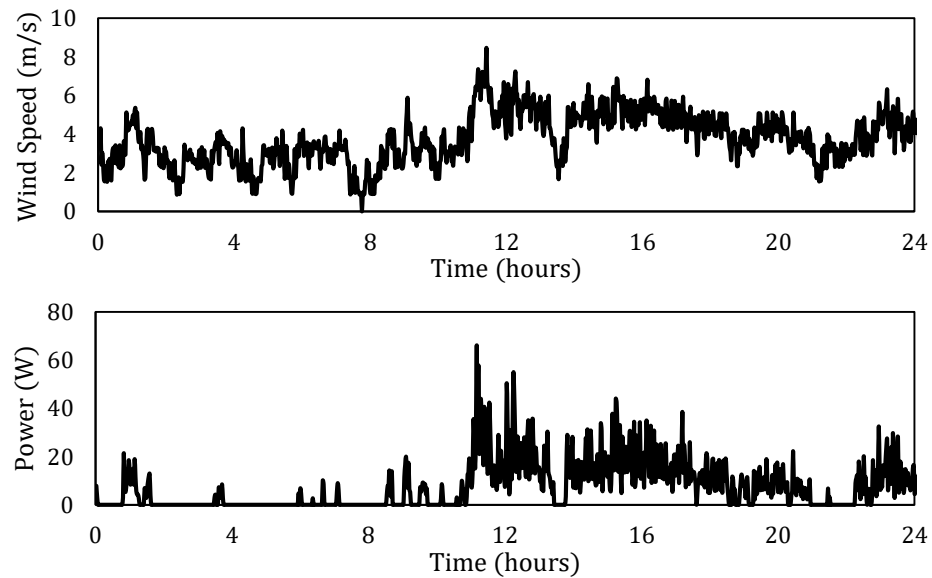


Figure 4.11 Wind speed and turbine power during a day with low wind

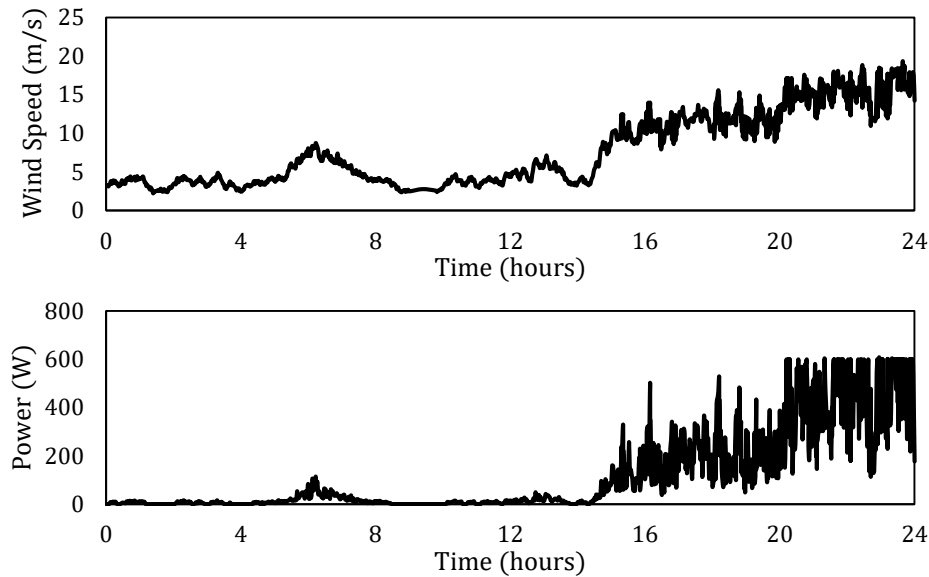


Figure 4.12 Wind speed and turbine power during a day with high wind

The main findings of the field tests were that the wind turbine performed well under moderate wind speeds, producing a consistent power output. The average wind speeds during the test days were 3.75, 5.88, and 8.48 m/s. The corresponding average hourly power produced by the wind turbine was 7.82, 29.43, and 143.02 Watts, respectively. During periods where the wind speed dropped below the turbine's starting speed, the wind turbine did not produce any power. The total time where no power was produced was approximately 440 minutes during the day with low wind and 158 minutes for the day with high wind.

The field testing of the wind turbine provides useful insights into its real-world performance, as it was tested under actual operating conditions. The data obtained from these tests is used to improve the final design of the wind turbine and optimize its performance. However, the limitations of field testing should also be considered. The results obtained from the field testing may not be as accurate as those obtained from

laboratory testing, as they are subject to external factors such as wind direction, turbulence, and atmospheric conditions. Additionally, the field testing equipment used may have measurement limitations, leading to errors or inaccuracies in the recorded data.

4.4 Comparison of Analytical, Numerical, and Experimental Results

The results from analytical, numerical, lab tests and field tests for the wind turbine were compared to evaluate the accuracy of different prediction methods. The power coefficient predicted by these methods at various TSRs is shown in Figure 4.13.

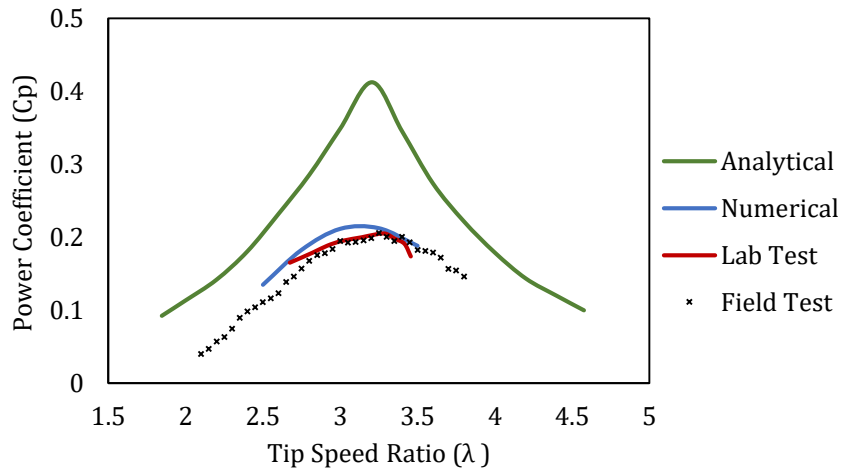


Figure 4.13 Comparison of Different Power Prediction Techniques

It was observed that the analytical method highly over-predicted the turbine power coefficient, whereas the numerical and lab test results were very close to each other. However, the actual turbine performance in field tests was slightly lower than predicted in numerical and lab tests.

This discrepancy between the predicted and actual turbine performance was attributed to the fact that both numerical model and lab tests are run with constant, steady and

unidirectional wind with very low turbulent intensity and planetary boundary layer effects. These effects reduce the actual turbine output in real world conditions. These effects are more pronounced at lower TSRs and negligible at higher TSRs where highly turbulent flow improves the turbine's performance. Additionally, it was observed that the numerical method and lab tests predicted lower TSR as the optimum operational conditions for the turbine compared to field tests. This difference in predicted optimal TSR are due to the effect of complex atmospheric conditions in the field tests, which were not accounted for in the numerical model and lab tests.

In conclusion, while the numerical model and lab tests provided accurate predictions for the turbine's performance under ideal, controlled conditions, the actual field tests revealed the impact of atmospheric and environmental factors on the turbine's performance. These findings emphasize the importance of considering real-world conditions and the need to model the impact of turbulent wind flow and atmospheric conditions on wind turbine performance.

CHAPTER 5

POWER ENHANCEMENT USING FLOW CONTROL

The most noteworthy disadvantage of H-Type VAWTs is their low power conversion efficiency when compared to Horizontal Axis wind turbines. During turbine rotation, the blades experience post stall AOA resulting in a dynamic stall of the blade. The flow separation over the surface of the blade reduces the output power of the turbine. Several efforts have been made to improve the blade aerodynamics and achieve stall delay and drag reduction on the VAWT blades. The flow over the stalled airfoils can be modified using specialized devices called “Flow control Devices” which improve their aerodynamic performance. These devices are categorized into active or passive methods based on their energy requirements. Passive techniques do not require any external energy input to modify the flow around an airfoil. These devices can be added to existing blades and are characterized by simpler and cost effective design.

A passive flow-control device for power augmentation is investigated by installing an off-surface micro-cylinder at the leading edge of the blade. The micro-cylinder is installed upstream of the blade's leading edge which spans the entire blade height. The vortex shedding from the cylinder travels over the blade's upper surface at higher angles of attack, energizing the flow and delaying the stall. This chapter explores different blade designs by varying the diameter and spacing of the micro-cylinder. The incremental

effects are calculated by comparing the turbine's power output to simple straight-bladed VAWT.

The first step was to conduct an experimental investigation of a 600-watt VAWT. This step involves setting up the turbine and collecting data to establish a baseline for the performance of a simple turbine. Then 2D and 2.5D CFD analysis is performed to validate the numerical model. This involves creating a numerical model of the turbine and simulating its operation at various Tip Speed Ratios. Finally, the simulation results are matched to the testing data to validate the CFD model's accuracy. After validating the CFD model, the next step is to analyze the new blade design. This step involves modifying the turbine's blade design by adding a leading-edge cylinder to improve performance. The blade design is analyzed using the validated CFD model, and the effect of different diameters and spacing on the VAWTs performance is investigated. Finally, a comparative analysis is carried out to identify the optimum leading edge cylinder diameter and spacing. The power output of the optimum design is compared to the power output of the simple turbine to evaluate the effectiveness of the leading-edge cylinder.

5.1 Numerical Model Validation

The model of manufactured turbine is used during the validation study. The numerical model is confirmed using the testing results generated during the lab testing. The mesh independence study used earlier was utilized and same mesh sizing was used for this analysis. The numerical analysis uses a double precision solver with RANS $k\omega$ -SST and DDES formulations. The results from these two turbulence models are compared for final selection of the turbulence model. The turbine is enclosed inside a circle and a cylinder for

2D and 2.5D analysis, respectively. 2D and 2.5D CFD assume uniform flow field in the direction perpendicular to the plane of the simulation, hence simulating a turbine with infinite blade height and no end effects as shown in Figure 5.1. However, 2.5D simulation is three-dimensional, and it captures some of the critical 3D effects that influence the power produced by the VAWT.

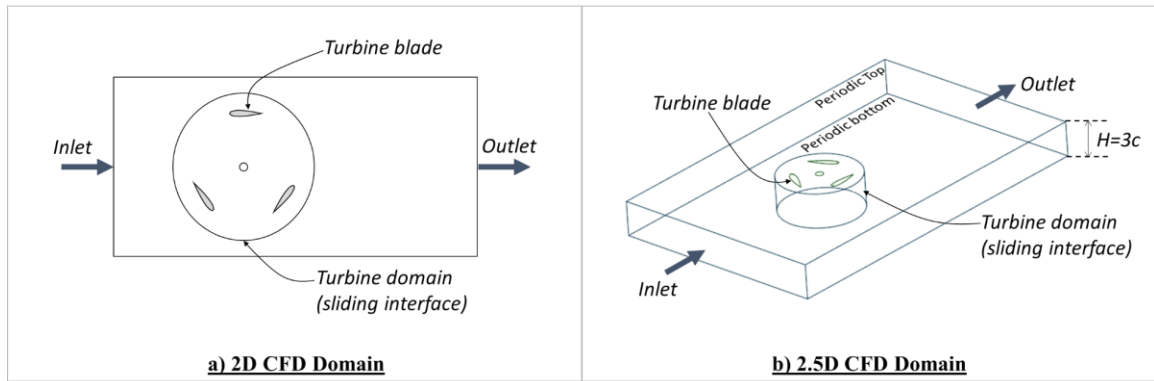


Figure 5.1 a) 2D and b) 2.5D CFD Domains

The turbine enclosure acts as a mesh density zone to allow finer mesh size in the vicinity of the wind turbine that gradually grows further away from the turbine blades. This enclosure is connected to the external domain through a sliding mesh interface. The rotational velocity of the enclosure controls the turbine RPMs and the operating TSR. The wind is introduced in the domain through a velocity inlet and leaves through a pressure outlet. The remaining sides of the domain are modeled as symmetry planes. To implement the sliding mesh interface formulation in ANSYS Fluent, separate mesh regions are created for each domain or part that undergoes movement or rotation. These mesh regions are then connected at the interface to define the sliding motion between them. Boundary conditions are applied at the interface to specify the relative motion or sliding behavior between the mesh regions.

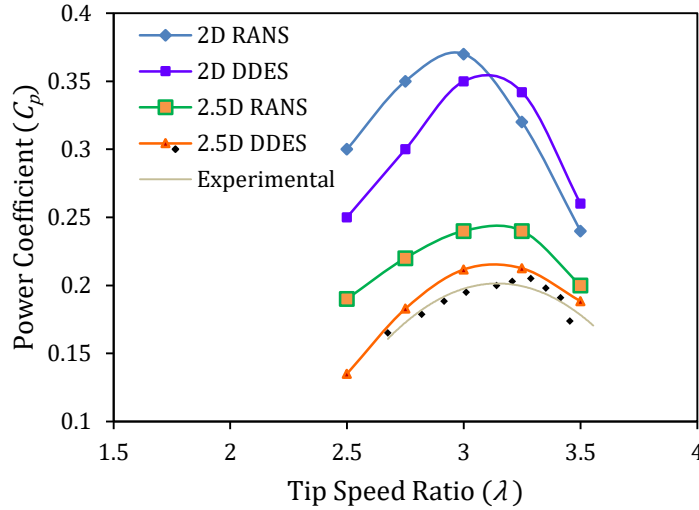


Figure 5.2 Validation results from different CFD formulations

The analysis was performed at different TSRs, and the results from different numerical formulations are compared to testing results in Figure 5.2. It is observed that both 2D and 2.5D formulations over-predict the power coefficient of the turbine. This is due to the absence of the blade tip effects, where some of the high pressure from the lower surface of the blade leaks across the blade tip toward the upper surface. This results in a wingtip vortex that causes a decrease in lift and an increase in the drag of the blade. However, 2.5D has the ability to capture the vortices that form over the blade's surface in the 3rd dimension. These vortices form over the blade at the turbine's forward half, then travel downstream, affecting the blades in the aft half. This complex interaction further degrades the turbine performance, and this effect is missing from the 2D formulation. When comparing RANS to DDES, it was observed that for 2D analysis, RANS did not predict the optimum TSR ratio for the turbine correctly. On the other hand, 2.5D DDES captured the optimum TSR and followed the power coefficient variation trend correctly. Based on this comparison, the 2.5D DDES formulation was selected for further analysis.

5.2 VAWT with a Leading Edge Cylinder (LEC)

Once the CFD model had been validated, VAWT models were created with a cylinder placed upstream of the blade. Since the turbine's blades have a symmetric profile of NACA 0022 airfoil, the cylinder having a diameter ' D ' was placed upstream in line with the chord of the blade at a spacing ' s ' as shown in Figure 5.3.

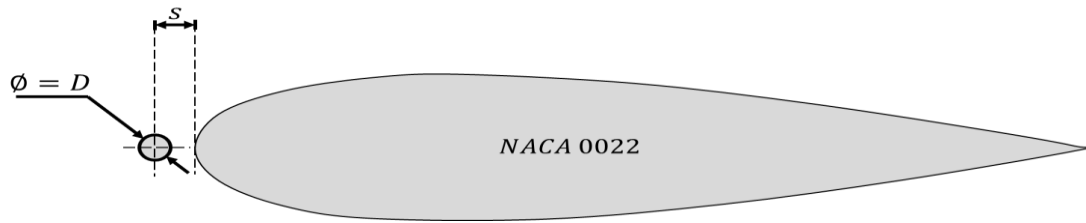


Figure 5.3 VAWT blade cross-section with a Leading Edge Cylinder

The CFD formulation and mesh density for the VAWT with new blades were the same as in the validation case. The blade and cylinder were meshed with seven prism layers along the surface to capture the viscous effects within the boundary layer. The mesh density around the blades and in the vicinity of the leading edge cylinder is shown in Figure 5.4. The diameter of the leading edge cylinder was varied from 1 mm to 4mm with a step of 1 mm. Whereas the spacing was varied from 5 to 10 mm with a step size of 2.5 mm.

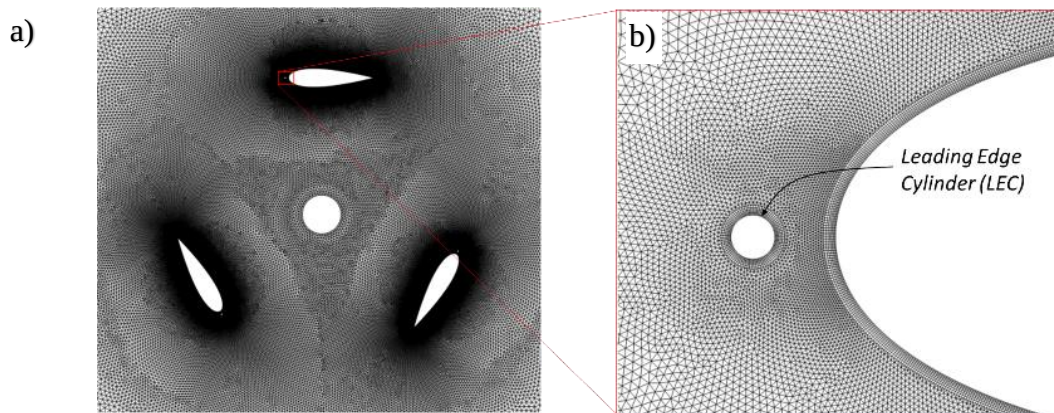


Figure 5.4 Mesh around the a) Blades and b) Leading Edge Cylinder

5.2.1 Effect of Leading Edge Cylinder Diameter

The effect of cylinder diameter on the power production capability of the turbine at different TSRs is shown in Figure 5.5. The simple VAWT in the legend refers to the simple VAWT with straight blades without the leading edge cylinder. The term LEC in the legend refers to a VAWT with a leading edge cylinder with ‘D’ and ‘S’ representing the leading edge cylinder's diameter and spacing, respectively.

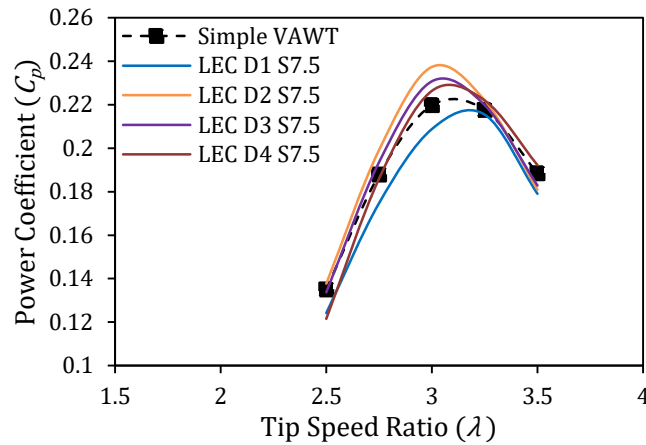


Figure 5.5 Effect of LEC diameter on turbine's performance

A comparison of power produced at different TSRs for turbines with the same spacing and different diameters of the LEC reveals that the effectiveness of specific diameter LEC depends on the turbine operating conditions. A larger diameter LEC is more effective at higher TSRs, and it degrades the power output of the turbine at lower TSRs. On the other hand, the smallest diameter LEC was found ineffective at all TSRs. This is attributed to the fact that at lower TSRs and smaller diameters, the flow and wake behind the cylinder are not strong enough to create turbulence and energize the flow. Hence larger diameter cylinders become more effective at higher TSRs. However, it was also observed that the moderate diameter size of the LEC was the most effective. Hence, the optimum LEC

diameter sizing and selection would be significantly affected by the wind conditions at the turbine's installation location.

5.2.2 Effect of Leading Edge Cylinder Spacing

The effect of cylinder spacing on the power coefficient of the turbine at different TSRs is shown in Figure 5.6 which uses the same nomenclature of Figure 5.5.

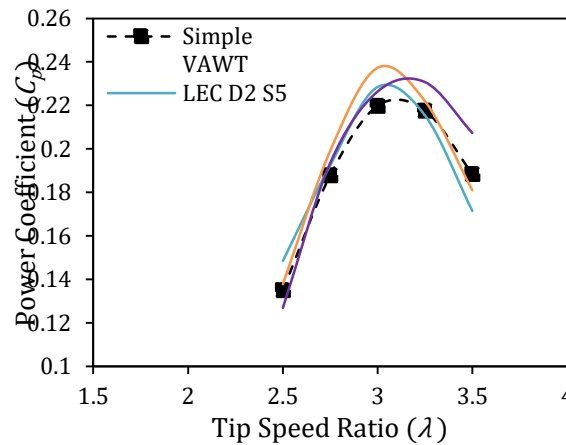


Figure 5.6 Effect of LEC spacing on turbine's performance

A comparison of results obtained by constant diameter LECs with different spacing reveals that the leading edge micro-cylinder's effectiveness depends on its position relative to the blade. At a definite distance from the blade, the cylinder produces the maximum benefit, as it generates vortices that effectively travel over the blade surface. However, if the cylinder is placed too close or too far from the blade, the vortices can adversely interfere with the flow over the blade, leading to separation and a decrease in lift. Therefore, it is essential to carefully optimize the placement of the micro cylinder to maximize its efficacy in improving the power generated by the turbine. In addition, the effectiveness is also dependent on the turbine's operating conditions in terms of TSR. At higher TSR values, the

maximum AOA seen by the blade reduces, and the blade moves at a higher speed. In this case, the cylinder needs to be a little further upstream from the leading edge so that the wake vortices of the cylinder can move toward the upper surface and energize the flow. Conversely, the cylinder must be placed slightly closer to the blade at lower TSRs to increase efficiency. This is evident from Fig. 8, where the closest cylinder achieves higher efficiency at lower TSRs, whereas the cylinder away from the blade performs better at higher TSR values.

5.2.3 Optimized Leading Edge Cylinder

The diameter of the leading edge cylinder was varied from 1 mm to 4mm with a step of 1 mm. Whereas the spacing was varied from 5 to 10 mm with a step of 2.5 mm. A full factorial design resulted in 12 configurations of VAWT with LEC. The 12 VAWT geometries with these LEC were modelled, meshed and numerically analyzed. The maximum power coefficient from all these LEC VAWT configurations are presented in Table 5.1. The maximum power output received among all these combinations is highlighted in bold.

Table 5.1 Maximum Cp for VAWTs with LEC

		LEC spacing		
		5.0 mm	7.5 mm	10.0 mm
LEC Diameter	1 mm	0.196786125	0.2087625	0.17839305
	2 mm	0.22854	0.23733	0.2263425
	3 mm	0.2020821	0.2307375	0.21502538
	4 mm	0.18187389	0.2263425	0.19352284

After evaluating all combinations of cylinder diameter and its distance from the blade, it was revealed that the optimum cylinder had a diameter of 2 mm, and the optimum spacing was found to be 7.5 mm. At optimum conditions, the maximum power coefficient of the wind turbine improved by 13%.

5.3 Effect of LEC on Flow Field

The VAWT has a vertical axis of rotation, and the blades are attached radially to the rotor. As the blade rotates, it experiences different wind speeds and directions, causing the AOA to change repeatedly during its operation. The exact pattern of the AOA variation depends on various factors, which includes the blade's shape and design, the turbine's rotational speed, and the wind speed and direction. As a result, the blade experiences post stall AOAs where the flow separates from the blade's surface, leading to a sudden reduction in lift accompanied by an increase in drag, reducing the turbine's overall efficiency. At lower TSRs, the dynamic stall is more severe since the blade achieves higher AOAs during each rotation.

When a micro cylinder is placed ahead of the leading edge of a VAWT blade, extending all through the length of the blade, it modifies the flow of air around the blade, creating a more favorable pressure gradient that increases the lift produced by the blade. The effect of the leading edge cylinder on the flow field and pressure field is different at each azimuthal position of the blade during the turbine's rotation. The contour plots for the magnitude of z-vorticity (where the z-axis is along the turbine rotation axis) at 0°, 60°, 120°, 180°, 240°, and 300° azimuthal positions of the blade mid-span plane are shown in Figures

5.7 through 5.12, respectively. Comparing the vorticity magnitude between the simple blade and the blade with LEC, it is found that the cylinder's wake travels across the blade's surface and results in a larger region with higher vorticity. However, when comparing the magnitude of vorticity, it is observed that the magnitude of the vorticity for the blade with LEC is less than that for the simple blade.

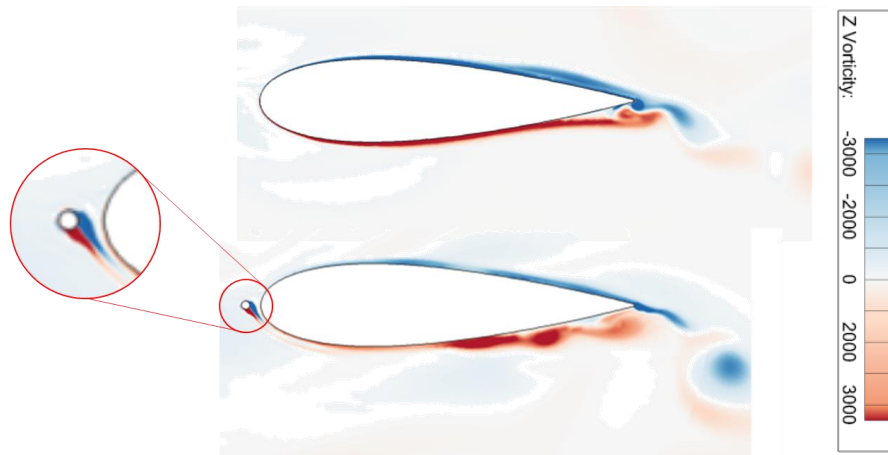


Figure 5.7 Z-vorticity around blades and LEC at 0° azimuthal angle

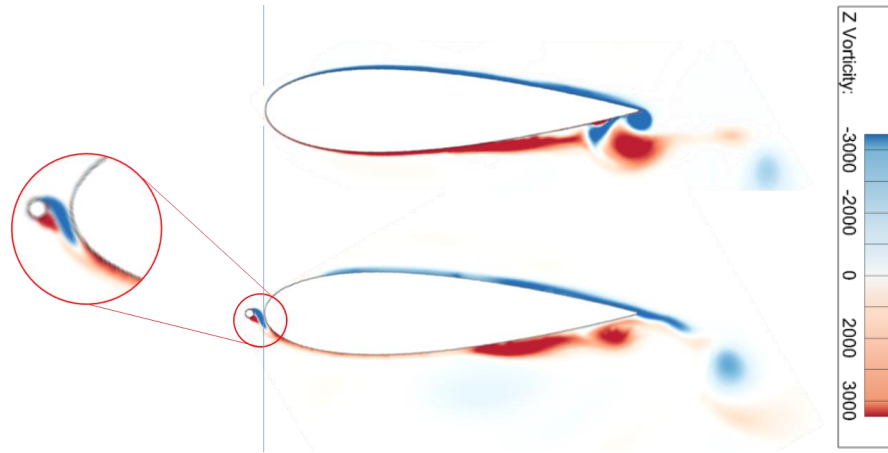


Figure 5.8 Z-vorticity around blades and LEC at 60° azimuthal angle

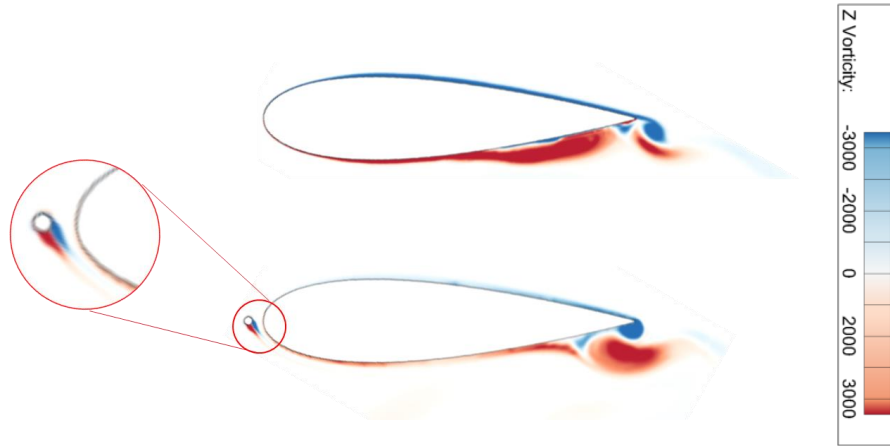


Figure 5.9 Z-vorticity around blades and LEC at 120° azimuthal angle

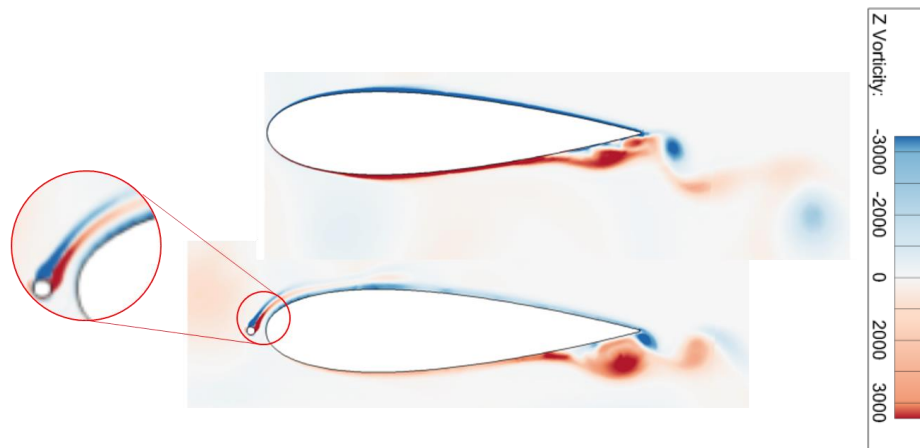


Figure 5.10 Z-vorticity around blades and LEC at 180° azimuthal angle

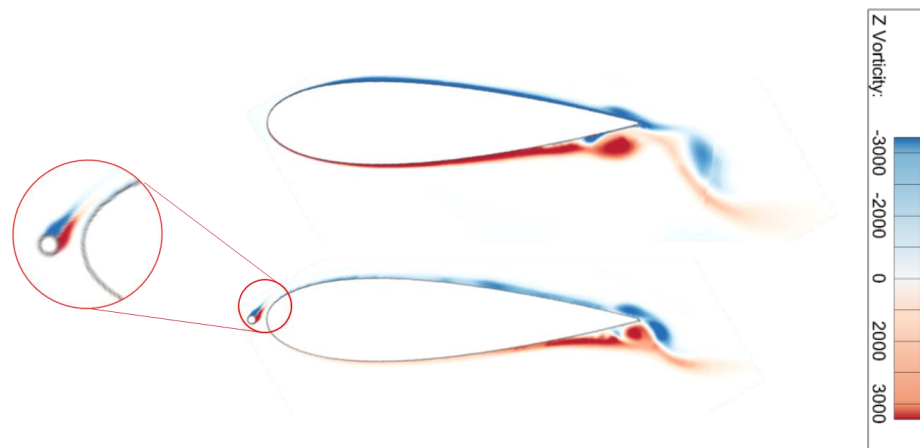


Figure 5.11 Z-vorticity around blades and LEC at 240° azimuthal angle

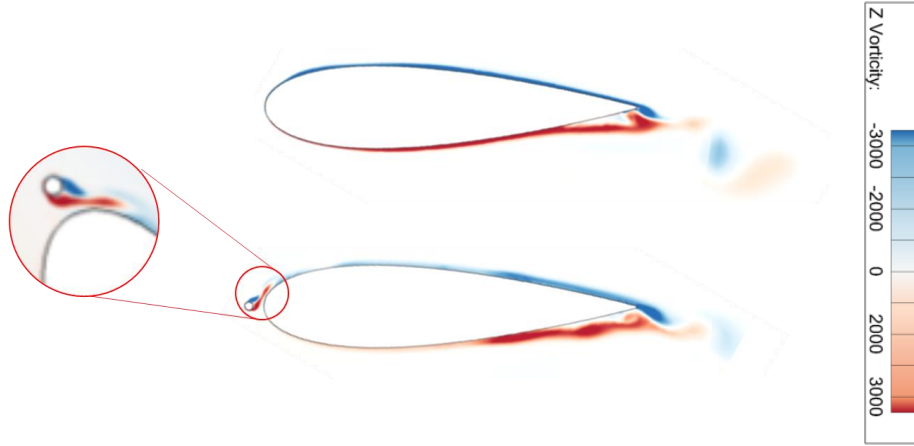


Figure 5.12 Z-vorticity around blades and LEC at 300° azimuthal angle

Similarly, when comparing the vorticity magnitude distribution around the blades at 240° azimuthal position, it is observed that the cylinder wake travels toward the upper surface and interacts with the boundary layer on the blade surface. The presence of LEC also affects the Trailing Edge Vortex (TEV) of the blade, which is created due to the pressure difference among the upper and lower surfaces of the blade. TEVs provide a rotational moment that contributes to the turbine's power output. The addition of the leading-edge cylinder to blade also affects the pressure field within the turbine rotor. The mid-plane pressure contours around the simple blade and the blade with LEC are compared at the azimuthal positions of 0°, 60°, 120°, 180°, 240°, and 300° in Figures 5.13 through 5.18, respectively. LEC's generated a high pressure region that reduced the blade surface's low-pressure region responsible for adverse pressure gradient. Moreover, the vortices produced at the blade's leading edge travel along the blade surface and affect the pressure distribution around the trailing edge as well. This effect is clearly visible when the effective AOA of the blade is higher corresponding to azimuthal positions of 60, 120° and 240°.

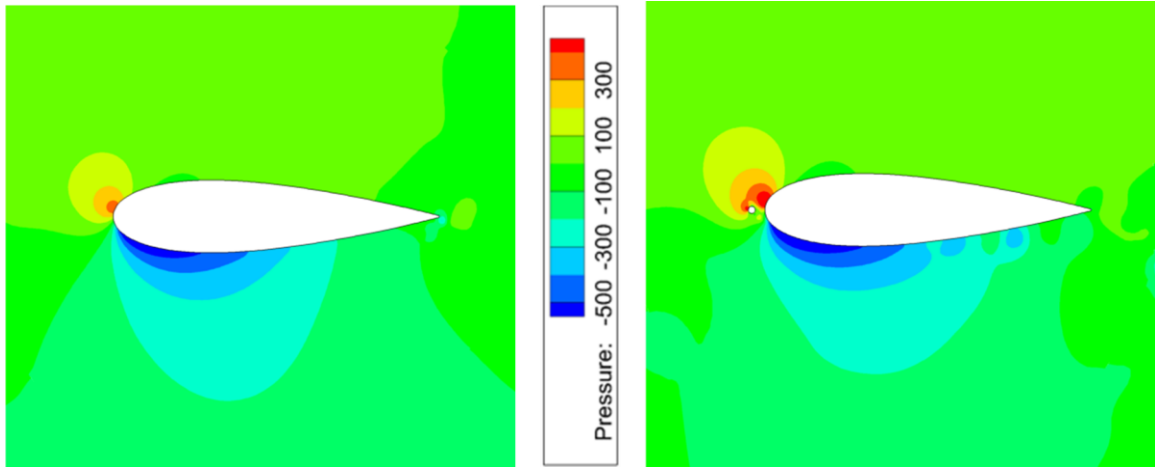


Figure 5.13 Pressure around blades and LEC at 0° azimuthal angle

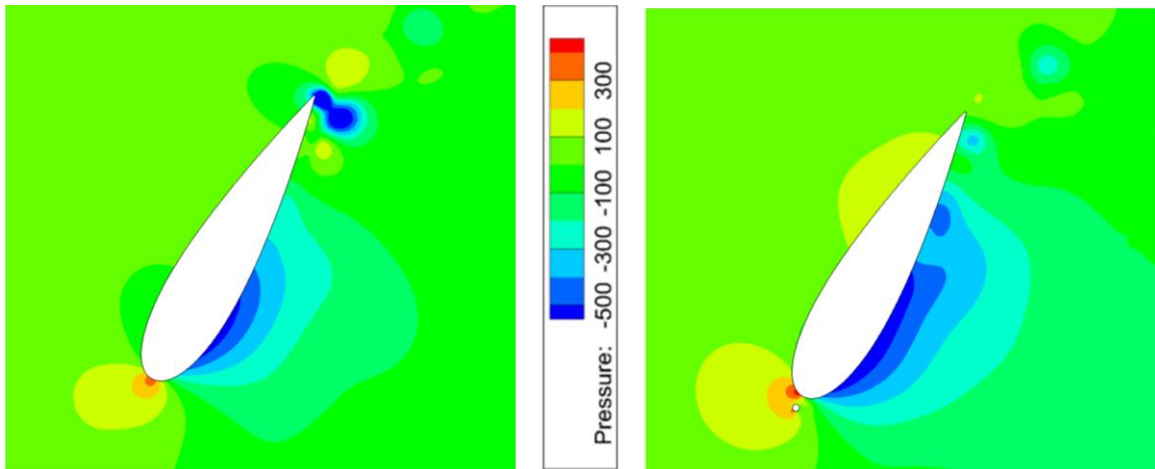


Figure 5.14 Pressure around blades and LEC at 60° azimuthal angle

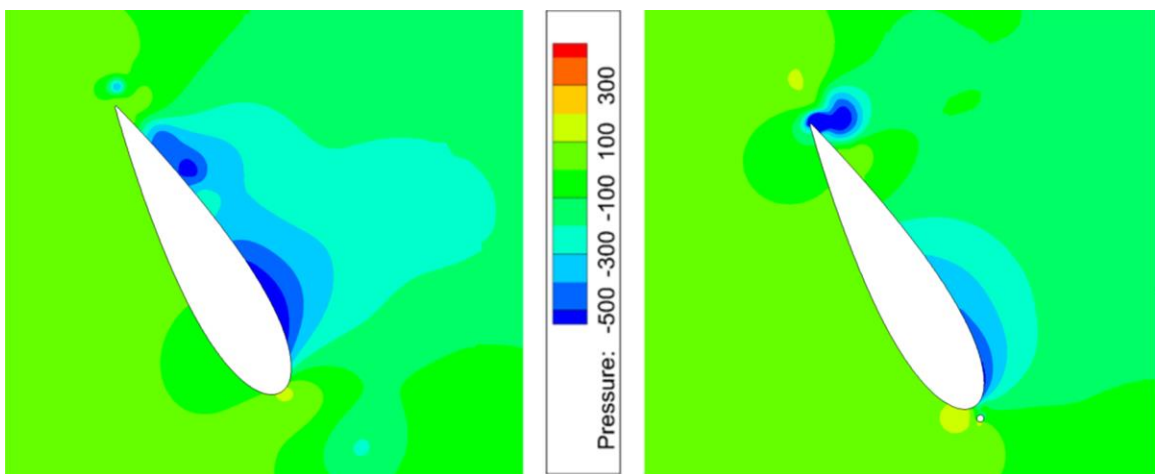


Figure 5.15 Pressure around blades and LEC at 120° azimuthal angle

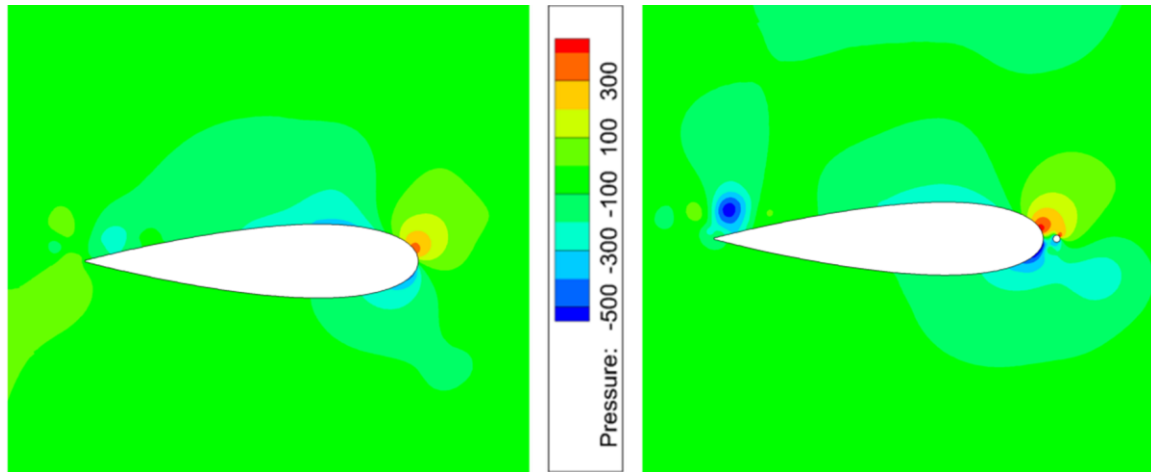


Figure 5.16 Pressure around blades and LEC at 180° azimuthal angle

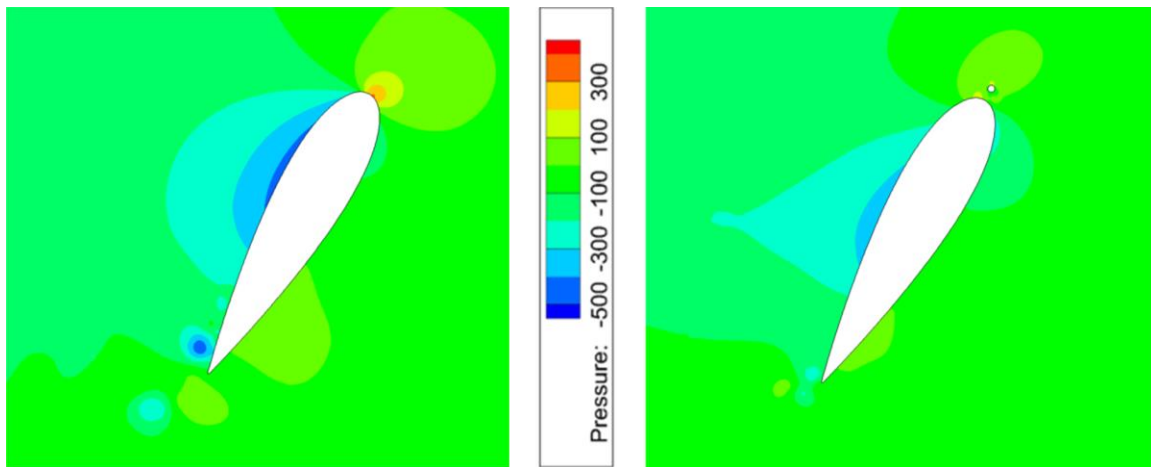


Figure 5.17 Pressure around blades and LEC at 240° azimuthal angle

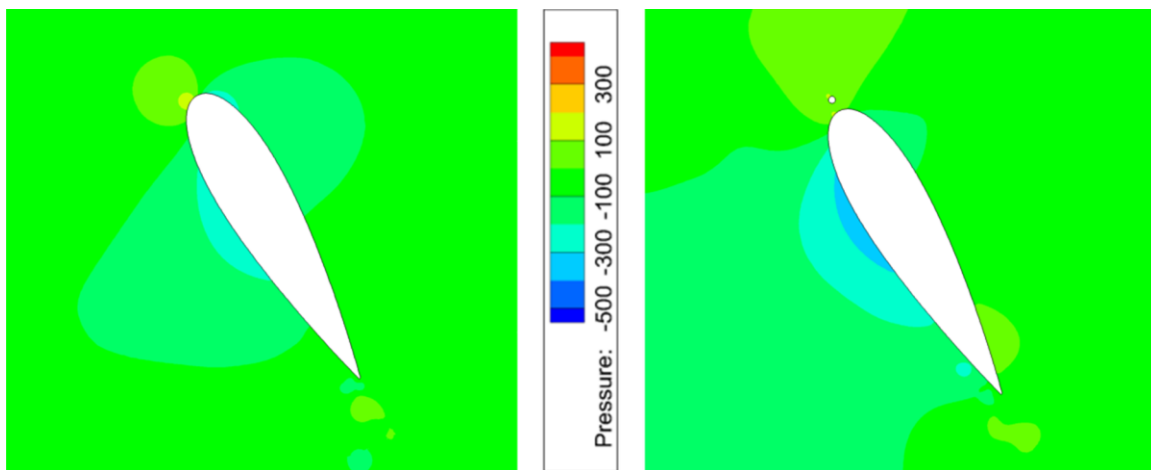


Figure 5.18 Pressure around blades and LEC at 300° azimuthal angle

This effectiveness of a micro Leading Edge Cylinder (LEC) as a flow control device to enhance the power coefficient of a VAWT is analyzed numerically. The investigation considered 12 configurations of the micro leading edge cylinder with varying diameters and spacing. The results have shown that the size and placement of the LEC significantly affect its effectiveness in increasing the power coefficient of the turbine. Specifically, a larger diameter LEC was found to be more effective at higher TSRs, while the moderate diameter size of the LEC was found to be the most effective. Moreover, if the cylinder is placed too close or too far from the blade, the vortices can adversely interfere with the flow over the blade. Therefore, it is essential to carefully optimize the size and placement of the micro cylinder to maximize its efficiency and increase the power coefficient of the turbine. The optimal positioning of the LEC was 7.5 mm away from the blade with a diameter of 2 mm, resulting in a 13% increase in the maximum power coefficient of the wind turbine. These findings highlight the potential of using LECs as passive flow-control devices to enhance the efficiency of vertical axis wind turbines.

CHAPTER 6

CONCLUSION

The threat of carbon emissions to the environment is well documented and it is imperative that we find ways to reduce our reliance on fossil fuels. Renewable energy sources are an important part of this solution, and wind energy, in particular, is an abundant and clean source that should be utilized. Wind turbines can be used in various settings, including on-shore, off-shore, and urban integration. Vertical Axis Wind Turbines (VAWTs) are particularly appropriate for urban integration due to their omni-directional design and ease of maintenance. However, VAWTs have traditionally been less efficient than Horizontal Axis Wind Turbines (HAWTs). This thesis provides a comprehensive roadmap for wind turbine process based on local wind conditions. The aerodynamics of VAWT blades is analyzed using analytical, numerical, and experimental methods, and a passive flow-control device to enhance the power produced by VAWTs is proposed.

In order to design efficient VAWT blades, accurate knowledge of the aerodynamic response of the airfoil is necessary. Despite the popularity of the NACA 0022 airfoil among researchers, its basic aerodynamic polar data was not available. Therefore, wind tunnel testing was conducted to obtain the static and dynamic aerodynamic polars of the NACA 0022 airfoil. To simulate the cyclic AOA experienced by the VAWT blade during operation, the airfoil was oscillated in a pitching motion. The results of the wind tunnel testing revealed that the NACA 0022 airfoil was superior to thinner NACA 0018 airfoil

due to its better stall characteristics and higher moment, as well as to the thicker NACA 0024 airfoil due to its lower drag, which remained fairly constant at shallow AOAs.

This thesis also provides a comprehensive roadmap for the wind turbine design process, specifically for local wind conditions. The first step was to analyze the wind data for Dhahran, which helped establish the design requirements. A preliminary design was carried out using analytical methods in Q-Blade. Various airfoils were analyzed, and based on the results, NACA 0022 was selected for the detailed design. The detailed design was carried out in ANSYS Fluent using computational fluid dynamics. The effect of blade height, blade chord length, number of blades, and rotor diameter were investigated. It was determined that a 3-bladed VAWT was most suitable for the local wind conditions. The final blade design had a length of 1m and a chord length of 0.2m. The design process can be adapted to any location by adjusting the design requirements according to local wind data. Once the design requirements are established, the same process can be used to design an optimal wind turbine for that specific location.

After the optimized design was finalized, the wind turbine was fabricated and subjected to both laboratory and field testing. In the laboratory, the turbine's performance was assessed under unidirectional and steady wind conditions, which provided an ideal performance baseline for validating numerical techniques. Field testing was conducted on a rooftop to evaluate the turbine's starting and operational characteristics in real-world conditions. The results of the laboratory and field testing were compared and analyzed, which provided insight into the real-world performance of the wind turbine and can be used for further improvement of the design.

In addition to the wind turbine design and testing, a novel flow-control device is proposed to improve the performance of VAWTs. The Leading Edge Cylinder (LEC) was analyzed to find its optimum size and placement. It was found that the LEC's optimal position depends on wind conditions and turbine TSR, and its diameter and position should be carefully chosen. The best performance improvement was found when the LEC was placed 7.5 mm away from the blade's leading edge with a diameter of 2 mm. The optimal LEC size and placement led to a 13% increase in the maximum power coefficient of the wind turbine. These findings demonstrate the potential of using LECs as passive flow-control devices to enhance the efficiency of vertical-axis wind turbines.

The following conclusions are drawn from this research:

1. Careful design of VAWT based on local wind conditions can enable its effective use for urban integration on rooftops. Local wind data analysis is vital to ascertain design requirements for the wind turbine.
2. A comprehensive VAWT design process can be developed by integrating various analytical and numerical methods for preliminary and detailed design phases, followed by experimental testing for verification and modifications.
3. The analytical method over-predicted the turbine power coefficient, while the numerical and lab test results were close to each other. The actual turbine performance was lower than predicted due to the effects of turbulent wind flow and atmospheric conditions. The importance of considering real-world conditions was emphasized for better modeling of wind turbine performance.

4. The use of Leading Edge Cylinders (LECs) can be an effective way to delay stall onset and improve the performance of VAWTs. The optimal LEC size and placement improved the maximum power coefficient of the wind turbine by 13%.

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“PARAMETRIC design of Leading Edge Cylinder (LEC)
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Software : ANSYS, Solid Works, Qblade, Gambit, MATLAB, Minitab,
Tecplot, RETScreen, Microsoft Office