DESIGN AND OPTIMIZATION OF A SAVONIUS HYDROKINETIC TURBINE USING UPSTREAM BLUFF BODIES

Author

Muneeb-Ur-Rehman

Registration No: 00000320478

Supervisor

Dr. Zaib Ali

DEPARTMENT OF DESIGN AND MANUFACTURING ENGINEERING

SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY (NUST), ISLAMABAD

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Author
Muneeb-Ur-Rehman
Registration No: 00000320478

A thesis submitted in partial fulfillment of the requirements for the degree of MS Design and Manufacturing Engineering

Supervisor
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Thesis Acceptance Certificate

THESIS ACCEPTANCE CERTIFICATE

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Signature: ____________

Name of Supervisor: Dr. Zaib Ali

Date: 7-9-23

DR. ZAIB ALI
Associate Professor
NUST School of Mecha
Manufacturing Engine
(SMME), NUST, Islam

Signature (HOD): ____________

Date: 8/9/23

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Declaration

I validate the legitimacy of this research work titled *"Design and Optimization of Savonius Hydrokinetic Turbine utilizing upstream bluff bodies-A Numerical Study*" and all the work in it is an original piece of my work. The content in this work that has been sourced from external references has been appropriately acknowledged through citations within the text. Furthermore, this research work has not been previously submitted, either entirely or partially, for any other academic qualification, degree, or evaluation at any other university or educational establishment.

This research was conducted under the guidance of Dr. Zaib Ali at the National University of Science and Technology (NUST), located in Islamabad.

Muneeb-Ur-Rehman

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It is certified that MS Thesis Titled "Design and optimization of a Savonius hydrokinetic turbine using upstream bluff bodies" by **Mr. Muneeb-Ur-Rehman,** Regn. No. **00000320478** has been examined by us. We undertake the follows:

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Associate Professor
NUST School of Mechanical
Manufacturing Engineering
(SMME), NUST, Islamabad

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I dedicate this achievement in my career to my parents, beloved siblings, and exceptional teachers. Their unwavering support, guidance, and cooperation have been instrumental in leading me to this wonderful milestone.

Abstract

Hydrokinetic turbines are emerging as a prominent solution for green and sustainable power generation. The Savonius hydrokinetic turbine, with its simple design, low-cost, ease of installation, low noise, and good start-up characteristics, is a promising technology for small-scale energy production. However, its performance suffers from certain limitations such as low efficiency and low starting torque. In this work, functionality of a conventional Savonius Hydrokinetic turbine (SHKT) was assessed using Computational Fluid Dynamics (CFD). The incorporation of streamlined bluff bodies upstream of the returning blade induced a flow diversion towards the advancing blade, consequently amplifying the power output. Cylinder, diamond, D-shaped (Half cylinder) and flat deflector plate were used as deflectors to analyse their impact on the turbine's performance. The results revealed that the diamond-shaped bluff body, in contrast to the conventional design, exhibited the maximum gain in turbine's power coefficient (C_p) of up to 31% more at R_x= 0.75D and R_y=0.51D, at tip speed ratio (λ) equal to 1.2. The inclusion of cylinder-shaped and D-shaped bluff bodies yielded significant improvements in turbine's operational performance at a consistent tip speed ratio (λ), with the former exhibiting a noteworthy increase of 11.83% and the latter demonstrating a substantial enhancement of 19.89% in turbine's coefficient of power (C_p). At λ=1, the diamond-shaped bluff body achieved turbine's peak power coefficient (C_p) of 0.298, signifying its optimal performance. Furthermore, through the inclusion of a 45^o angled flat plate deflector positioned ahead of the driving blade and in combination with the diamond-shaped bluff body, the overall power coefficient (C_p) of the turbine experienced an additional enhancement of 29.58% at a tip speed ratio (λ)=1.2. Additionally, the diamond-shaped bluff body, in combination with a flat plate deflector, demonstrated maximum average power coefficient (C_p) of 0.491 at a tip speed ratio (λ)=0.8. This outcome demonstrates a notable improvement in the performance of the Savonius Hydrokinetic turbine when utilizing upstream bluff bodies and deflector plates. Thus, the use of these augmentation can significantly increase the efficiency of the Savonius Hydrokinetic turbine systems.

List of Figures:

List of Tables:

Abbreviations:

CFD: Computational Fluid Dynamics

HKT: Hydrokinetic Turbine

SHKT: Savonius Hydrokinetic Turbine

SMM: Sliding Mesh Model

VAWT: Vertical Axis Wind Turbines

TSR: Tip Speed Ratio

AR: Aspect Ratio

UNDP: United Nations Development Program

NEPRA: National Electric Power Regulatory Authority

TSS: Time Step Size

IRENA: International Renewable Energy Agency

STEEPLE: Social, Technological, Environmental, Economic, Political, and Legal

RANS: Reynolds-averaged Navier-Stokes

LES: Large Eddy Simulation

DNS: Direct Numerical Simulation

DNS: Direct Numerical Simulation

SST: Shear Stress Transport

SIMPLE: Semi-Implicit Method for Pressure-Linked Equations

Nomenclature:

A_s=Swept area

H=Height of the turbine

D=Rotor diameter

R=Rotor radius

d_b=Blade Diameter

d_c=Cylinder diameter

d_D=D-Shape bluff Body diameter

a= Horizontal distance between blades

V_i=Inlet Velocity

ω= Angular velocity

T= Moment

P_{av}=Available power

P_{rotor}=Rotor Power

C_p= Coefficient of Power

C_m= Coefficient of Moment

C_{pmax}= Maximum Power Coefficient

C_m= Moment Coefficient

P_f= Force at fracture

ρ_w= Density of water

λ= Tip speed ratio

Contents

CHAPTER 1: INTRODUCTION

1.1 Research Context and Scope:

To have sustainable development, researchers and scientists are trying to find new ways to minimize the effect of fossil fuels on the environment. The reliance on conventional energy sources (non-renewable) which includes oil, natural gas, coal etc. for energy production has detrimental environmental impacts, including the occurrence of acid rain and the exacerbation of the greenhouse effect. These sources exhibit remarkable efficiency in fulfilling the escalating energy requirements. However, their utilization poses significant environmental and human health challenges. As global development progresses at an accelerated pace, the energy demand across the world continues to surge. This surge places additional strain on non-renewable resources, intensifying their detrimental effects on ecosystems and human well-being. The human search for new ways to produce energy to meet the demand fosters the evolution of sustainable technologies. Renewable sources of energy have fewer effects on the ecosystem and environment and have huge potential to meet the burgeoning energy demand increasing worldwide [1]. A hydrokinetic turbine is a turbo machine designed to tap into the kinetic energy present in flowing fluids and turn it into usable mechanical power. These turbines do not require the heavy structure of dams or other extensive facilities and that's why these turbines are a more reliable and low-cost source of energy for remote power generation. These turbines are typically installed in open water environments, including free-flowing rivers, riverbanks, and areas where currents create distinct flow paths, such as expansive oceans and energetic tidal currents [2].

1.1.1 Global Hydro Energy Trends:

Global energy demand especially in developing countries is increasing exponentially due to population and economic growth. This is a positive indicator for the economic rise but it also shows alarming indicators for environmental changes such as global warming etc. The increase in energy demand globally also poses new challenges in the energy sector. Fossil fuels are still dominant in the global energy supply and contribute majorly according to the International Energy Agency report of 2020 as shown in Figure 1. The capacity of hydroelectric power stations globally has been steadily amplifying over the preceding decades. According to the International Hydropower Association, the total installed capacity of hydroelectric power plants in the world reached 1,308 GW in 2020, which is an increase of 1.2% from the previous year [3]. Hydropower is a green, non-polluting, and economical energy source outlet. It is one of the dominant components of renewable energy. In

2009, 3329TWh electricity has been produced by hydro energy and represents 16.5% of the share of world electricity [4].

While large-scale hydroelectric power plants still dominate the industry, there has been a trend towards smaller-scale hydropower plants in recent years. This is because smaller plants can be more easily built in remote areas and can be better suited for off-grid power generation. Emerging economies have witnessed notable advancements in the adoption of hydroelectric power as a sustainable energy source. This is driven by the need to increase access to electricity and reduce dependence on fossil fuels. In a broader perspective, hydroelectric power maintains its significance as a pivotal renewable energy source on a global scale. Its continuous expansion and sustainable development serve as a key component in satisfying the expanding energy demands globally, all while mitigating carbon emissions.

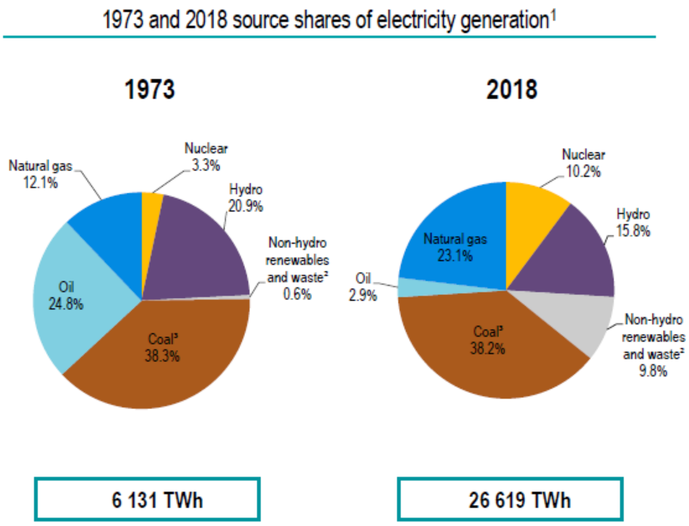

Figure 1: Shares of Electricity Generation Sources.

1.1.2 Hydro Energy Trend in Pakistan:

Hydroelectric power plays a vital role in Pakistan's electricity generation, accounting for a significant portion of the country's power supply. Following its independence in 1947, Pakistan started its journey with a power capacity of 60 MW, as per the inherited infrastructure [5]. However, the widening gap between electricity demand and supply has been exacerbated by rapid population growth, urbanization, and industrialization. While some progress was initially made in the energy sector, the insufficient addition of electricity to the power grid over the years has led Pakistan to face significant energy shortages, transforming the energy crisis into a national security concern. Despite Pakistan's abundance of natural energy resources, the energy crisis has severely impacted various sectors including social, economic, agricultural, and industrial. The power sector in Pakistan heavily relies on fossil fuel-based resources like natural gas and oil, which dominate the country's energy mix. Driven by economic expansion, the appetite for electricity is on an upward trajectory, leading to the import of hydrocarbons and expenditure of approximately 20% of foreign exchange reserves, as Pakistan possesses limited indigenous fossil fuel reserves. Currently, the overall energy mix in Pakistan comprises 61% fossil fuels, 29% hydroelectric power, 4% nuclear power, and 6% other sources [6].Figure 2 represents the energy mix of Pakistan in 2020. Despite having significant hydroelectric power resources, Pakistan is still considered to be underutilizing its potential. There are various challenges to the development of hydroelectric power in Pakistan, including financing, land acquisition, and environmental concerns. The country has been working to address these challenges through policy measures and partnerships with international organizations exploring opportunities for the development of new hydroelectric power plants. Pakistan's hydroelectric power plants include large dams, run-of-the-river plants, and small-scale hydropower plants. The country has been focusing on developing run-of-the-river and small-scale hydropower plants in recent years. For instance, the 108 MW Golen Gol hydropower project, which is a run-of-the-river plant, was completed in 2020. Pakistan possesses abundant reserves of renewable energy resources, including hydro, wind, and solar. These vast resources present a significant opportunity for Pakistan to harness renewable energy and effectively meet the demands of its energy sector. Hydroelectric power, in particular, holds great importance within Pakistan's energy mix. Further development and expansion of hydroelectric projects are vital for fulfilling the country's increasing energy requirements while simultaneously reducing dependence on fossil fuels.

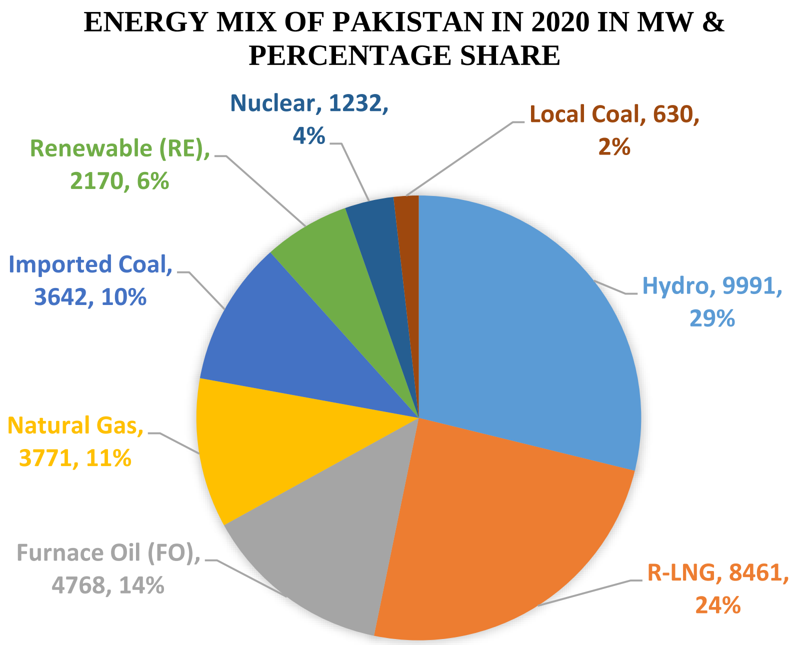

Figure 2: Percentage Share Energy Mix of Pakistan.

1.2 Scope and Motivation:

Based on a survey conducted by the UNDP (United Nations Development Program), it is estimated that approximately 1.7 to 2 billion individuals worldwide lack access to grid-based energy. The majority of these individuals reside in rural or remote areas [7]. In today's era of progress and development, access to electricity has become a fundamental necessity. The natural resources present in remote areas hold significant potential as sustainable and reliable sources of energy for generating electricity. Various methods enable the retrieval of energy from different sources like streams, rivers, etc. to provide electricity to those areas that have access to flowing water. Potential energy and kinetic energy can be extracted from water to produce electricity. Conventionally, there was a greater emphasis on exploiting water’s potential energy by storing it in large dams and converting potential energy to electrical energy using different types of turbines like Kaplan, Francis, and Pelton. To reduce further exploitation of larger hydro potential sites, hydrokinetic energy conversion is a viable solution to meet the demand for electricity in underserved regions. Despite having significant hydroelectric power resources, Pakistan is still considered to be underutilizing its potential. To cater the escalating demand for energy and the potential utilization of natural resources hydrokinetic technology is a feasible solution. The primary goal of this research is to ascertain the practicality of Savonius hydrokinetic turbines for use in small-scale or off-grid applications, where conventional hydropower plants are not practical or feasible. The objective of this research is also to explore the potential of Savonius hydrokinetic turbines for harnessing energy from sluggish water flows like in rivers and tidal pathways. The assessment of environmental impacts and sustainability of Savonius hydrokinetic turbines compared to other forms of renewable energy generation will also be the scope of this research.

The driving force behind this research stems from the imperative need to address climate change and reduce dependency on fossil fuels by exploring green and sustainable energy sources. The pressing need to address the energy requirements of remote or rural areas, where an interconnected power system is lacking or unreliable, acts as the impetus behind this research. It also explores the opportunity to harness energy from low-speed water currents that are currently underutilized. The desire to develop and improve technologies that have low environmental impacts and are compatible with aquatic ecosystems is also a major motivation behind this research work.

1.3 STEEPLE Factors Analysis:

This research work on Savonius Hydrokinetic turbine was not chosen just because of its technical characteristics but it also highlights concerns associated with social economic, political, legal, and environmental.

Socially, the presented research work aims to provide small scale clean, and cheap energy generation for those living in secluded regions with no access to electricity and no connection to the grid. The project highlights how using this alternative source of electricity can be generated in remote areas where people have continuously flowing water, streams, or rivers. This thesis also aims to increase awareness related to the adoption of sustainable energy alternatives. The project also highlights the issue of energy and the environment and presents how energy and environmental issues can be minimized using renewable resources efficiently.

Technologically, this research work represents the optimization of Vertical Axis Savonius hydrokinetic turbines through numerical analysis using upstream bluff bodies or deflectors. This research involves the testing of Savonius hydrokinetic turbine through computer simulation using Ansys fluent. The purpose of the presented thesis work is to enhance the power coefficient (C_p) using deflectors and bluff bodies. Toward these objectives, we are actively taking part develop renewable energy technologies to minimize our energy crisis.

Environmentally, the intention of this research work is to offer an optimized source of energy that would not damage our environment and would be an alternative source to fossil fuel-based energy generation which are major sources of CO_2 emissions and greenhouse effect. The project highlights energy generation through Savonius hydrokinetic turbines that unitize energy in free-flowing water streams or canals which will reduce to use of non-renewable sources and our environmental footprint.

Economically, this research work represents the optimization of conventional Savonius hydrokinetic turbines numerically to unitize the energy available in free-flowing water in rivers, streams, and man-made canals to provide an alternative source of energy for people living in remote areas near these renewable resources.

Politically, this project aims to provide an alternative source of electricity to the people who are living in remote areas and don’t have access to the national grid. Also, this research highlights the usefulness of a clean source of energy and would be a step forward to minimize the country's energy crisis by providing an independent source of clean and cheap renewable source of energy.

From a legal perspective, this research work is in accordance with the recommendations outlined in Pakistan's Alternate Renewable Energy policy. The policy sets forth ambitious goals to augment the impact of renewable and sustainable alternatives in the country's national power grid, aiming to increase the share from 5% to 20% by 2025 and further to 30% by 2030. Additionally, IRENA has identified a substantial potential of approximately 60 GW within Pakistan's hydropower sector. World Bank also suggested in 2020 that Pakistan should quickly implement a major scale-up of renewable energy generation and this research work represents a step in this direction using energy generation through optimized Savonius hydrokinetic turbines. This project also highlights small-scale energy generation according to NEPRA (Distributed Generation/Net Metering) Rules 2014 which allows injecting generated energy to the National grid of Pakistan.

Ethically, this thesis aims to reduce the destruction we caused to our environment by using non-renewable resources. A huge percentage of energy that we are using around the world still comes from conventional resources (non-renewable) such as oil, coal, or gas that are environmentally destructive. This project highlights that by using renewable energy resources we can take part to protect our environment. The projects provide and clean and cheap renewable source of energy and empower people in remote areas having no access to electricity.

1.4 Framework and Limitation of the Research Work:

1.4.1 Framework of the thesis:

The format of this thesis encompasses four primary chapters, with the first chapter comprising two sections. Chapter one offers an introductory overview and background on the subject of hydrokinetic turbines. It discussed the basic concept and scope of hydrokinetic turbines to cater to small-scale energy needs in remote and rural locations and current hydro energy trends globally and in Pakistan and also discusses the history and current trends of Hydrokinetic turbines. The second section discusses the Social, Technological, Environmental, Economic, Political, and Legal (STEEPLE) analysis, organization, and limitation of the presented research work. Chapter two presents a comprehensive literature review of previous studies conducted on Savonius turbines, along with geometrical details of the present model used in this study. This chapter provides a detailed investigation of the design features and parameters that influence turbine’s performance. In Chapter three, a detailed account is provided on the numerical modeling approach utilized in this study, emphasizing the utilization of CFD techniques to optimize the effectiveness of the Savonius turbine. Chapter four encompasses the presentation and extensive analysis of the results obtained from the numerical simulations. In the chapter, a comprehensive overview is given of the comparisons between the performance features of the conventional Savonius turbine and the optimized turbine, along with an exploration of the impact of various bluff bodies on the turbine's performance. Additionally, this chapter concludes the study, highlighting key findings, and proposes potential avenues for future research. Lastly, chapter five gives a conclusion of the presented research and highlights key findings of the research future directions.

1.4.2 Limitations of the research work:

This research work primarily focused on analyzing the operational effectiveness and performance features of the Savonius Hydrokinetic turbine through 2D analysis, based on the premise of an even distribution of quantities along the height of the rotor. It is important to note that two-dimensional analysis may lead to an overestimation of the turbine's performance, representing a fundamental limitation of this study.

Utilizing CFD analysis, the 2D analysis of the Savonius turbine provided valuable insights into flow patterns and performance characteristics. However, it is crucial to acknowledge that this approach cannot fully capture the three-dimensional flow dynamics observed in real-world scenarios. Conducting a comprehensive three-dimensional analysis would require more extensive computational resources and time, which could have confined the scope of this work. While the numerical results of the conventional Savonius turbine presented in this investigation have been validated against experimental data from Sheldahl [8], it is crucial to acknowledge that the experimental results for the modified turbine's design are still pending and, therefore, not included in this research work. It is worth mentioning that CFD simulations can impose significant demands on computational resources, including high-performance computing resources. This aspect can pose limitations for research projects with limited access to such resources.

Although hydrokinetic turbines, including the Savonius Hydrokinetic turbine, offer a promising alternative to traditional sources of energy, they do have limitations that must be taken into consideration. One major limitation is the need for strong currents or flow rates to generate enough power to be economically viable. In locations where currents are weak or inconsistent, hydrokinetic turbines may not be a viable option. Another factor that limits the use of hydrokinetic turbines, including Savonius turbines, can be limited by regulatory and environmental concerns. The placement of turbines in waterways must take into account potential impacts on navigation, recreation, and wildlife, and permits may be required before installation can take place. Additionally, concerns about noise pollution and visual impacts may limit the number of locations where hydrokinetic turbines can be installed.

CHAPTER 2: LITERATURE REVIEW

2.1 Concept of Hydrokinetic Power:

Hydrokinetic technologies are specifically engineered for deployment in diverse aquatic environments, encompassing unconstrained rivers, marine currents, and artificial waterways. Hydrokinetic turbines fall into the "zero-head" category which taps into the kinetic energy of water movement rather than relying on the potential energy of descending water. These turbines are designed for effective minimum speed of about 0.25 m/s of flowing water can be installed in different configurations like underwater, floating, fixed, anchored, or towed where the effective. The power generation of a hydrokinetic turbine is tied to the velocity of the water flow, similar to a wind turbine's power production is linked to the speed to the wind. Equation (2.1) represents the power density (PHK) of turbine:

$$PHK = \frac{1}{2} E\rho V^3 \quad \ldots\ldots\ldots\ldots\ldots (2.1)$$

And the output power can be written as in equation (2.2);

$$P = \frac{1}{2} C_p \rho A V^3 \quad \ldots\ldots\ldots\ldots\ldots (2.2)$$

Where;

E= Device efficiency specified by manufacturer

C_p= Coefficient of Power

ρ =Fluid Density

V= Fluid Velocity

A= Turbine Swept Area

Generation of electricity from kinetic energy extracted from flowing fluid is determined by overall coefficient of power (C_p). The coefficient of power (C_p) of the system is typically estimated to be around 0.35 in practical scenarios. Compared to similar rated power wind turbine, hydrokinetic turbine with fluid velocity of 2-3 m/s can yield up to four time more energy per square meter of rotor-swept area. The utilization of high-energy tidal sources outweighs the associated expenses, despite the initial costliness of harnessing tidal energy. Across various tip speed ratios, power performance tests are typically carried out to determine coefficient of power (C_p) can be calculated using hydrokinetic power or power density (PHK) as in equation (2.3);

$$C_p = PHK\tau \times \omega …………… (2.3)$$

2.2 Hydrokinetic Turbines:

When compared to other renewable energy resources, hydro energy is considered highly dependable and affordable. Hydrokinetic energy is the kinetic energy that is available in unimpeded rivers, irrigation channels, upstream/downstream of dams, or lakes. This available kinetic energy can be converted for small-scale hydropower generation and can be utilized through turbines known as hydrokinetic turbines to generate electricity [9]. Hydrokinetic turbines belong to the category of power-generating technologies engineered to utilize the available hydrokinetic energy of incoming flowing fluid with low head and low velocity [10]. According to the report of the US Department of Energy in 1981 hydrokinetic turbines can be defined as "Low-Pressure run-off-the-river ultra-low-head turbines that operate equivalent or less than 0.2m head"[11]. Hydrokinetic turbines alternatively referred to as free-flow turbines, zero-head turbines, ultra-low-head turbines, or water-current turbines and have huge potential to exploit the available kinetic energy found in unrestricted/free-flowing fluid such as rivers, tides, irrigation channels, and canals [12].

2.3 Hydrokinetic Turbines Types:

Hydrokinetic turbines can be typically classified into two main groups: axial flow and cross-flow hydrokinetic turbines. This broad classification relies on the pivot axis of the rotor concerning the direction of the flow of fluid. Axial flow turbines are designed to rotate with their axis parallel or horizontal to the direction of fluid flow. These turbines are also known as propeller turbines as these turbines work similarly to ship propellers. As flow is parallel to pivot axis of the rotor in axial flow turbines, these turbines are ideal for rivers or irrigation channels where flow is more likely streamline. The rotor of axial flow turbines could have two, three, or multi-blades according to power or moment requirements. Solid mooring and buoyant mooring are examples of axial flow turbine configurations. Cross-flow turbines are designed to rotate with their rotational pivot perpendicular to the direction of fluid flow. Cross-flow turbines are further classified as horizontal-axis and vertical-axis cross-flow turbines. Cross-flow turbines can capture the water from any direction and utilize the channel depth efficiently due to their cylindrical shape. Cross-flow turbine can have two, three, or multi-blades similar to axial flow turbines depending on the power or torque requirement. H-Darrius, Darrius (Straight blade), Gorlov, and Savonius (Straight/Helical blade) are examples of cross-flow hydrokinetic turbines [13]. The physical arrangement of hydrokinetic turbines is presented in Figure 3.

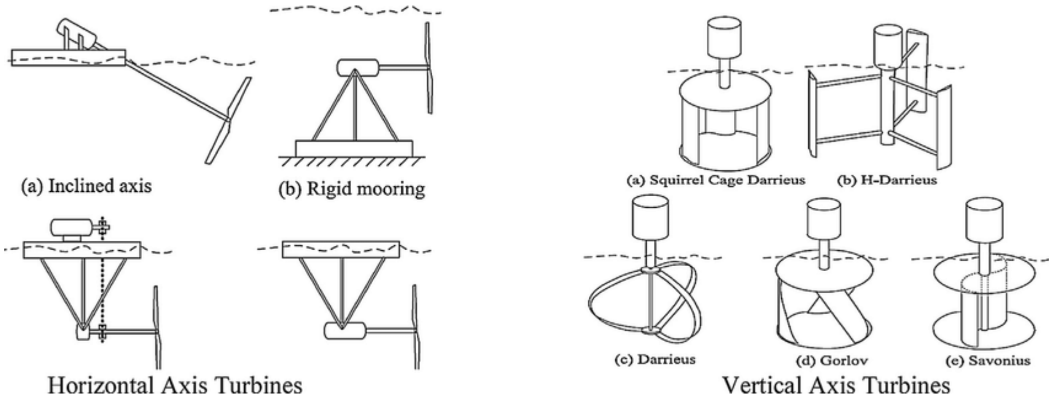

Figure 3: Classification of Vertical and Horizontal HKT [14].

Based on driving force, cross-flow turbines are further classified as:

- Lift Force-Based Hydrokinetic Turbines (Darrius Turbine, H-Darrius, Gorlov Helical Darrius, Achard Turbine, Lucid Spherical Turbine)
- Drag Force Based Hydrokinetic Turbines (Savonius Turbine, Bronzinus Turbine, CU Turbine, Flipping Turbine, Hunter Turbine, Tideng Turbine)
- Combined (Lift and Drag) Based Hydrokinetic Turbines (Darrius Outside-Savonius Inside, J-Shaped Rotor, Darrius downside-Savonius Upside, Darrius Upside-Savonius Downside

Some of the other types of Hydrokinetic turbines are:

Archimedes Screw Turbines: These consist of a screw-like rotor that rotates as water flows through it. These turbines are often used in low-head applications, such as irrigation canals.

Oscillating Hydrofoils: These have blades that oscillate back and forth in the water to generate power. Oscillating hydrofoils are typically used in low-velocity environments, such as tidal flows and slow-moving rivers.

Hydrodynamic Turbines: These turbines work by utilizing the forces of drag and lift exerting on the blades as water flows over them. These turbines commonly employed in rivers, canals, and tidal flows.

Each type of hydrokinetic turbine has its own strengths and weaknesses, and the choice of a particular type depends on factors like water velocity, head, and site conditions. Figure 4 represents the summary of the basic classification of hydrokinetic turbines.

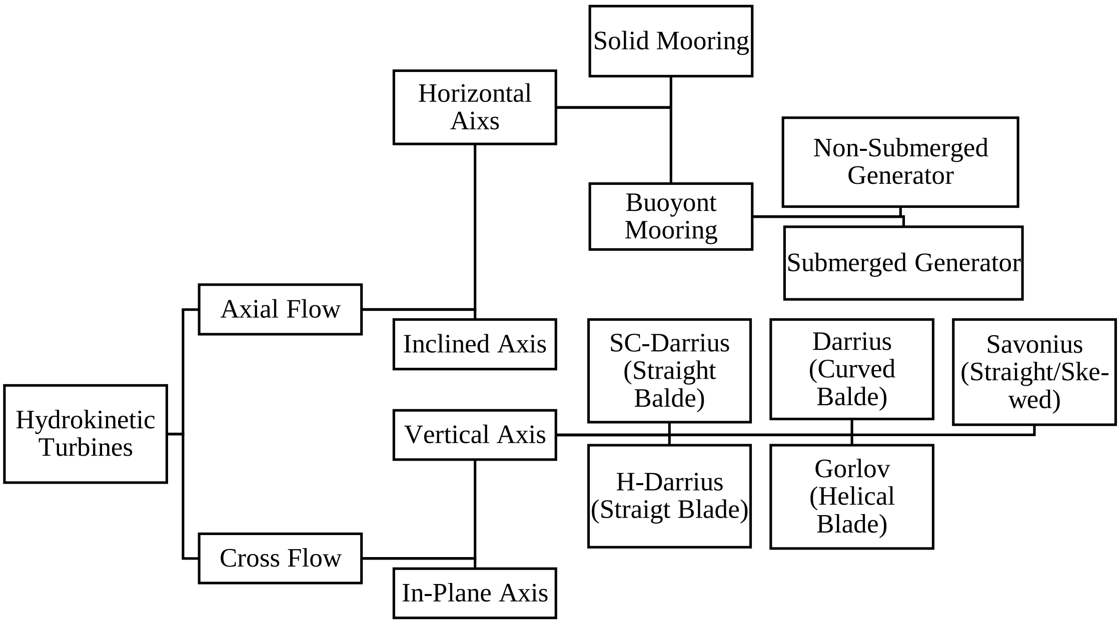

Figure 4: Categorization of Hydrokinetic Turbines.

2.4 Advantages and Disadvantages of Hydrokinetic Turbines:

Hydrokinetic turbines are mechanical systems that extract kinetic energy of water in motion and generate electricity. These turbines are typically installed in rivers, tidal streams, or ocean currents, and can provide a source of renewable energy with minimal environmental impact. However, like any technology, hydrokinetic turbines have both advantages and disadvantages.

One key benefit of hydrokinetic turbines is their ability to generate electricity from a dependable, consistent and reliable source of energy. Unlike wind and solar power, which can be variable and intermittent, the flow of water in rivers and oceans is relatively consistent and can be harnessed continuously. Hydrokinetic turbines also have minimal environmental impact compared to other forms of hydropower, such as large-scale dams, which can cause significant disruption to river ecosystems and fish populations. Another advantage of hydrokinetic turbines is their versatility. These turbines can be deployed across diverse water environments, capable of harnessing energy from fast-flowing rivers to slow-moving tidal currents. They also offer scalability, allowing for easy adjustments in size to meet energy needs of the local community or industry.

However, hydrokinetic turbines also have some disadvantages. A significant hurdle is the high capital cost of installation and maintenance. Hydrokinetic turbines require specialized engineering and infrastructure to install and maintain, which can be expensive and time-consuming. The turbines can also be vulnerable to damage from debris and extreme weather events, which can lead to downtime and repair costs. Another disadvantage of hydrokinetic turbines is their potential impact on aquatic life. The rotating blades of the turbine can pose a hazard to fish and other organisms and the installation of the turbines can disrupt fish migration patterns and alter sediment flow, which can affect aquatic ecosystems.

In conclusion, hydrokinetic turbines have several advantages and disadvantages as a renewable and sustainable energy source. While they offer a predictable and versatile source of electricity with minimal environmental impact, they also face challenges related to high capital costs and potential impacts on aquatic life. As with any technology, careful consideration of the benefits and drawbacks of hydrokinetic turbines is necessary to ensure their responsible and sustainable use [15-16].

2.5 Savonius Hydrokinetic Turbine:

The Savonius turbine, invented by Sigurd J. Savonius in 1922, is a drag-type turbine that is designed specifically for low fluid speed [17]. The Savonius rotor is a vertical axis rotor made up of two semicircular blades arranged in an "S" shape designed to capture energy through drag forces as shown in Figure 5. The convex side of one half-cylinder and the concave side of another half-cylinder simultaneously face the fluid. The concave side of the half-cylinder experiences a higher drag force due to its higher drag coefficient compared to the convex side. The variance in drag force initiates the spinning motion of the rotor and develops mechanical power. The Savonius turbine serves as an alternative source for generating small-scale energy. Its key advantages includes simplicity, good starting ability, low cost, easy installation, low operating speed, and independence from the fluid's direction [18].

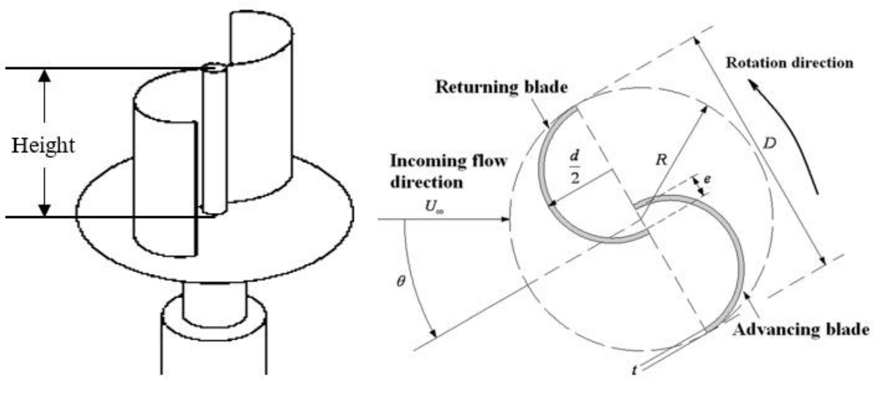

Figure 5: Schematic view of Savonius Hydrokinetic Turbine.

2.6 Augmentation Techniques in Savonius Turbines:

Savonius turbines are cheap, simple to design and construct, less operation cost compared to other vertical axis turbines but it has poor efficiency comparatively. Numerous researchers are working for many years to fix this problem of Savonius turbines. Numerous efforts have been undertaken to optimize the effectiveness of Savonius turbines either by adjusting the geometric configurations or employing various augmentation techniques. To boost the performance features and effectiveness of the Savonius turbine, several techniques employed, such as deflector plates, concentrators, curtain plates, advancing and returning blade deflectors, venting slots, and the employment of valves, etc. Some of these devices are elaborated below.

2.6.1 Adoption of Guide Vanes:

Guide vanes are blades installed upstream of the Savonius rotor that redirect the flow of water, increasing its velocity and pressure before it reaches the turbine blades. Applying this technique has demonstrated a substantial boost in the operational performance of Savonius turbines, leading to higher power output and efficiency. Studies conducted on guide vane adoption for Savonius turbines have reported significant improvements in the coefficient of power (C_p), indicating a substantial increase in the energy yield that can be extracted from the water flow. The adoption of guide vanes for performance improvement of Savonius turbines is a promising area of research that has the potential to make these turbines more efficient and widely applicable for small-scale energy generation.

An investigation conducted by Aldoss et al. demonstrated that the inclusion of guide vanes can boost the power coefficient (C_p) of the Savonius turbine by up to 54% [19]. Similarly, another study by Saha et al. reported that the adoption of guide vanes can increase the operational performance and effectiveness of Savonius turbines by up to 78%. These findings indicate that the use of guide vanes is a promising approach to improving the efficiency and power output of Savonius turbines, making them more suitable for small-scale energy generation [20]. A study conducted by Tariq et al. on the performance of a Savonius turbine by utilizing guide vanes. The findings of the study revealed a substantial boost in the power coefficient of the turbine, reaching as high as 43%, attributed to the implementation of guide vanes [21].

2.6.2 Deflector Plates:

Deflectors are plates that are installed upstream of the Savonius rotor at an angle. These plates assist in diverting the water towards the turbine blades, increasing the velocity and pressure of the water. The function of deflector plates is to steer the incoming flow specifically towards the advancing blade of the Savonius turbine. Past studies have demonstrated that the deployment of deflector plates significantly boost he effectiveness of the Savonius turbine. In a study conducted by Habib and Rahman, it was reported that the incorporation of deflector plates had a substantial impact on the power coefficient (C_p) of the Savonius turbine, resulting in an impressive increase of up to 46% [22]. Another investigation conducted by Oyewola et al. reported an improvement in the power coefficient (C_P) of the Savonius turbine by 53% through incorporation of deflector plate [23]. Similarly, Singh et al. performed an investigation and reported an enhancement in the effectiveness of the Savonius turbine with the use of deflector plates [24].

2.6.3 Spoilers Plates:

Spoilers are flat plates that are affixed to the surface of the blades in a Savonius turbine. They create turbulence in the flow of water, which helps to upgrade the coefficient of power (C_p) of the turbine. Research studies have shown that spoilers can boost the performance of Savonius turbines. For example, a study conducted by Hossain et al. and reported improvement in the power coefficient (C_p) of a Savonius turbine by up to 50% through the use of spoiler plates [25]. Another study by Rahman et al. reported an improvement in effectiveness of a Savonius turbine by 20% using spoilers [26]. Similarly, Kumar et al. also performed an investigation and reported that the performance of the Savonius turbine can be enhanced with the use of spoilers [27].

2.6.4 Venting Slots:

Venting slots are small openings that are strategically positioned on the upstream side of the Savonius turbine rotor to enable air to be released from the upper section during rotation, thereby enhancing efficiency by minimizing turbine drag. Wijekoon et al. examined the effect of venting slots on Savonius turbines and found that adding venting slots improved the turbine's power coefficient (C_p) by up to 36% [28]. Another study conducted by Habib et al. on the deployment of venting slots to improve turbine’s efficiency and reported 37% better results in power coefficient (C_p) of Savonius turbine through the utilization of venting slots [29].

2.6.5 Concentrators:

Concentrators are devices that are used to increase the velocity and pressure of the incoming fluid by concentrating the flow before it reaches the rotor of the Savonius turbine. This is achieved by using a converging section of the duct or nozzle, which narrows down the flow area and increases the fluid velocity. Habib et al. examined a Savonius turbine equipped with a converging nozzle as a concentrator and reported that this configuration increased the turbine's power coefficient by as much as 29% [30]. Another study conducted by Mohammadi et al. on Savonius turbine integrated with a converging nozzle as a concentrator and found that this setup increased the turbine's coefficient of power (C_p) up to 38% [31].

2.6.6 Valves:

Valves play a crucial role in regulating fluid flow into the Savonius turbine, enabling control over flow rate, pressure, and velocity, thereby enhancing the overall performance of the turbine. A study by Yilmaz and Keskin investigated the Savonius turbine performance by incorporating valves and reported improvement in turbine's performance up to 26% [32]. Similarly, Chauhan et al. also investigated Savonius turbine performance and found increase up to 20% in coefficient of power (C_p) using a valve to control the flow rate [33].

2.6.7 Bluff Bodies:

Recent research has extensively examined how the performance features of Savonius turbines can be enhanced by adding bluff bodies. Bluff body attachments have been shown in multiple studies to have a notable influence on the aerodynamic characteristics and overall performance of Savonius turbines. For instance, a study by Yang et al. examined the significance of different bluff body shapes on the turbine's performance. In the research, cylindrical bluff bodies were examined, varying in diameter and length. The research findings indicated that the installation of properly designed bluff bodies resulted in enhanced power coefficient and increased moment generation, leading to improved overall turbine performance [34]. Another study conducted by Wang et al. focused on optimizing the bluff body configuration for a Savonius turbine using numerical simulations and experimental validation. In the research, the use of rectangular bluff bodies, and adjusting their dimensions and positioning were studied. The research concluded that the strategic placement and shape of bluff bodies positively influenced the turbine's performance by promoting better flow control and reducing negative effects such as drag. These studies offer valuable information on how bluff bodies can effectively enhance the performance of Savonius turbines, providing guidance for future design improvements and practical applications [35].

2.7 Previous research on Augmentation Techniques:

Considerable work has been dedicated to improving the efficiency of the Savonius turbine through experimental, numerical, and theoretical approaches. Multiple studies were conducted in recent years for conventional Savonius turbines to boost their performance features. In their research, Kailash Golecha et.al investigated conducted experiments on modified Savonius turbine experimentally by adding a deflector plate upstream of the returning blade and reported the turbine achieved a maximum power coefficient (C_p) of 0.21 at λ=0.82. Eight different positions of the deflector plate were examined and identified the optimum position. At optimum position of deflector, two and three-stage modified turbine rotors were tested. The results showed a 42% and 31% increase in power coefficient (C_p) for a 0-degree and 90-degree phase shift of the deflector respectively. Additionally, a modified three-stage rotor demonstrated a 17% amelioration in the maximum power coefficient (C_p) [36]. Kaprawi Sahim et.al conducted an experimental study on a hybrid (Savonius-Darrius) turbine. Savonius buckets incorporated into the Darrius turbine configuration and reported that self–starting capability of Darrius turbine improved due to the presence of Savonius rotors even at low velocity conditions. Further, concluded that Savonius rotor elements should be positioned near the shaft and placed in the middle of Darrius's wing avoiding alignment with the same arm of Darrius’s wing for optimal performance [37]. Kaprawi S. et.al investigated a hybrid (Darrius-Savonius) hydrokinetic turbine experimentally operating at a constant speed of 0.8 m/s. To address the issue of low moment in the standalone Darrius turbine, a deflector plate upstream of the returning blade of turbine’s rotor was installed. The findings revealed an improvement of 18% in the coefficient of power (C_p) and 16% in the coefficient of moment (C_m). The study recommended an optimum deflector angle of 30^o for better performance [38]. Mosbahi et.al investigated the efficiency of a novel deflector system for a Savonius hydrokinetic turbine utilizing numerical analysis to improve turbine’s coefficient of power (C_p). Results revealed that, at tip speed ratio (TSR) =0.7 maximum power coefficient (C_p) was achieved 0.14 with modified turbine compared to 0.125 for a turbine without a novel deflector [39]. Kuo-Tsai Wu et.al conducted a study to examine the design parameters of Savonius turbine using both numerical and experimental approaches. The impact of various design parameters of blades such as arc angles, placement angles, and number of blades on turbine’s performance were investigated. The results indicated that turbine with six blades and arc angle of 135^o and placement angle of 0^o was the most suitable design considering higher moment, better performance, and cost [40]. Mohd Badrul Salleh et.al investigated two and three blades Savonius hydrokinetic turbine incorporated with a deflector experimentally and reported that the performance of both rotors improved significantly. The coefficient of power (C_p) enhanced by 128.38% for the two-bladed turbine and increase by 604.62% for three blades Savonius hydrokinetic turbine [41].Shashikumar C M et al. examined the effect of different V-angles ranging from 90^o to 40^o on modified V-shaped turbine utilizing experimental and numerical methods. All the experiments were conducted for constant value of 0.7 for arc radius, edge length and aspect ratio (AR). The maximum coefficient of performance (C_p) reported was 0.2279 at a tip speed ratio (λ) of 0.9 and incoming velocity of 0.3090 m/s for an 80^o V-angle blade profile. Performance improved by 86.13% when rotor with three plates (two end plates and one middle) with an aspect ratio of 1.75 was used compared to turbine with two end plates [42]. Ramin Alipour et.al investigated a Savonius turbine numerically with a parabolic blade shape by manipulating semicircular and arc shapes followed by straight arc blade shapes. The results revealed that the maximum coefficient of performance (C_p) was improved by 7.7% for the proposed turbine shape compare to the arc shape followed by the straight arc and 12% gain compared to the semicircular shape blade [43]. Sourish Singha and R. P. Saini conducted a numerical study on new modified Savonius hydrokinetic turbine having twisted blades to analyse its performance in multiple operational situations. The results revealed that the maximum coefficient of power (C_p) obtained 0.30 at a tip speed ratio (λ) of 1.4 and water upstream velocity of 2m/s [44]. Thochi Seb Rengma investigates the interaction of twin Savonius Hydrokinetic turbines experimentally. Concerning gap distance and phase shift, different configurations of clusters were studied under low water velocity of 0.75 m/s. The results revealed that the turbine achieved its maximum power coefficient (C_p) achieved of 0.15 at a λ=0.3. Moreover, the most effective configuration included a gap distance between the turbines equivalent to 0.6 times the turbine diameter along with 30^o phase shift between the turbines [45]. Priyo Agus Setiawan et.al numerically investigated the impact of different cylinder diameters positioned alongside the advancing blade on the operational effectiveness of the Savonius hydrokinetic turbine. Results revealed that the turbine achieved maximum coefficient of power (C_p) at d_s/D ratio of 0.7 and a λ=0.7 with a gain of 28% compared to conventional turbine [46].

The literature review highlighted the significant impact of using deflector as an augmentation device on the overall performance of the Savonius turbine which has sparked the interest of researchers. The backward facing (returning blade) of the Savonius turbine generates a negative moment leading to a substantial decrease in both power and moment output of turbine. To overcome this drawback, several augmentation techniques adopted in previous studies but utilizing flat plate deflectors greatly influence the returning blade by creating large vortices in the wake region causing instability of flow. To mitigate the formation of vortices and reduce the turbulent intensity, it is necessary to incorporate an effective method that disrupts the wake zone. Moreover, utilizing an obstacle in the hydrokinetic Savonius turbine is advantageous compared to the Savonius wind turbine because it operates with a consistent water flow direction, unlike the unpredictable wind flow in wind turbine. Previous studies have explored the use of curtains to enhance turbine's performance but the simplicity has not been prioritized in those approaches. Therefore, in this research paper, simple bluff bodies are utilized upstream to the returning blade of the Savonius hydrokinetic turbine (SHKT) to optimize the performance. Moreover, a deflector plate is also utilized in front of the driving blade to analyse the effect on the performance along with bluff bodies.

CHAPTER 3: NUMERICAL MODELING

3.1 Introduction:

The flow movement surrounding a Savonius rotor is highly fluctuating over time and performing CFD simulation for accurate results is a challenging task. The fluid dynamics surrounding a Savonius rotor is highly time-sensitive and performing CFD simulation for accurate results is a challenging task. Turbulence modeling is a computational technique employed in fluid dynamics to simulate the impact of turbulence behavior on flow of fluids. Turbulence is an intricate phenomenon that arises when fluid flows rapidly or encounters obstacles leading to complex patterns of swirling and unforeseeable movement within the flow. It results in random fluctuations in the flow, which can exert a notable influence on the efficiency and output of wind turbine, including Savonius turbine. These turbines are meticulously planned to extract energy from the wind by using the lift and drag forces on blades as they spin around a central axis. Turbulence modeling is required for Savonius turbines because the turbulent flow around the blades can have a significant impact on their performance. Turbulence triggers fluctuations in the forces of lift and drag that affect the blades, which can lead to unsteady forces and vibrations. This can reduce the efficiency of the turbine and increase the risk of mechanical failure. By simulating the effects of turbulence using CFD, engineers can better understand the flow around the turbine and optimize its design to improve performance and reliability. Several different types of turbulence models can be used for CFD simulations, each with its strengths and weaknesses. Some models, like the RANS (Reynolds-averaged Navier-Stokes) models use averaging techniques and are computationally efficient but may not capture all the intricacies of turbulent flow. Other models, such as LES (large eddy simulation) and DNS (direct numerical simulation), require significant computational resources but can provide more accurate results. Overall, turbulence modeling is an important tool for engineers designing Savonius turbines and other wind energy systems. By accurately simulating the effects of turbulence on fluid flow, they can optimize the design of these systems to maximize energy extraction and minimize the risk of mechanical failure.

3.1.1 RANS (Reynolds Averaged Navier Stokes) Equation:

The flow around the hydrokinetic turbines operating in water is turbulent and assumed to be unsteady and incompressible. RANS (Reynolds Averaged Navier Stokes) turbulence models are still extensively utilized as CFD solvers for examining vertical axis turbines. Due to complex flow behavior over rotating hydrokinetic turbines RANS turbulence models present overall accurate results with low computational cost.

The flow around the hydrokinetic turbines operating in water is turbulent and assumed to be unsteady and incompressible. Due to complex flow behavior over rotating hydrokinetic turbines RANS turbulence models present overall accurate results with low computational cost. The RANS (Reynolds-averaged Navier-Stokes) equations is a set of equations used in computational studies of fluid dynamics to model and simulate turbulent fluid flows. It relies on the Navier-Stokes equations, which elucidate the movement of fluid particles, and includes an additional term that accounts for the effects of turbulence. The RANS equation can be written as equation (3.1);

$$\rho\left(\frac{\partial u}{\partial t}+u.\nabla u\right)=-\nabla p+\mu\nabla^{2u}-\rho(1-F)\epsilon \quad \ldots\ldots\ldots\ldots (3.1)$$

Where;

ρ = density of the fluid

u =velocity vector

p=pressure

μ =dynamic viscosity

F= damping function (Model specific)

ϵ=turbulent kinetic energy dissipation rate

The RANS equation can be broken down into its individual components to provide a precise understanding. The left-hand side represents the time rate of change of momentum of the fluid and the convective acceleration due to the movement of the fluid. Similarly, the terms on the right-hand side of the equation represents the forces acting on the fluid, including the pressure gradient, viscous forces, and turbulent dissipation.

The term (1-F) ε in the RANS equation represents the impact of turbulence on the flow of fluid. Turbulence is distinguished by small-scale, chaotic fluctuations in velocity and pressure that are difficult to resolve in a CFD simulation. The term (1-F) ε is a model-specific damping function that is used to approximate the consequence of turbulence on the flow. The value of ‘F’ varies depending on the turbulence model being used and is typically determined through empirical testing or validation against experimental data.

In summary, the RANS equation is a fundamental equation used in CFD simulations to model turbulent fluid flows. It accounts for the implication of turbulence on the behavior of fluid’s flow by including an additional term that represents the rate of dissipation in the context of turbulent kinetic energy. The value of the damping function ‘F’ is determined through empirical testing or validation against experimental data and varies depending on the turbulence model being used.

3.2 Mathematical Model of Savonius Rotor:

According to the mathematical model proposed by Paraschivoiu, the total moment exerted by Savonius turbine's rotor is the aggregate of the individual moments acting on each blade of the rotor [30]. Mathematically total moment is given by equation (3.2);

$$Q = Q_M + Q_D \text{ .... (3.2)}$$

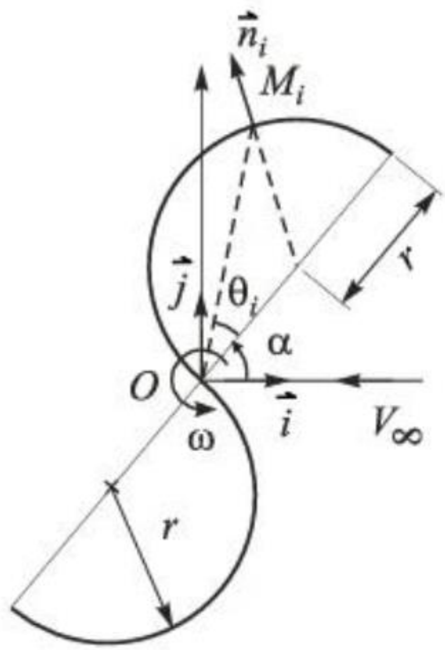

Figure 6: Savonius rotor mathematical modeling scheme.

The difference in pressure between both blades of turbine can be utilized to obtain total moment. This can be mathematically presented as in eq. (3.3);

$$Q = 2r^2 H \int_0^{\frac{\pi}{2}} (\Delta P_M - \Delta P_D) Sin2\theta \, d\theta \text{ .... (3.3)}$$

r= Rotor blade radius

H=Turbine height

θ= Angular position of the rotor blade

ΔP_M= Pressure difference on advancing blade

ΔP_D= Pressure difference on returning/drag blade

Based on experimental procedures, the derived correlation for pressure difference based on gauge measurement is given by equation (3.4) and (3.5);

$$K = \frac{\Delta P_{M(f)}}{\frac{1}{2}\rho V_e^2} \text{ .... } (3.4)$$

And,

$$K' = \frac{\Delta P_{D(f)}}{\frac{1}{2}\rho V_i^2} \text{................ } (3.5)$$

Where; K= f (α) and K'=f (α)

α= blade azimuthal angle

Similarly;

$$V_e = V_\infty - V_i \text{ .... } (3.6)$$

Where;

V_∞ =Free-stream velocity

V_i= Absolute velocity at point M_i (shown in Figure 6)

Using equation (3.4), (3.5) in equation (3.3) gives;

$$Q_M = \rho r^2 HK[V_\infty^2 + 2\dot{\alpha}^2 r^2 - \frac{\pi}{2} V_\infty \dot{\alpha} r cos\alpha - 2V_\infty \dot{\alpha} r sin\alpha] \text{ ....} (3.7)$$

$$Q_{D=} 2\rho r^4 H\dot{\alpha}^2 K' \text{ .... } (3.8)$$

Mathematically, average power (P) and normalized coefficient of power (C_p^*) can be represented as in equations (3.9, 3.10);

$$P = \omega . Q = \frac{\omega}{\pi}\int_0^\pi Q d\alpha \text{ .... } (3.9)$$

$$C_p^* = \frac{P}{\frac{1}{2}\rho V_\infty^3 A_s} \text{............... } (3.10)$$

Where * represents a normalized variable

ω= Angular velocity

A_s=Swept area

By combining equations 3.7, 3.8, 3.9, and 3.10 and making K=K` gives

$$C_P^* = \left[\frac{1}{2}\frac{K\lambda}{2} - \frac{K\lambda^2}{2\pi}\right] \text{.................... } (3.11)$$

For Maximum power coefficient;

$$\frac{dC_p^*}{d\lambda} = 0 \text{ .... } (3.12)$$

Solving equation (3.12) gives;

$$C_P^* = C_{Pm}^* 16\left(\frac{\lambda}{\pi}\right)\left[\frac{1}{2} - \left(\frac{\lambda}{\pi}\right)\right] \text{ .... } (3.13)$$

By solving the resulting equations after setting C_p^* equal toC_{pm}^*, a tip speed ratio (λ) of 0.79 is obtained as the value that maximizes the coefficient of power (C_p). This finding demonstrate a favourable correspondence with the results from Sandia National Laboratories, where the maximum coefficient of power (C_p) was conducted on a Savonius turbine having two blades with s/d= 0 for tip speed ratio (λ) approximately 0.8.

3.3 Evaluation Metrics of Savonius Turbine:

Performance metrics or operational parameters of the Savonius rotor included angular velocity (ω), tip speed ratio (λ) , total power (P), power coefficient (C_p), rotor moment (T), and moment coefficient (C_m). These parameters impact the performance of the Savonius turbine and relate to each other.

3.3.1 Tip Speed Ratio (λ):

Tip speed ratio is "the ratio of blade tip velocity or tangential velocity (V_{tip}) to the free stream velocity (V_o) of the fluid". The mathematical representation of tip speed ratio is given below in equation (3.14);

$$\lambda = \frac{V_{tip}}{V_o} = \frac{R\omega}{V_o} \text{ .... } (3.14)$$

Where; R= Radius of the rotor and ω= Angular velocity

3.3.2 Available Power, Rotor Power, and Power Coefficient:

Available power is the power that is carried by incoming fluid to the Savonius turbine and the rotor captures this power. Fluid incoming velocity, density, and area highly influence available power. The available power can be expressed mathematically using equation (3.15);

$$P_{avl} = \frac{1}{2}\rho A {V_o}^3 \text{ .... } (3.15)$$

Where;

A= Swept Area

ρ= Density of fluid and $V_o =$ Incoming velocity of the fluid

The power that the rotor of the turbine captures from incoming fluid is known as "rotor power" and it is the function of the total moment and angular velocity (ω) of the turbine. Mathematically can be represented as in equation (3.16);

$$P_{rotor} = T * \omega \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.16)}$$

Coefficient of power can be defined as "the ratio of mechanical power captured by the rotor (*P_{rotor}*) and available power (*P_{avl})* to the turbine is known as and it is denoted as C_p. Mathematically, the it can be expressed as in equation (3.17);

$$C_p = \frac{P_{rotor}}{P_{avl}} = \frac{T\omega}{0.5\rho A {V_o}^3} \ldots\ldots\ldots\ldots\ldots \text{(3.17)}$$

The power coefficient (C_p) of a turbine can be related to tip speed ratio (λ) as in equation (3.18);

$$C_p = \frac{P_{rotor}}{P_{avl}} = \frac{T}{0.5\rho A {V_o}^2 R} * \lambda \ \ldots\ldots\ldots\ldots \text{(3.18)}$$

3.3.3 Moment Coefficient and Its relation with Power Coefficient:

The moment coefficient is the ratio of turbine moment that the turbine develops and the available moment (the ability of fluid to generate moment). The moment coefficient can be mathematically written as in equation (3.19);

$$C_m = \frac{T}{0.5\rho A {V_o}^2 R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.19)}$$

Using equation (3.18) and (3.19) power coefficient (C_p) and moment coefficient (C_m) can be related as in equation (3.20);

$$C_p = C_m * \lambda \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.20)}$$

At different Reynolds numbers (Re) and tip speed ratio (λ) turbine's performance can be conveniently measured. Based on incoming water speed and the turbine's diameter, the Reynolds number can be defined as in equation (3.21);

$$Re = \frac{V_O D}{\mathrm{v}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.21)}$$

Where V_o, D, and v represent incoming velocity, turbine's diameter, and kinematic viscosity of water.

3.4 Design Parameters of Savonius Rotor:

The effectiveness of vertical axis Savonius turbine is typically affected by certain design parameters, including the aspect ratio (AR), overlap distance between two buckets of turbine, blade's count, multi-staging, end plate dimensions, blades profile or geometry and presence of turbine shaft [47].

3.4.1 Aspect Ratio and Its effect on turbine performance:

The aspect ratio (AR) is a crucial design parameter that has a significant impact on how well the vertical axis Savonius turbine performs. The aspect ratio (AR) is "the ratio of turbine's height (H) and turbine's diameter (D)". It is often expressed as in equation (3.22);

$$AR = \frac{H}{D} \text{ ………………….. (3.22)}$$

Many researchers conducted investigations to examine consequence of aspect ratio (AR) on the power coefficient (C_p) of Savonius turbines. It is suggested that, for aspect ratio (AR) should be less than 1.5 for achieving structural stability of turbine. Moment generation increases for large diameters with a simultaneous reduction in speed or rotational velocity.

A study conducted by Kim et al. evaluated significance of aspect ratio on the functionality of a Savonius turbine. The study highlighted that the optimal aspect ratio (AR) was spanned from 0.5 to 1.0 for Savonius turbine having two blades. Beyond this range, the effectiveness of the turbine decreased due to more drag [48]. Another study conducted by Oyewola et al. also assessed the consequence of aspect ratio on the productivity of a Savonius turbine with different configurations. The study showed that the optimal aspect ratio for a Savonius turbine with two blades was 0.8 yielding 30% more coefficient of performance compared to an aspect ratio of 0.6 [49].

3.4.2 Overlap Ratio and its effect:

Overlap ratio (β) can be defined as "the ratio of overlap distance (e) between the blades of the rotor and the rotor diameter (D). It is often expressed as in equation (3.23);

$$\beta = \frac{e}{D} \text{ …………………….. (3.23)}$$

The overlap ratio greatly affects the effectiveness of the Savonius turbine. Rotor having overlapping distance enhances the starting ability of Savonius turbine because due to overlapping flow, the negative moment decreases and consequently the average power increases. A larger overlap distance increases the vortex effect in the overlap region and decreases the moment. A higher overlap ratio can result in increased moment and power coefficient due to increased interaction between the blades. However, too much overlap can lead to increased drag and reduced efficiency. On the contrary, a lower overlap ratio (β) can lead to reduced power output but also reduced drag and increased efficiency.

A study conducted by Chen and Chang probed the outcome of overlap ratio (β) on the execution of a Savonius turbine. The analysis exhibited that an overlap ratio (β) of 0.5 resulted in the highest performance for a two-bladed rotor.

Beyond an overlap ratio (β) of 0.5, resulted in a decrease in the performance of turbine [50]. Another study conducted by Bhattarai et al. also evaluated the impact of overlap ratio (β) on output efficiency of Savonius turbine with a twisted blade configuration. The study highlighted that an overlap ratio (β) of 0.1 resulted in the highest power coefficient for a twisted-blade Savonius rotor. Further increasing the overlap ratio beyond 0.1 led to a reduction in the power coefficient (C_p) [51].

In conclusion, the overlap ratio of a Savonius turbine is an important design parameter that affects its performance. An optimal overlap ratio can result in an increased power coefficient, but increasing it beyond a certain limit can lead to a reduction in performance due to increased drag.

3.4.3 Blades count and its effect:

The Savonius rotor can equipped with two, three or more blades. The number of blades is a significant design factor that impacts the effectiveness of turbine, influencing the moment and power coefficient, as well as the start-up and cut-in wind speed of the turbine. A higher number of blades can result in increased moment and power coefficient due to increased interaction with the flow of air or water through the rotor. However, too many blades can lead to increased drag and reduced efficiency. On the other hand, a lower number of blades can lead to reduced power output but also reduced drag and increased efficiency.

Gandhi et al. explored the impact of blade number on the effectiveness of a turbine. The study showed, increasing the number of blades from two to three resulted in a 14% increase in the coefficient of the moment (C_m) and a 13% more yielding in the power coefficient (C_p). However, further to four or five blades resulted in low performance [52]. Another study conducted by Oyewola et al. also assessed the consequence of blade number on turbine's performance. The study showed that increasing the number of blades from two to three resulted in a 39% increase in the coefficient of the moment (C_m) and 27% more yielding in turbine's power coefficient (C_p). However, increasing the number of blades beyond three led to a reduction in performance [53].

In conclusion, blade count is an important design element that affects turbine's performance. An optimal number of blades can result in an increased power coefficient, but increasing it beyond a certain limit can lead to a reduction in performance due to increased drag.

3.4.4 Endplates diameter and its role:

Endplates are an important design feature of a Savonius turbine, as they can affect the aerodynamics and performance of the turbine. The diameter of the endplates, representing the circular ends of the turbine, can influence both turbine's moment and power coefficient. A smaller endplate diameter can result in reduced drag and increased efficiency, but can also lead to reduced power output due to reduced interaction with the flow of air or water. Conversely, a larger endplate diameter can result in increased interaction with the flow and increased power output, but can also lead to increased drag and reduced efficiency.

A study conducted by Choi et al. explored the outcome of endplate diameter on the execution of a Savonius turbine. The study showed that increasing the endplate diameter from 0.6D to 1.2D resulted in a 16% increase in turbine's coefficient of moment (C_m) and a 17% more yield in turbine's power coefficient (C_p). However, further increasing the endplate diameter to 1.5D or 2D led to a reduction in performance due to increased drag [54]. Another study conducted by Fong et al. also probed the outcome of endplate diameter on turbine's productivity. The study showed that increasing the endplate diameter from 0.5D to 1.5D resulted in a 33% increase in turbine's moment coefficient (C_m) and a 39% increase in the power coefficient (C_p). However, further increasing the endplate diameter to 2.0D or 2.5D led to a reduction in performance due to increased drag [55].

In conclusion, the diameter of the endplates is an important design feature that affects the performance of a Savonius turbine. An optimal endplate diameter can result in increased power output, but increasing it beyond a certain limit can lead to a reduction in performance due to increased drag.

3.4.5 Blades geometric profile and its role:

The geometric profile of the blades is a critical design feature that determines the aerodynamic characteristics of the turbine, which can significantly affect the coefficient of moment and power coefficient. Various blade profiles have been investigated in research studies, such as semi-circular, semi-elliptical, and flat plates. The semi-circular blade profile is the most common due to its simplicity and ease of manufacture. However, other blade profiles can potentially offer higher performance due to improved aerodynamics.

A study conducted by Nidamanuri et al. assessed the effect of altering the blade profile on the effectiveness of Savonius turbine. The study showed that a blade profile with a curvature ratio of 0.7, which is between semi-circular and semi-elliptical, yielded the highest coefficient of moment and power coefficient. This blade profile offered a 17% increase in the coefficient of the moment (C_m) and a 16% more gained in the power coefficient (C_p) compared to the semi-circular blade profile [56]. Another study conducted by Hong et al. also examined the consequence of blade profile on the efficiency turbine. The study showed that a blade profile with an a symmetrical airfoil shape resulted in a 23% more yield in the coefficient of the moment and a 20% enhancement in the power coefficient compared to the semi-circular blade profile [57].

3.4.6 Multi-staging and its effect:

Multi-staging is a technique where multiple Savonius rotors are stacked together in series or parallel to enhance turbine's performance. This technique has been investigated in several research studies to determine its effect on moment coefficient and power coefficient.

A study conducted by Mohamed et al. explored the outcome of multi-staging on the Savonius turbine's performance. The study revealed, that a two-stage Savonius turbine resulted in a 69% increase in the coefficient of the moment (C_m) and a 30% increase in the coefficient of power (C_p) compared to a single-stage Savonius turbine. The study also found that the angle between the two stages had a significant on turbine's performance [58]. Another study conducted by Hossain et al. evaluated the effect of parallel multi-staging on the turbine's performance. The study revealed, that a three-stage Savonius turbine resulted in a 23% increase in the moment coefficient and a 46% increase in the power coefficient compared to a single-stage Savonius turbine [59].

3.5 Turbine Design Parameters and Modeling:

3.5.1 Design Specifications and Geometric Representation*:*

Previous studies has revealed that the presence of deflectors greatly influence the performance features of the Savonius turbine. By incorporating deflectors, the adverse moment produced by the blade's return motion in the Savonius turbine is mitigated, resulting a noticeable decrease in the overall generated net moment generated by the turbine. The negative moment can be reduced by installing simple bluff bodies as deflectors which restrict the flow towards returning blade and deflect toward driving blade consequently increasing the overall performance of turbine.

Figure 1 portrays a schematic view of the Savonius rotor augmented with a simple bluff body and flat plate deflector utilized in this research to optimize turbine's performance. The dimensional parameters of the conventional turbine and proposed Savonius Hydrokinetic turbine with a bluff body and deflector plate installed upstream are presented in Tables 1, and 2, and are illustrated in Figure 7 and Figure 8. The same parameters for the Savonius rotor were also reported in previous studies of Hossein Alizadeh et.al [60] and Esmaeel Fatahian et.al [61].

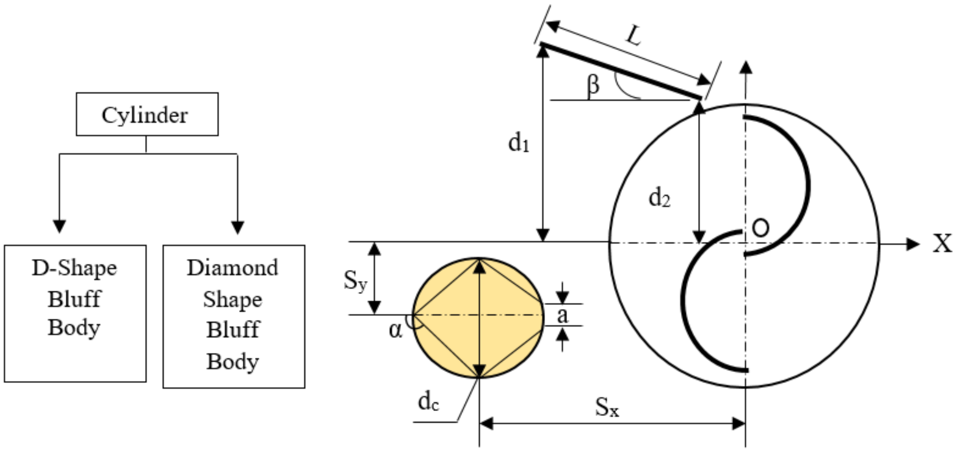

Figure 7: Schematic view of Proposed design with geometric parameters.

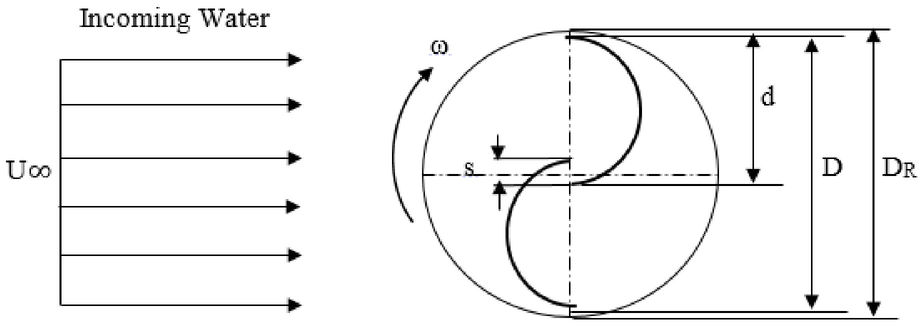

Figure 8: Dimensional metrics of Savonius rotor.

Table 1: Dimensional metrics of Savonius rotor.

Parameters	**Values**
Rotor Diameter (D)	0.909 (m)
Blade Diameter (d)	0.5 (m)
Height (H)	1 (m)
Turbine Rotor Area (A)	0.909 (m^2)
Rotor Blade ‘Thickness	0.01 (m)
Distance between blades (s)	0.071 (m)
Aspect Ratio	1.1
Number of blades	2
Centre coordinates of the rotor	(0,0)

Table 2: Dimensional metrics of the bluff body and deflector's positioning.

Parameters			**Values**
Diameter of Cylinder (d_c/D)			[0.3,0.4,0.5]
Angle (α)			135°
Tail Height (a)			0.079 (m)
Centre Distance from X-axis (R_y/D)			[0.75,1,1,25]
Centre Distance from Y-axis (R_x/D)			[0.23,0.37,0.51]
Geometrical parameters for deflector plate positioning			
d_1 (m)	d_2 (m)	L (m)	β
0.88	0.51	0.52	45°

3.6 Computational Approach and Boundary Setting:

3.6.1 Computational Domain and Grid:

The size of the domain plays vital role for accurate results and computational time. The larger domain size increases the computational cost and time but leads to accurate results. On the other hand, a small computational domain leads to inaccurate results but reduces the computational cost and time. The meticulous choice of an optimal domain size holds utmost significance in attaining precise outcomes, while concurrently optimizing computational efficiency and cost effectiveness. Figure 9 illustrates the computational domain employed in this work. The generation of the computational domain is accomplished through the utilization of ANSYS [62]. For computation with and without bluff bodies have some differences. The computational domain is partitioned into two subdomains for cases without bluff bodies and flat deflector plates: an inner rotating zone of computational domain consisting of turbine blades with a specified diameter denotes as "D" and a larger stationary zone situated outside the rotating zone. The demarcation between the rotating and stationary zones is established by means of an interface, enabling the rotation of rotating zone at defined rotational velocity, while maintaining the stationary zone in a fixed position. The diameter of the rotating domain is set to 1.1D, ensuring a proportional expansion of the rotational zone. The upstream boundary is positioned at 8D, while the downstream boundary is maintained at 16D. Additionally, the upper and lower boundaries are positioned at 10D from the centerline of the turbine. In cases involving the presence of bluff bodies, the computation domain is partitioned into three distinct sub-domains: an inner domain (rotating), an outer domain (stationary), and a dedicated domain encompassing the bluff bodies and flat deflector plate, referred to as the bluff body domain. This division facilitates accurate and analysis of complex flow interactions within the system.

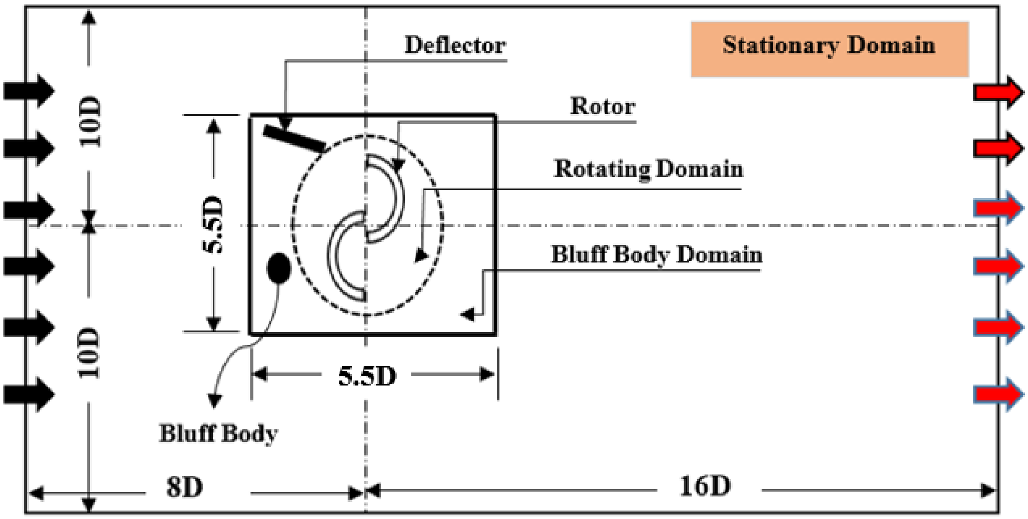

Figure 9: Computational Domain.

Figure 10 shows the boundary conditions representation applied in this study. The boundary conditions are carefully enforced to ensure that the Reynolds number aligns with the experimental conditions. At the upper and lower boundaries of the domain, symmetry boundary conditions are prescribed, effectively mirroring the flow characteristics. In consideration of the inlet boundary condition, an inlet velocity is specified, with the magnitude of 0.48 m/s, corresponding to a Reynolds number of 4.32×10^5 aligning with the experimental conditions. The surface of the rotor, bluff body, and flat plate deflector is subjected to no-slip boundary conditions, signifying that the fluid velocity at these surfaces is zero, thereby assuming a complete adherence of the fluid to the solid boundaries. Pressure outlet (atmospheric pressure) applied as a boundary condition to the outlet and common surface between the rotating and stationary domain was considered as interface.

The grid generated for the computational domain was a combination of structure and unstructured elements. The structured mesh was used for the stationary domain with rectangular elements to improve mesh quality and make the mesh more controllable. The grid of the rotating domain and bluff body domain was built using unstructured triangular elements but to satisfy the turbulence model requirements, a structured mesh with a boundary layer was implemented near the wall. This approach ensures that the value of y+ remains below 1, guaranteeing accurate modeling and capturing of the near-wall flow characteristics. In order to achieve a target y+ value of one or lower ($y+ \leq 1$), a structured mesh consisting of 20 layers was employed on the blades, with an expansion ratio of 1.2. The initial distance of the first cell from the wall was determined to be 0.1 mm. The grid configuration depicting the grid structure used in the computational domain is depicted in Figure 11.

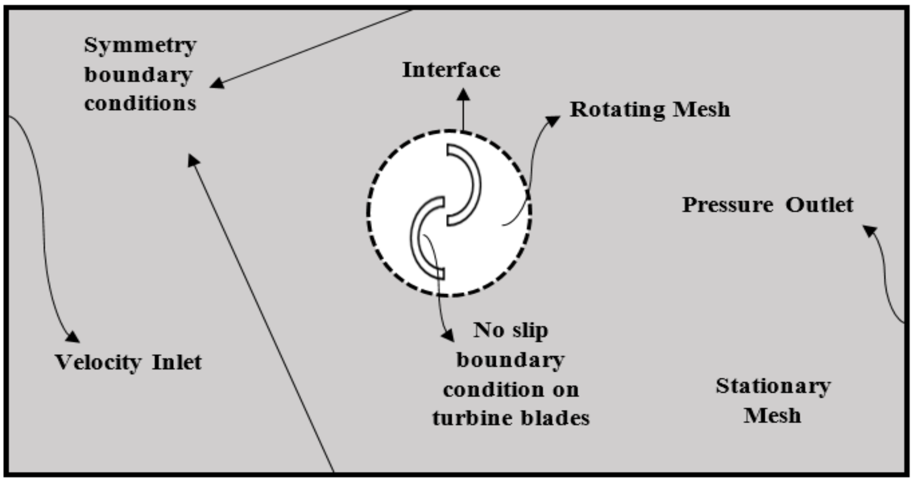

Figure 10: Representation of Boundary Conditions.

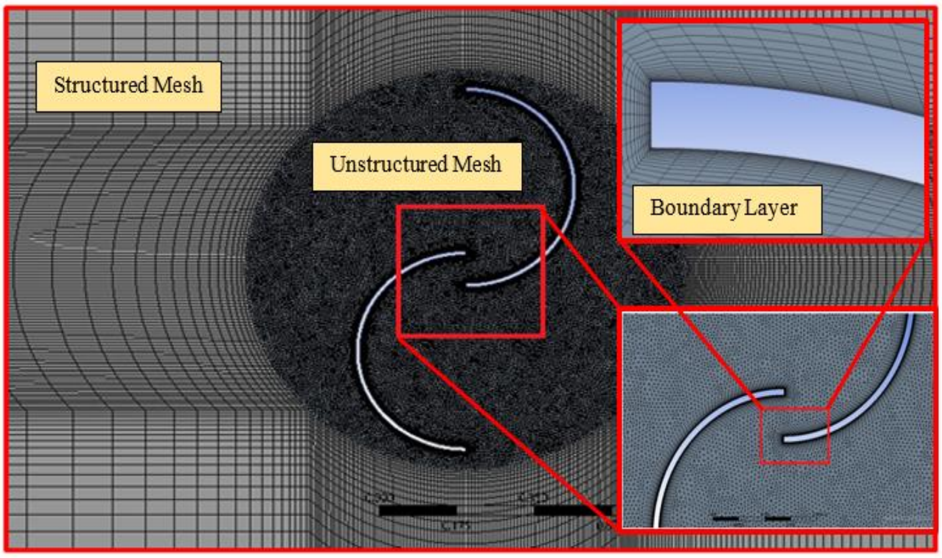

Figure 11: Meshing Detail of Computational Domain.

3.6.2 Turbulence Model and Solver Setting:

CFD simulations were conducted using ANSYS Fluent software to analyse and investigate the flow behavior within the system. In this study, we adopted the $(k - \omega)$ SST (Shear Stress Transport) turbulence model as suggested by Balduzzi et al. [63] for CFD simulations. This model is advantageous for accurately predicting the performance of the turbine as it combines the favorable characteristics of the $k - \omega$ model in near-wall zones and $k - \epsilon$ model in the far-field zones beyond the boundary layer thickness. By integrating these attributes, the model effectively captures the flow dynamics in both near-wall and far-field regions, resulting in reliable performance predictions for the turbine. The SST (Shear Stress Transport) turbulence model, originally proposed by F. R. Menter [64], is a hybrid formulation that combines the advantageous features of both the

$k - \omega$ and $k - \epsilon$ turbulence models. By integrating the strengths of these models, the SST turbulence model offers improved accuracy and robustness in capturing a wide range of flow phenomena and turbulence characteristics as the $k - \epsilon$ model is unpredictable near-wall zones and shows better attributes in the free flow outside the boundary layer and $k - \omega$ is useful near-wall zones. The transport equations associated with the $k - \omega$ SST (Shear Stress Transport) turbulence model can be described as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \text{ ……………………. (3.24)}$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \text{ ……………. (3.25)}$$

Where;

G_k= Turbulent kinetic energy generation

G_ω= Specific dissipation rate generation

Γ_k, Γ_ω = The effective diffusivity of k and ω.

Y_k, Y_ω are a dissipation of k and ω due to turbulence.

D_ω = Cross-diffusion term.

S_k, S_ω are source terms.

The relations for the calculation of effective diffusivity (Γ_k,Γ_ω) generation of turbulent kinetic energy (G_k), dissipation of k and ω (Y_ω, Y_k), cross-diffusion (D_ω) are presented in below mentioned relations.

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \text{ …………………….. (3.26)}$$

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \text{ ……………………. (3.27)}$$

Where σ =Turbulent Prandtl number

$\mu_t = Turbulent\ Viscosity$

$$G_\omega = \frac{\alpha}{\nu_t} G_k \text{ ……………………. (3.28)}$$

G_k is computed using procedures mentioned in the $k - \omega$ standard model [64].

$$Y_\omega = \rho \beta \omega^2 \text{ ………………… (3.29)}$$

$$Y_k = \rho \beta^* \omega k \text{ ………………….. (3.30)}$$

Where 'β' depends on the blending function.

$$D_\omega = 2(1-F_1)\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{x_j} \text{ .... (3.31)}$$

Where

F_1 = Blending function (Value Range: 0-1)

The value of the blending function near the wall is 1 and activates $k-\omega$ turbulence model and its value is zero in the far-field region which activates $k-\epsilon$ turbulence model. Cross diffusion (D_ω) and blending function (F_1) are the two important factors that differentiated SST ($k-\omega$) model form $k-\omega$ and $k-\epsilon$ turbulence model. SST ($k-\omega$) turbulence model is robust and precise for intricate flow problems and behaves correctly for both near-wall zones and far-field regions.

This research examines the performance features of the Savonius hydrokinetic turbine by exploring a range of tip speed ratios, varying from 0.4 to 1.2 with an increment of 0.2, in each simulation. A grid of 79,000 elements was used and the simulation utilizes the Sliding Mesh Model (SMM) for rotational effects and the SST $k-\omega$ model for turbulence modeling. Regarding the turbulence conditions, at the inlet, the turbulence intensity is 1% and the turbulent viscosity ratio is 10%. At the outlet, the turbulence intensity is 5% with the same turbulent viscosity ratio of 10%. The time-step and sub-iterations were set at 1 degree and 20 per time step, respectively. The solution method employed in the CFD simulation was a transient-pressure based approach, utilizing the SIMPLE algorithm as the solver. The scheme used for solving the equations involved the application of a least squares cell-based method for gradient computation. Additionally, a second-order upwind discretization scheme was implemented for ensuring accurate and stable calculations of the governing equations. These discretization methods are known for their ability to capture the complex flow behavior and provide reliable numerical solutions in computational fluid dynamics simulations. Additionally, a convergence criterion of 10^{-5} was set for each variable. Equation (3.32) was used to calculate the time step for each simulation.

$$\Delta t_{|\theta^o} = \frac{\theta}{\omega\frac{180}{\pi}} \text{ .... (3.32)}$$

3.7 Grid Independence and Time Step Study:

3.7.1 Grid Independence Analysis:

Achieving grid independence is crucial to balance computational time and numerical accuracy effectively. It ensures that the results of the simulation remain stable and reliable, reducing the need for excessive computational resources while maintaining accuracy. The accuracy and reliability of results obtained through simulation highly depend on the size of the mesh. Conducting a grid independence study aids in determining the optimal grid size that validates the invariance of the solution as the mesh undergoes refinement. As the mesh is refined with smaller elements or cells, the resulting solution yields higher accuracy in capturing the desired outcome but with the expense of long computational time and more data processing. So, a grid independence analysis is necessary to determine an adequate mesh size that balances computing time, data processing, and result quality effectively.

In this study, a grid independence analysis is conducted utilizing three distinct grid configurations, namely coarse, medium, and fine grids. The purpose of this study is to ensure the solution's mesh independence by identifying the optimal mesh resolution. The computational grid was refined from coarse (47k Cells), and medium (79k Cells) to fine (154k Cells) maintaining the same mesh quality and distributions. The examined parameter for the grid independence study was the moment coefficient (C_m) and the grid independence study for three grids was carried out until no significant change was observed in the moment coefficient (C_m). For the mesh or grid independence study, all the simulations were performed with the same solution parameters. All the study is performed for λ=1 and the average moment coefficient is calculated for all three girds to find the appropriate grid.

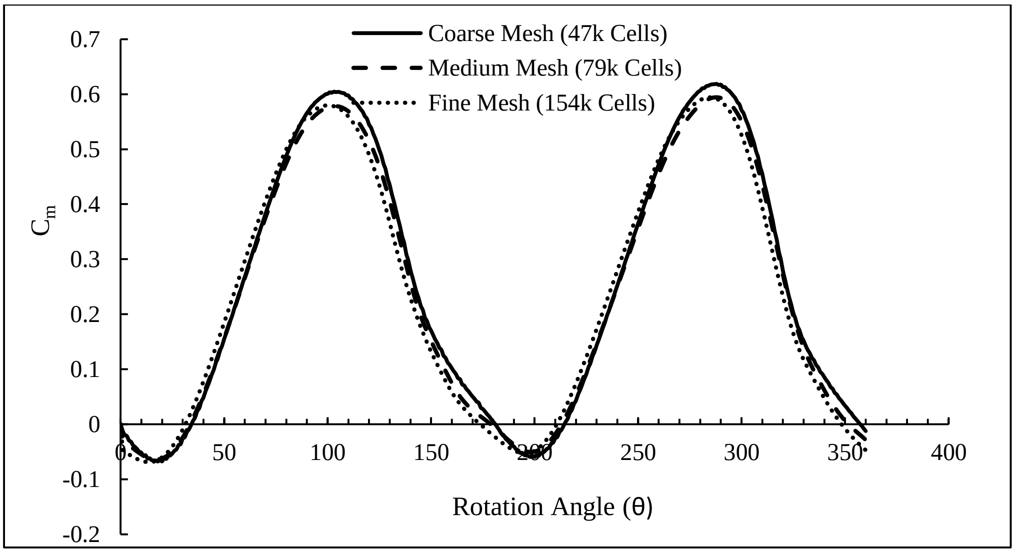

Figure 12: Grid independence test.

Figure 12 shows the grid independence test for coarse, medium, and fine grid sizes. The numerical results for medium grid size are nearly equal to fine mesh and both meshes were compatible. It can be observed that the moment coefficient (C_m) curve is consistent for fine and medium mesh. The error between captured moment coefficient (C_m) results for fine and medium mesh was 0.294%. The influence of fine mesh was very little on results and so medium mesh is selected for further computations as it can correctly predict the rotor performance according to computed results as shown in Figure 13.

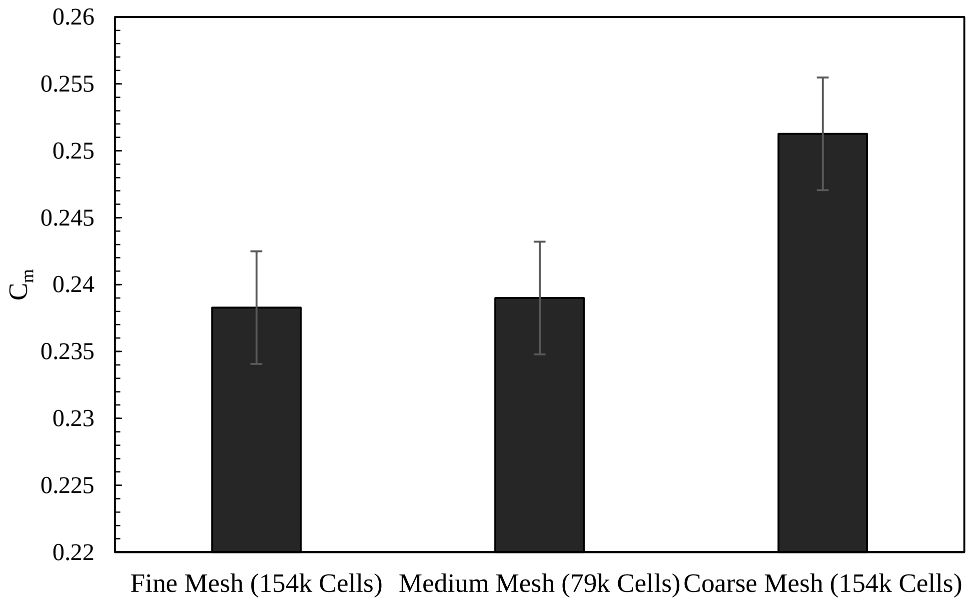

Figure 13: Comparison of Moment Coefficient (C_m) for different grids.

3.7.2 Time Step Study:

After performing the mesh independence test and selecting a medium grid with 79k Cells, time step study is also performed to select the optimum time-step size for further simulations. Given the unsteady nature of the present study, determining an optimal time-step size is imperative to ensure precise simulation results while minimizing computational data processing time requirements. To ascertain the optimal time step size, a series of two-dimensional computational fluid dynamics (CFD) simulations were conducted, employing three different time-steps of 0.5^o, 1^o and 2^o, respectively. All the simulations for different time steps were performed using a medium-mesh or grid (79k Cells) at $\lambda=1$. Consistency was maintained in the parameters across all simulations with varying time-steps. Figure 14 illustrates the moment coefficient (C_m) captured for various time-steps, spanning from 0.5^o to 2^o. It can be observed that moment coefficient (C_m) curve is consistent for time-step size (TSS) of 0.5^o and 1^o. So, time step-size (TSS) equal to 1^o is selected for further simulations for appropriate CFD results with less computational time.

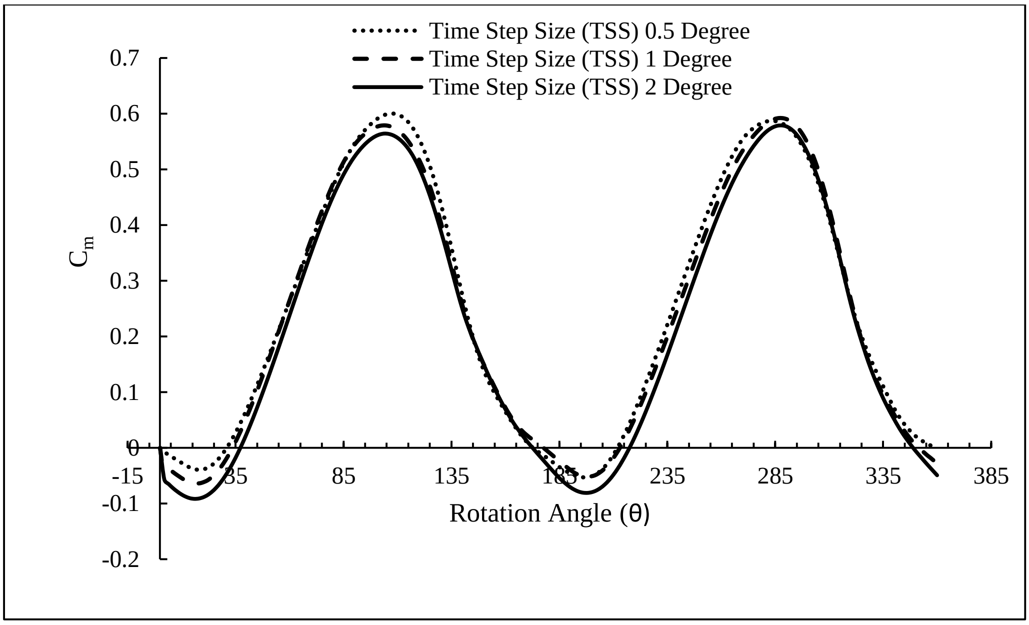

Figure 14: Time step independence test.

3.8 Validation:

The numerical model's validation was conducted through a comparison with experimental results from a comprehensive series of tests performed Robert E. Sheldahl at Sandia Laboratories on two and three-bucket Savonius wind turbines [60]. Hence, this research opted to utilize a two-bucket Savonius turbine, and the experimental findings form Sandia Laboratories were employed to assess the accuracy and reliability of numerical results. To validate the numerical results, the analysis was executed at a constant wind speed of 7 m/s. This wind speed corresponded to a nominal Reynolds number per unit length of $4.32x10^5$, ensuring the reliability and accuracy of the obtained numerical findings. Figure 15 depicts the variation of the moment coefficient (C_m) with the turbine's instantaneous angle of rotation at a tip speed ratio (TSR) of 1. In this research, ten rotation cycles were simulated for each CFD analysis. The average value of the last rotation cycle was employed as it was determined that the relative difference becomes negligible after five rotation cycles, indicating solution convergence.

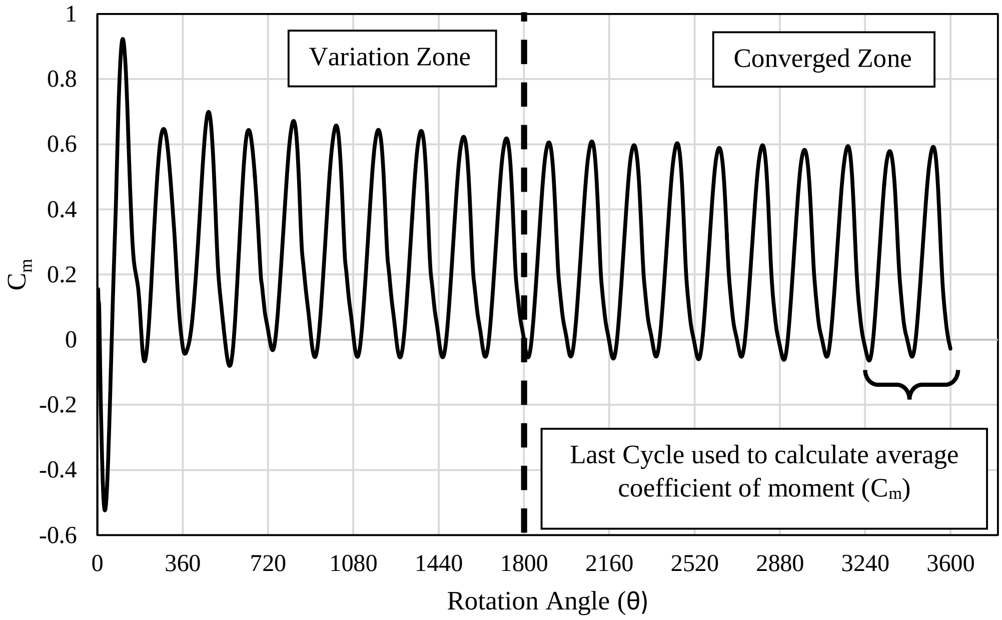

Figure 15: Variance of Coefficient of moment (C_m) at λ=1.

Figure 16 demonstrates the computed results of the moment coefficient (C_m) and Figure 17 presents the outcomes of the power coefficient (C_p) analysis for Savonius turbine, showcasing the variation of tip speed ratio (TSR) spanning from 0.4 to 1.2 with an increment of 0.2. The obtained results were compared with experimental findings reported by Sandia Laboratories, ensuring a comprehensive evaluation of the turbine's performance. It could be claimed that the numerical simulation results demonstrates a notable concurrence with the experimental results in terms of tip speed ratio (TSR), affirming a satisfactory agreement between the two approaches. The evident agreement between the current model and both experimental findings and other numerical studies underscores its reliability and suitability for predicting the performance of low-Reynolds number hydrokinetic turbines.

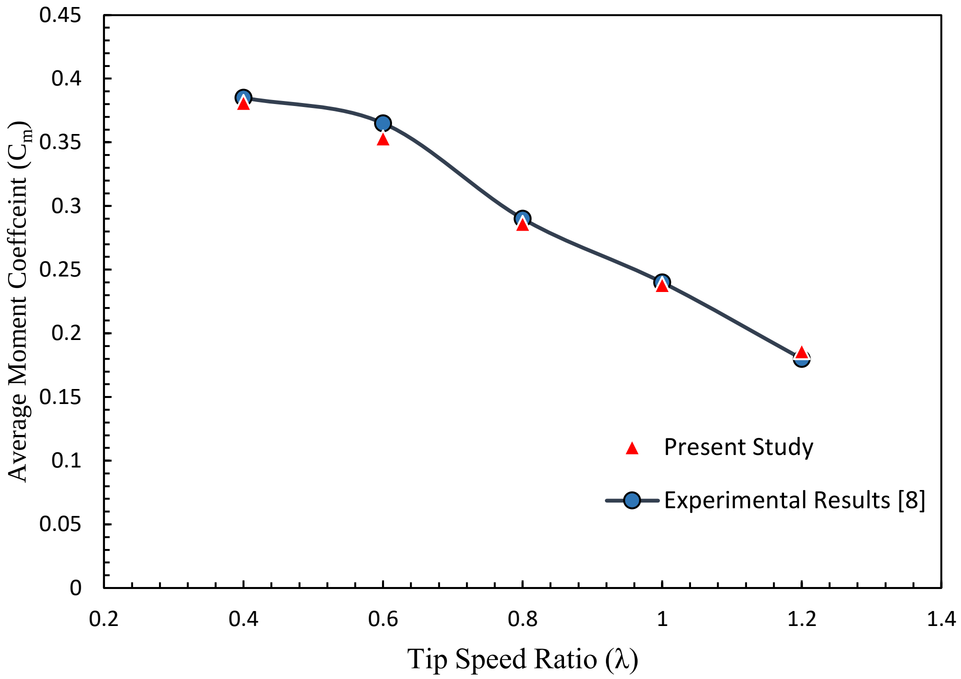

Figure 16: Evaluating Moment Coefficient (C_m) against experimental results.

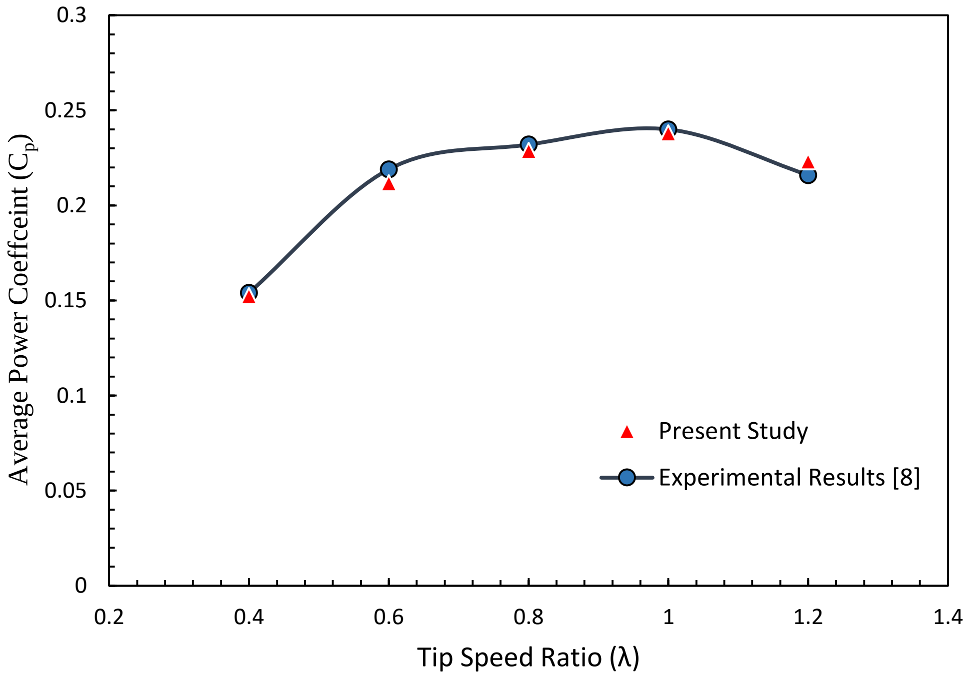

Figure 17: Evaluating Power Coefficient (C_p) against experimental results.

CHAPTER 4: RESULT AND DISCUSSION

This chapter will encompass the findings and in-depth discourse derived from CFD analysis of the Savonius hydrokinetic turbine with upstream bluff bodies. The obtained results and subsequent discussion will provide a detailed insight into the performance indicators and characteristics of turbine, facilitating a comprehensive understanding of dynamic behavior.

4.1 Savonius turbine with bluff bodies:

4.1.1 Performance Characteristics:

Moment and power coefficient are important parameters for investigating the operational performance of the Savonius turbine. To determine the turbine's optimum operational performance, studying the turbine's average power and average moment characteristics is an effective and widely adopted technique. To achieve this objective, the average moment and power coefficient numerically investigated with respect to the tip speed ratio (λ) for all cases considered in this research. The addition of bluff bodies upstream of the turbine's returning blade greatly influence the turbine's operational performance. The cylinder, half-cylinder, and diamond shape bluff bodies were utilized in this research. In the beginning, the cylinder has been selected for the optimization of the horizontal (R_x) and vertical (R_y) distances of bluff bodies from the center (0, 0) of the Savonius rotor. Furthermore, the diameter of the cylinder is also optimized for three cases to find the optimum diameter of the cylinder for the present research. The same diameter has been used as a reference for half-cylinder and diamond shape bluff bodies. To find the optimum conditions for the cylinder, which was subsequently employed for other bluff bodies, an investigation was conducted using three different y-direction distances of the cylinder positioned upstream of the turbine as $R_y/D=0.23$, $R_y/D=0.37$ and $R_y/D=0.51$ were studied with conventional design for tip speed ratio 0.4-1.2 with fixed x-direction distance at $R_x/D=1$ and cylinder diameter (d_c/D) =0.5.

Based on the outcomes illustrated in Figure 18, the average moment coefficient (C_m) boosted by almost 17.3% and 14.6% at λ=0.4 after installing the cylinder at $R_y=0.37$ and $R_y=0.51$ in relation to conventional Savonius Hydrokinetic turbine without any augmentation device. The gain in turbine's average moment and power coefficient found at all tip speed ratios for distance $R_y/D=0.37$ and $R_y/D=0.51$. At distance $R_y/D=0.23$ turbine's average moment and power coefficient decreased and this reduction can be attributed to the installation of the cylinder at this particular distance, which effectively covers the turbine's advancing blade. Consequently, this leads to a reduction in positive pressure on the concave side of advancing blade, as well as a decrease in pressure on the convex side of returning blade. This passive control mechanism contributes to the observed decrease in both average moment and power coefficient. Maximum power coefficient (C_p) equal to 0.254 achieved at λ=1 which is a 5.8% increase compared to conventional design as shown in Figure 19.

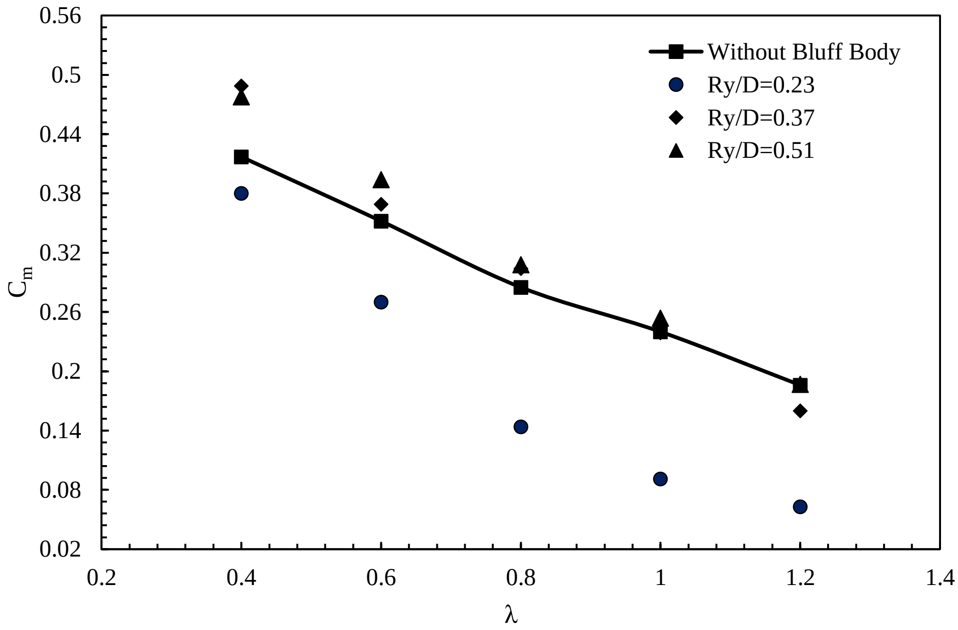

Figure 18: Evaluating average moment coefficient (C_m) for the cylinder.

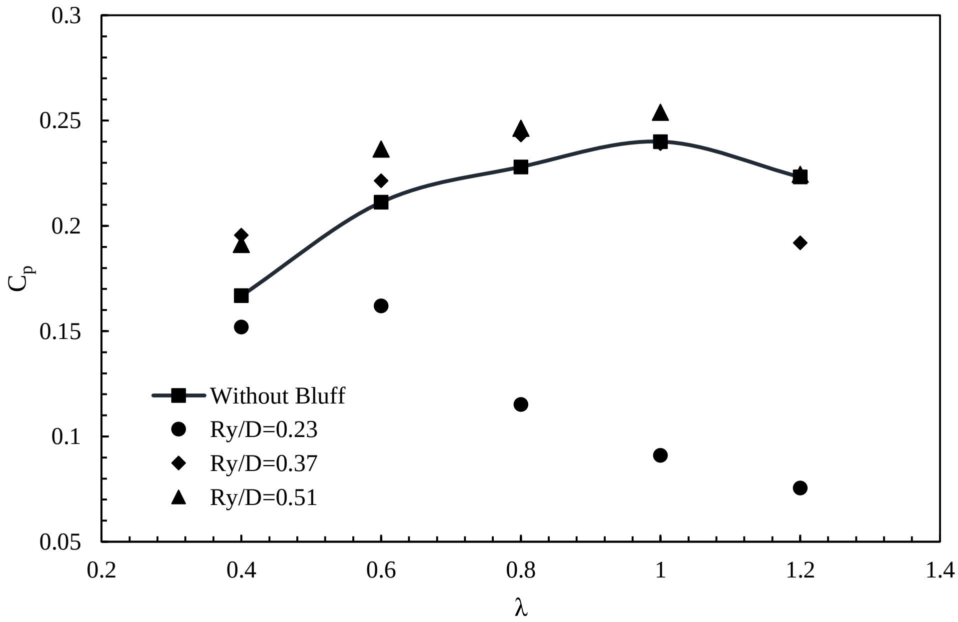

Figure 19: Evaluating average power coefficient (C_p) for the cylinder.

After optimizing vertical position (y-direction) of the cylinder, the impact of the cylinder's horizontal position (x-direction) on the operational performance of the Savonius hydrokinetic turbine was investigated. Three different x-direction distances $R_x/D=0.75$, $R_x/D=1$, and $R_x/D=1.25$ were compared to the case without cylinder, while keeping the y-direction distance unchanged at $R_y/D=0.51$ and cylinder's diameter (d_c/D) =0.5. The results of all the cases, including the average moment coefficient (C_m) and power coefficient (C_p) across all tip speed ratio range of 0.4-1.2, are presented in Figures 20 and 21.

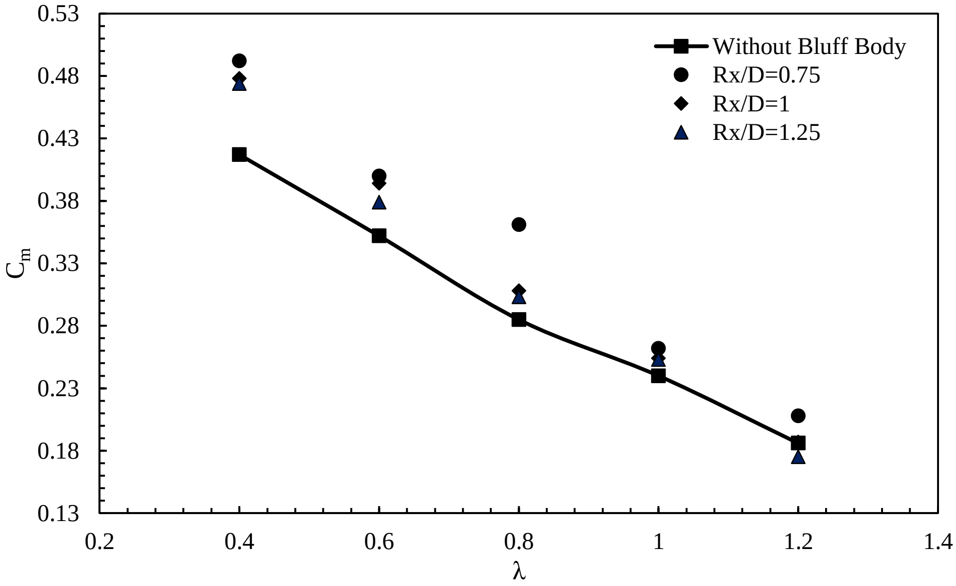

Figure 20: Evaluating average moment coefficient (C_m) for the cylinder.

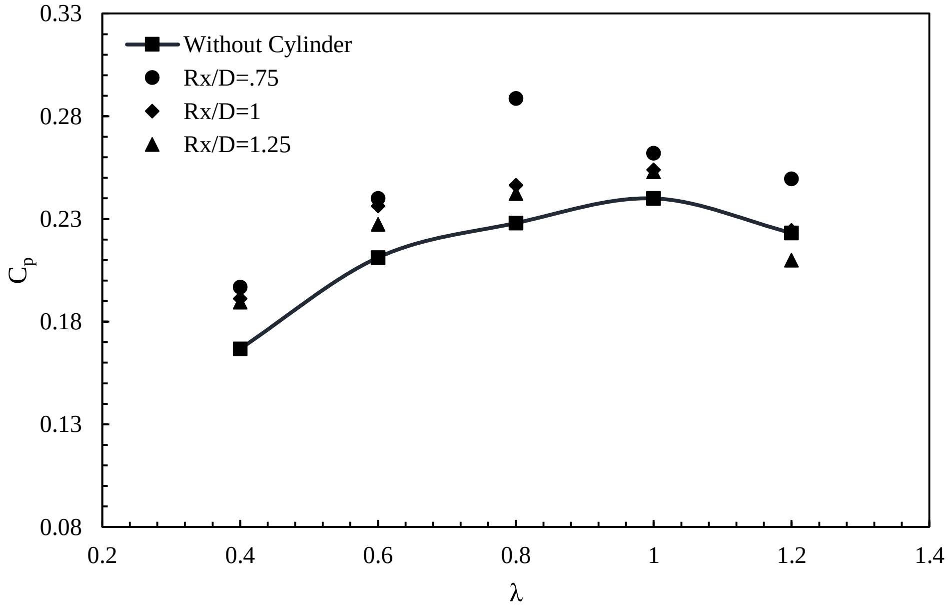

Figure 21: Evaluating average power coefficient (C_p) for the cylinder.

The turbine’s average moment and power coefficient exhibits a notable increase almost all tip speed ratios, with the maximum value attained at x-direction distance of R_x/D=0.75. The maximum average power coefficient (C_p) = 0.2888 obtained for λ=0.8 yielding 26.7% more compared to the conventional design. The average power coefficient (C_p) demonstrated a consistent increase as the tip speed ratio values were raised, reaching its peak at a certain point. Subsequently, it started to decline, aligning well with the findings from previous studies. As the horizontal distance of the cylinder was increased and positioned farther away from returning blade, the turbine’s performance experienced a decline. This reduction in performance can be attributed to the diminishing impact of the cylinder in mitigating the negative moment on turbine’s returning blade.

After optimizing the horizontal (R_x) and vertical (R_y) distance for each of the three cases, the turbine’s operational performance was examined by varying the diameter of the cylinders. The x-direction distance was unchanged at R_x/D=0.75 and y-direction distance constant at R_y/D=0.51D. Three different cylinder diameters (d_c/D=0.3, d_c/D=0.4, and d_c/D=0.5) were studied and compared to the conventional design without a cylinder, serving as a defector bluff body. As shown in Figure 22, the average moment coefficient (C_m) was declined by raising the tip speed ratio (λ), and the maximum average moment coefficient (C_m) =0.492 obtained λ=0.4 for cylinder diameter (d_c/D) =0.5. Maximum average power coefficient (C_p) = 0.2888 achieved at λ =0.8 for cylinder diameter (d_c/D) =0.5 which is 26.7% higher compared to conventional design.

The diameter of the cylinder plays a crucial role in influencing the performance of the Savonius turbine. The installation of the cylinder resulted in an increase in turbine’s average moment coefficient across the entire range of tip speed ratios, from 0.4 to 1.2. For cylinder diameter of d_c/D=0.3 and d_c/D=0.4, the maximum average moment coefficient increased by 14.4 % and 20.4% respectively, at λ=0.4 and λ=0.8, compared to the cases without a cylinder. It is obvious that when the diameter of the cylinder is increased enough, it will restrict the upstream flow so the selection of the diameter of the cylinder should be large enough that it will not restrict the upstream flow to the driving blade. In this research, we obtained the optimum diameter of cylinder d_c/D =0.5 compared to d_c/D=0.3 and d_c/D=0.4 as maximum average power coefficient (C_p) obtained 0.2888 which is 26.67% enhanced at λ=0.8 for cylinder diameter (d_c/D) =0.5 as shown in Figure 23. After investigating these results, x-direction distance (R_x) =0.75 and y-direction distance (R_y) =0.51, and cylinder diameter (d_c/D) =0.5 was selected as reference for further investigation on performance after installing half circle and diamond shape bluff body as an augmentation device.

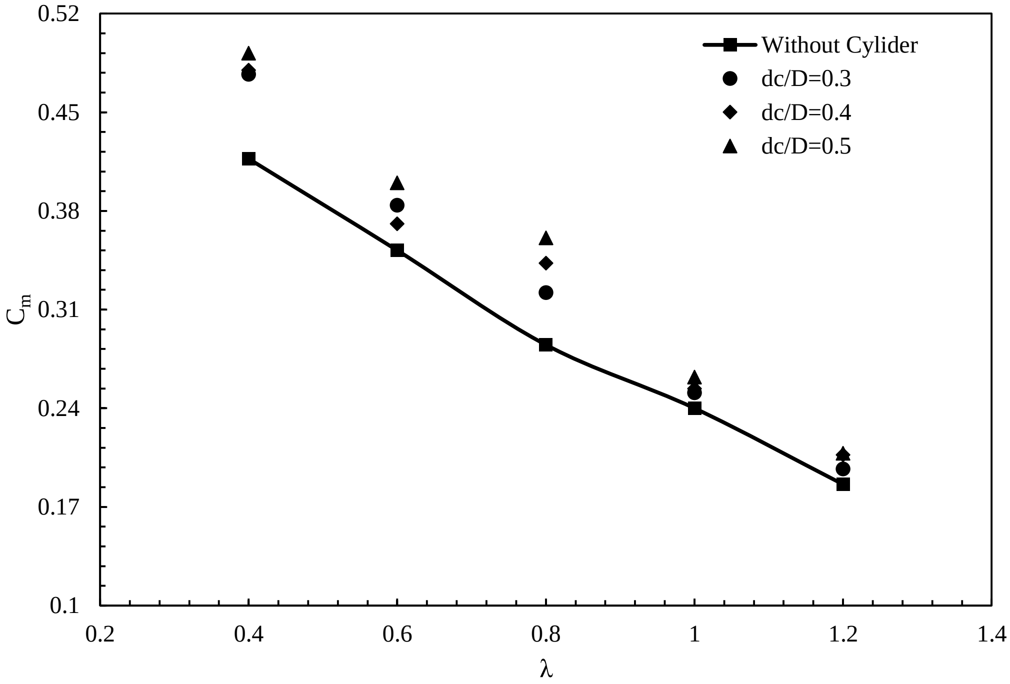

Figure 22: Evaluating average moment coefficient (C_m) for the cylinder.

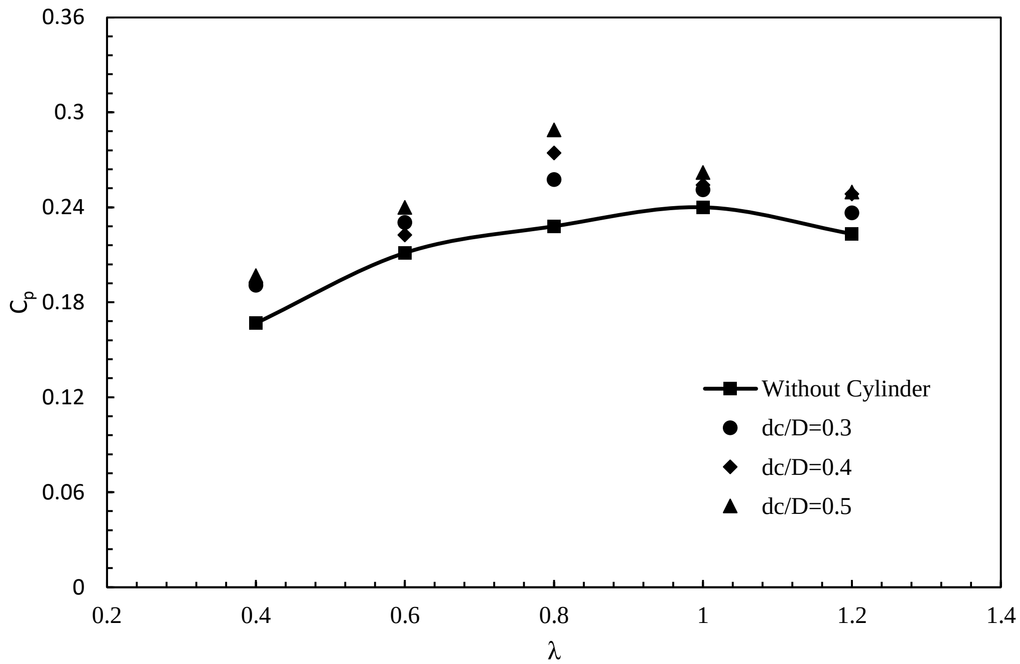

Figure 23: Evaluating average power coefficient (C_p) for the cylinder.

After investigating turbine's average moment and average power coefficient incorporated with the cylinder and deciding the optimum horizontal and vertical position of cylinder, the half-cylinder (D-shape bluff body) and diamond-shaped bluff bodies were positioned upstream of the turbine's returning blade to examine the impact on the performance of the Savonius turbine. Half-cylinder (D-shape body) was installed at optimum horizontal distance (R_x/D) =0.75 vertical distance (R_y/D) =0.51 and the diameter (d_c/D) =0.5. Similarly, a diamond-shaped bluff body was made from that optimized cylinder, and the consequence of diamond-shaped bluff body on turbine's performance was also investigated.

As the results depicted that installing different types of bluff bodies upstream to turbine's returning blade alters its average moment and power coefficient in contract to the base case without any augmentation technique. Figure 24, and 25 depicts the evaluation of average moment and average power coefficient for all the cases for cylinder, half-cylinder (D-shape body), and diamond-shaped bluff bodies corresponding to tip speed ratio spanning from 0.4 to 1.2. The result depicted that the average moment coefficient (C_m) was reduced by increasing the tip speed ratio and it showed good agreement with previous studies and maximum average moment coefficient (C_m) = 0.493 obtained at λ=0.4 for D-shape bluff body as a deflector. Maximum gain in average power coefficient (C_p) achieved by diamond shape bluff body at λ=1.2 which is 30.11% higher compared to the base case without any augmentation technique.

At tip speed ratio (λ) equal to 1.2 maximum gain of 11.83% and 19.89% in average power coefficient obtained for cylinder and half-cylinder (D-shape bluff body) compared to conventional design. Considering the half-cylinder (D-shape body) and cylinder as a deflector, a maximum average power coefficient (C_p) equal to 0.27 and 0.29 was achieved at λ=1.2 and λ=0.8. The percentage increase compare to different augmentation techniques is lower as reported in previous studies but those techniques are applied using complex structures like meander duct nozzles, long curtains, specific blade profiles, etc. Instead, deploying bluff bodies like a cylinder, half-cylinder (D-shape), and diamond shape bluff body as presented in this research not only boosts the performance of the Savonius hydrokinetic turbine (SHKT) but also provides a simple design without imposing any complexity on turbine's design.

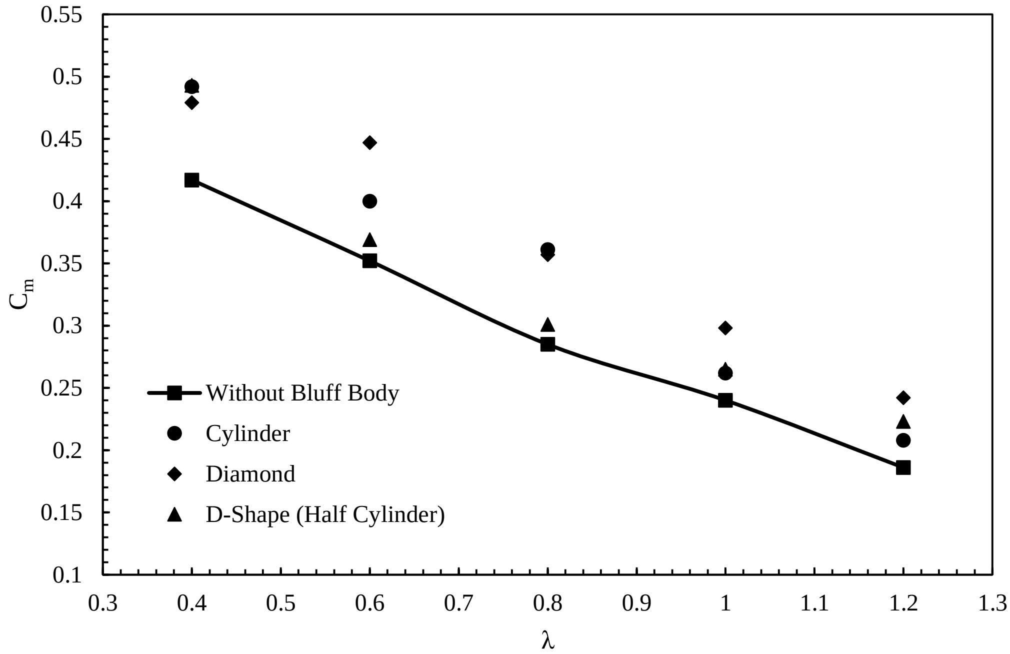

Figure 24: Evaluating average moment coefficient (C_m) for bluff bodies.

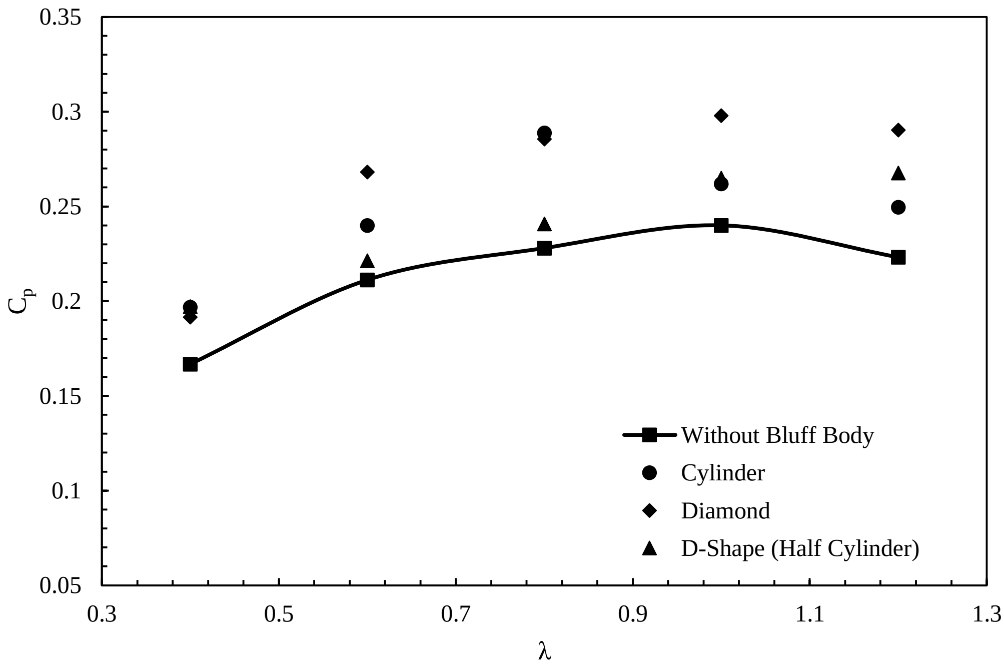

Figure 25: Evaluating average power coefficient (Cm) for bluff bodies.

Prior to delving into the analysis of flow structure and the presentation of pressure and velocity contours, it is crucial to determine the angle at which the maximum average moment coefficient was observed. In Figure 23 coefficient of the moment (C_m) corresponding to the rotation angle at λ=1.2 was compared using different bluff bodies with base case to investigate the effect on turbine's operational performance. Upon careful examination and comparison of the results, it was established that the installation of the cylinder, diamond, and D-shape bluff bodies upstream of the returning blade led to a considerable increase in the positive moment coefficient (C_m) when compared to the base case scenario. Notably, substantial enhancements in the moment coefficient (C_m) were observed within the angular ranges of $90^o < \theta < 210^o$ and $270^o < \theta < 360^o$. Furthermore, it was noted that higher peaks of the instantaneous moment coefficient were observed for all the bodies in the angular ranges of $90^o < \theta < 120^o$ and $270^o < \theta < 300^o$.

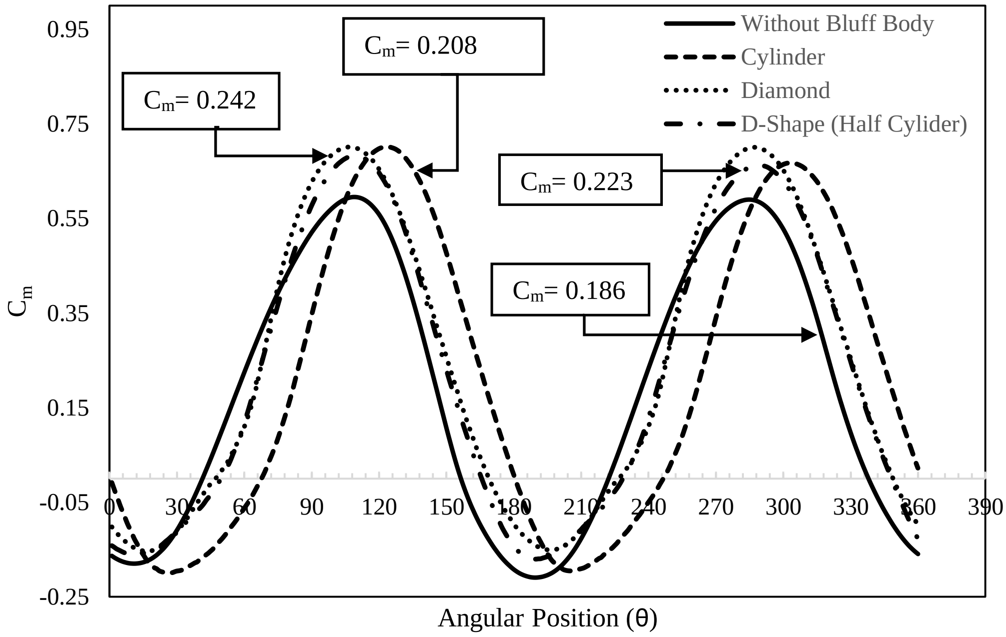

Figure 26: Evaluation of Coefficient of Moment (C_m) at λ=1.2.

4.1.2 Flow Structure Analysis:

In order to comprehensively comprehend the impact of various bluff bodies on the operational performance of the Savonius Hydrokinetic turbine, detailed contours of pressure, velocity, and turbulence intensity are presented at an angular position of 120^o. These contours serve as informative visual representations, unveiling critical insights into the intricate flow dynamics and elucidating the intricate interplay between the bluff bodies and the turbine. The installation of bluff bodies resulted in an increased pressure on the inwardly curved (concave) side of the advancing blade, surpassing the pressure observed in the absence of bluff bodies. This finding highlights the influence of bluff bodies on the pressure distribution and demonstrates their ability to modify the flow characteristics around the turbine. Consequently, the incorporation of bluff bodies yielded a higher drag coefficient, thereby enhancing the overall performance of the turbine.

Figure 27 illustrates the pressure distribution around the Savonius rotor at an angular position of 120°, showcasing a comparison between the conventional turbine and the turbine equipped with upstream bluff bodies. The installation of a deflector redirects a significant portion of the incoming flow towards the advancing blade, resulting in an amplification of positive pressure. This quantitative enhancement is visually represented in Figures 28, 29, and 30, providing a comprehensive understanding of the effect of the deflector on pressure distribution. After the installation of bluff bodies, a notable reduction in pressure is observed on the convex side of the returning blade. The desirable effect of bluff bodies on the turbine's performance can be attributed to their impact on the moment coefficient (C_m).

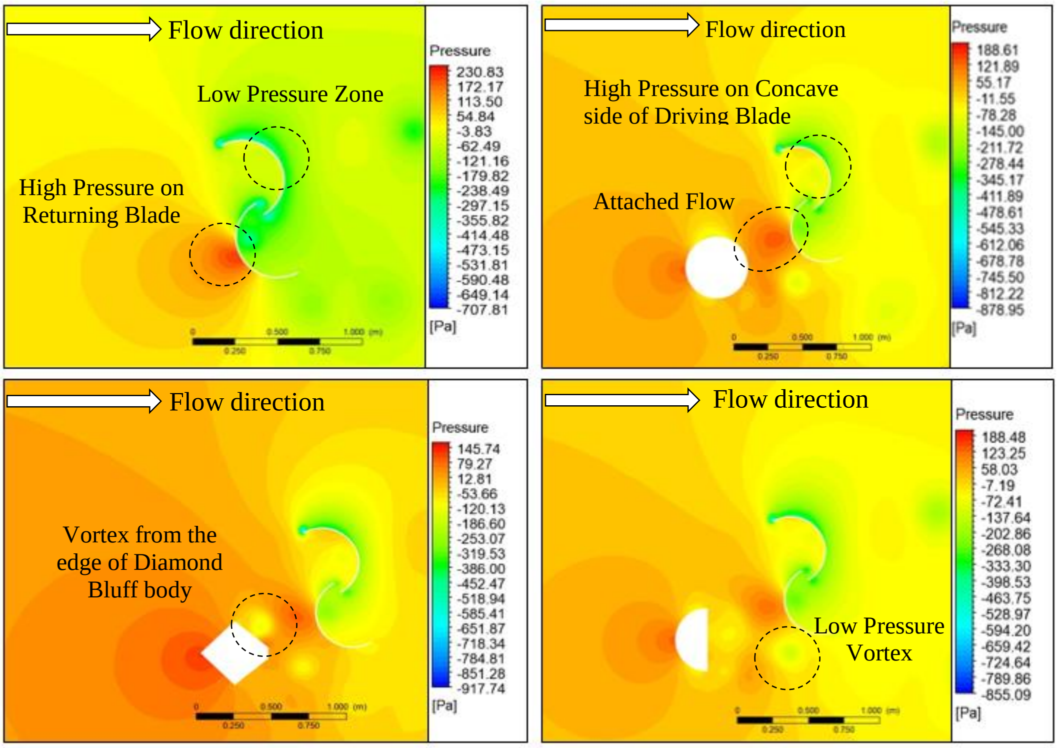

Figure 27: Pressure distribution around rotor with and without bluff bodies.

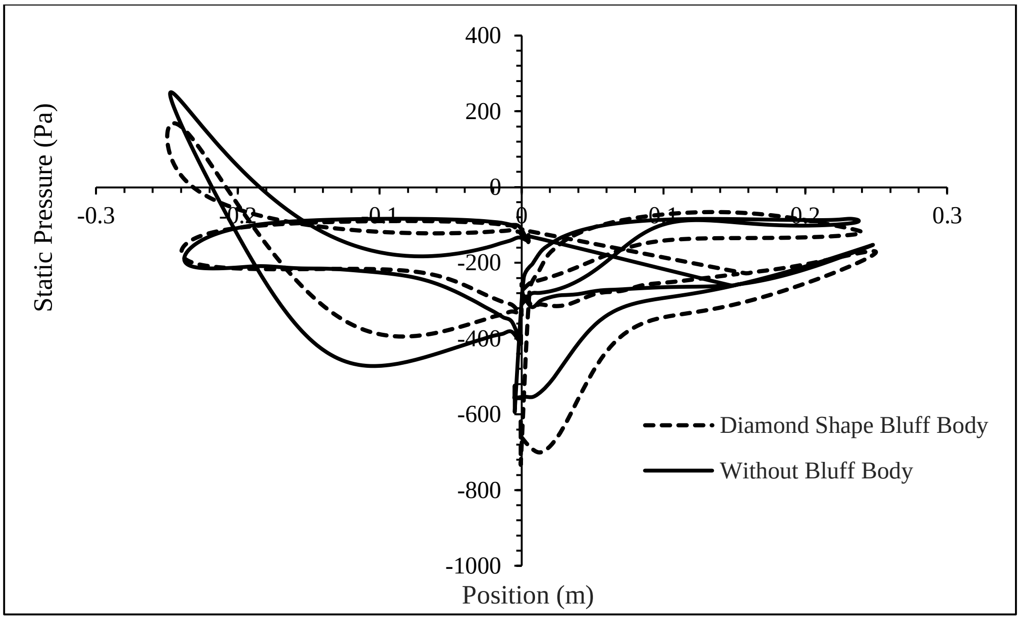

Figure 28: Evaluating pressure distribution with and without bluff bodies at λ=1.2.

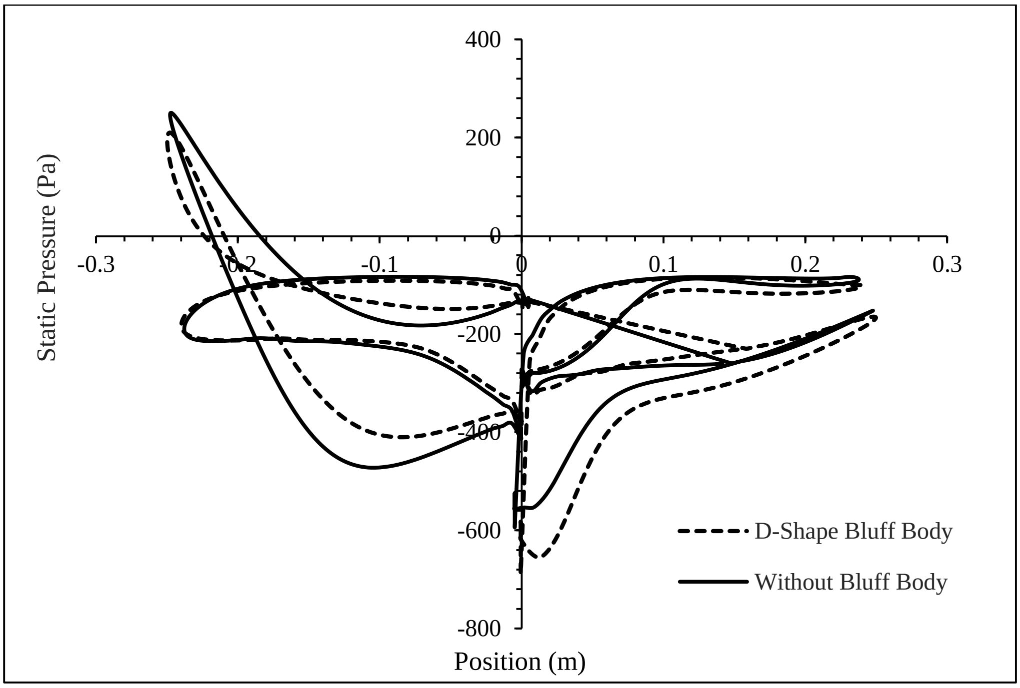

Figure 29: Evaluating pressure distribution with and without bluff bodies at λ =1.2.

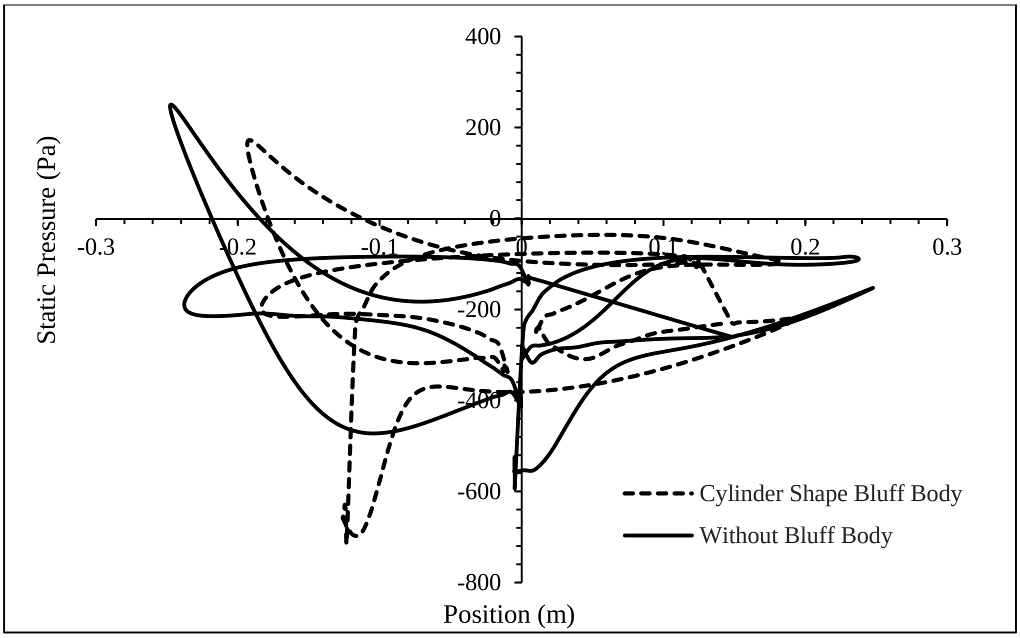

Figure 30: Evaluating pressure distribution with and without bluff bodies at λ =1.2.

Figure 31 showcases the impact of bluff bodies on the distribution of turbulence intensity around the Savonius Hydrokinetic turbine, specifically at a tip speed ratio of 1.2. The figure provides a comprehensive visual representation, highlighting the advantage of employing bluff bodies in minimizing the direct contact of the incoming flow with the turbine blades. This reduction in direct contact leads to a more controlled and organized flow, resulting in decreased turbulence intensity. Such advantageous effects of bluff bodies contribute to improved performance and operational stability of the turbine. Without the presence of bluff bodies upstream of the returning blade, the incoming flow makes direct contact with the blade surface. This contact leads to increased drag force due to the pressure exerted on the returning blade.

The increased drag force on the returning blade reduces the disparity in drag force between the rotor blades, ultimately leading to a decrease in power and moment coefficients. This effect arises due to the altered pressure distribution and flow dynamics resulting from the absence of bluff bodies. By implementing bluff bodies, the direct contact of the incoming flow with the returning blade is limited, resulting in an enhanced differential drag force between the rotor blades. This observation is further reinforced by the quantitative findings depicted in Figure 26, validating the effectiveness of bluff bodies in improving the turbine's performance.

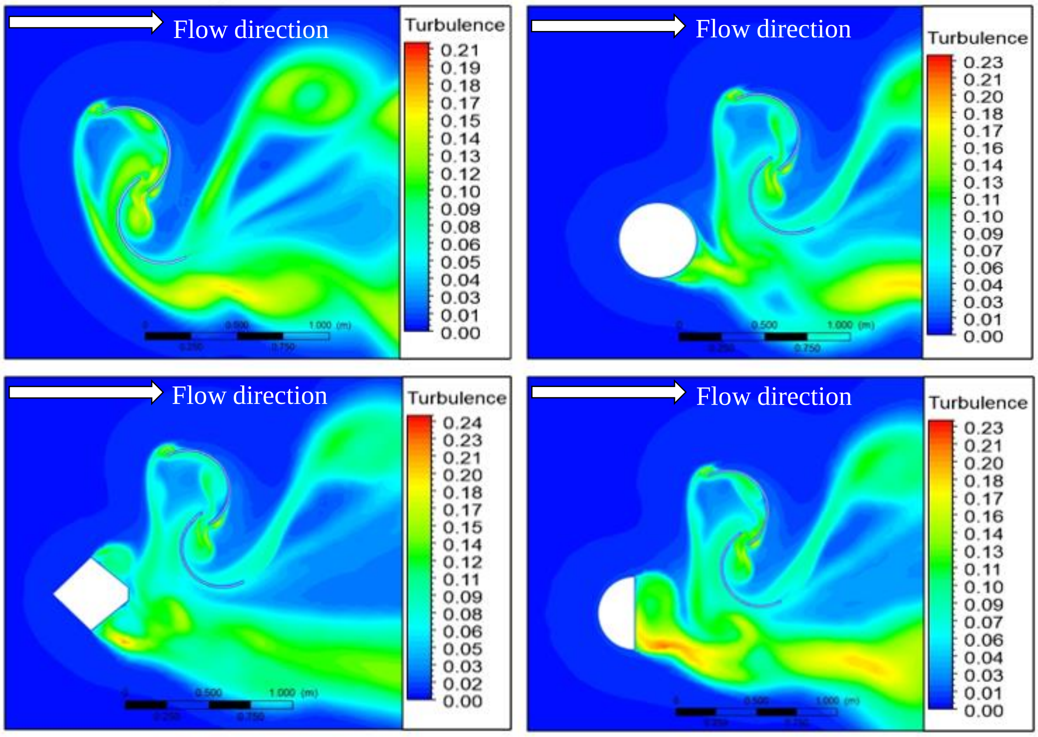

Figure 31: Turbulence Intensity around rotor with and with bluff bodies.

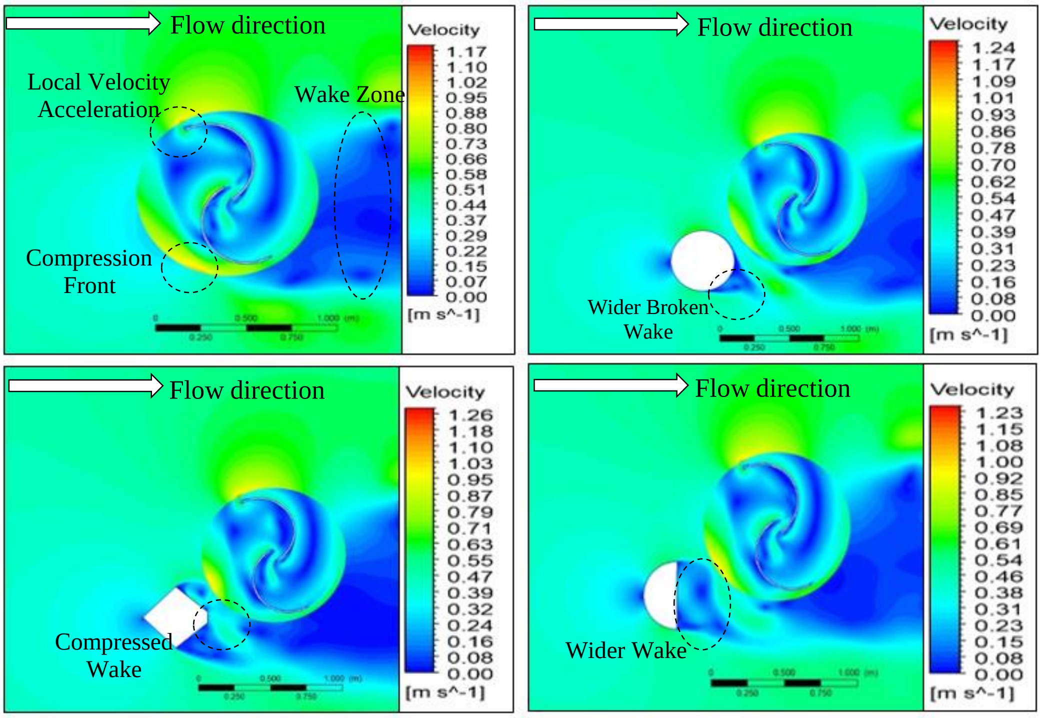

Figure 32: Velocity distribution around rotor with and without bluff bodies.

Figure 32 illustrates the impact of bluff bodies on the velocity distribution around the Savonius rotor, specifically at a tip speed ratio (λ) of 1.2. The wake region is observed downstream of the turbine, accompanied by a high-velocity zone at the tip of the advancing blade. With the implementation of bluff bodies upstream of the returning blade, the incoming flow is diverted towards the advancing blade instead of directly contacting the convex side of the returning blade. This redirection of flow contributes to an enhancement in the power coefficient of the Savonius Hydrokinetic turbine, highlighting the effectiveness of bluff bodies in optimizing turbine performance.

4.2 Savonius Rotor with Bluff Bodies and Flat Plate Deflector:

By examining the impact of bluff bodies as deflectors positioned upstream of the returning blade in the Savonius Hydrokinetic turbine, further investigation was conducted by incorporating a deflector plate. This additional configuration allowed for studying the combined effect of both bluff bodies and the deflector plate. The findings, represented by the average moment coefficient (C_m) and average power coefficient (C_p) at various tip speed ratios (TSR), are presented in Figures 33 and 34. These results shed light on the performance enhancements achieved by integrating both bluff bodies and a deflector plate into the turbine design. The performance of the Savonius Hydrokinetic turbine (SHKT) was significantly enhanced by incorporating a deflector plate in addition to bluff bodies. The highest average moment coefficient (C_m) of 0.491 was attained when utilizing a diamond-shaped bluff body in conjunction with a deflector plate at a tip speed ratio (λ) of 0.8. Similarly, the maximum average power coefficient of 0.416 was obtained by employing a diamond-shaped bluff body as a deflector along with a flat deflector at λ=1. By incorporating a diamond-shaped bluff body as a deflector, a significant improvement of 30.11% was achieved at a tip speed ratio (TSR) of 1.2 compared to the conventional design. Furthermore, the addition of a deflector plate upstream of the driving blade further enhanced the performance, resulting in an additional gain of 29.57%. This demonstrates the combined effect of utilizing both the diamond-shaped bluff body and deflector plate in enhancing the overall efficiency of the Savonius Hydrokinetic turbine. As in cases without deflector plate maximum gain in average power coefficient (C_p) obtained at λ=1.2 so, contours of pressure and velocity have been taken for these cases and compared with conventional design without any augmentation technique. The contours of pressure, velocity and turbulence distribution around turbine are presented in Figures 35, 36 and 37.

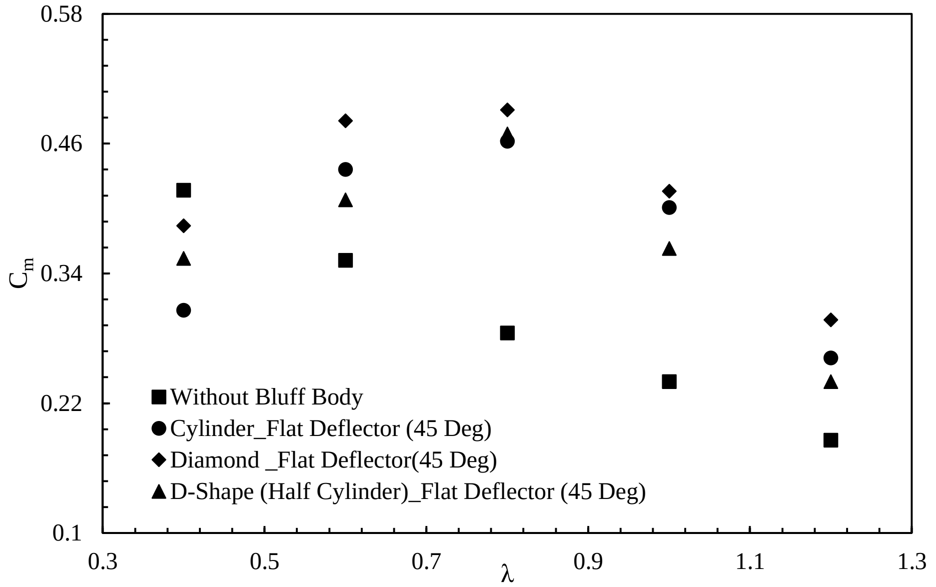

Figure 33: Evaluating average moment coefficient (C_m) for bluff bodies with deflector.

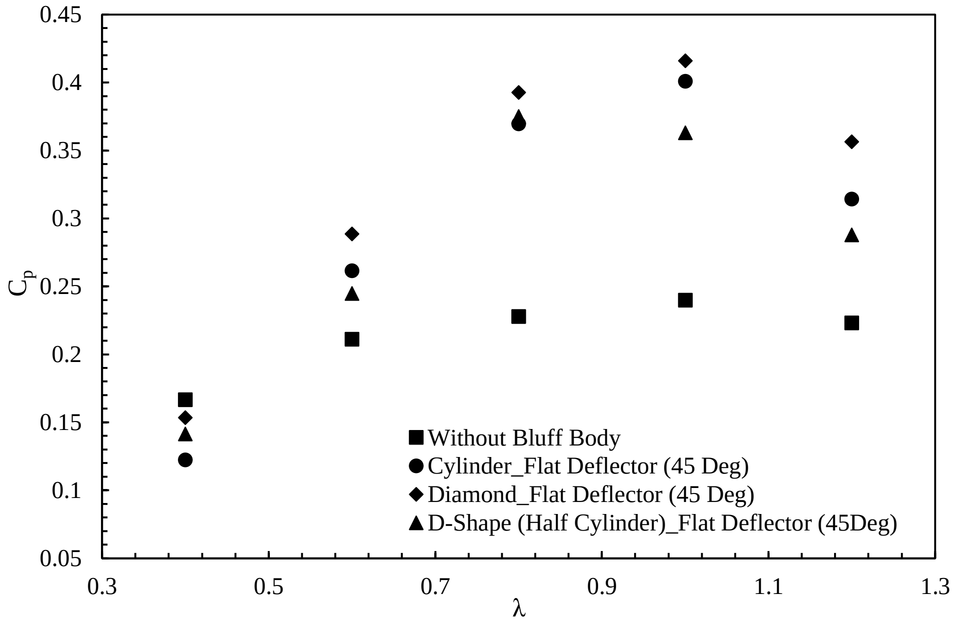

Figure 34: Evaluating average power coefficient (C_p) for bluff bodies with deflector.

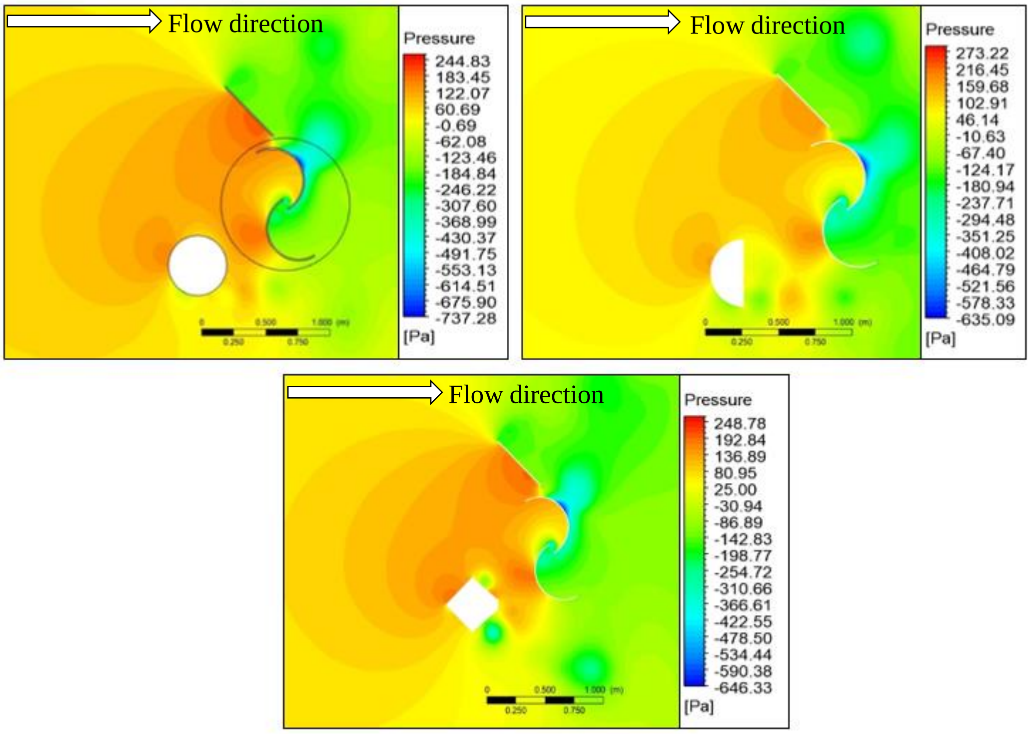

Figure 35: Pressure distribution with bluff bodies and flat deflector (45°).

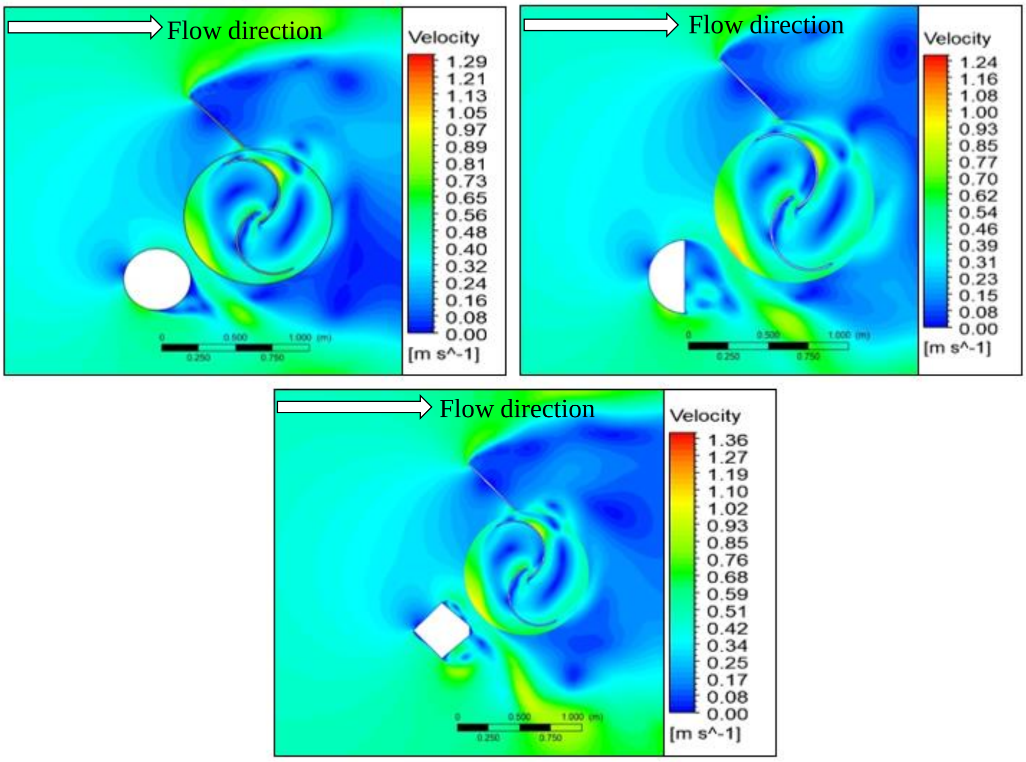

Figure 36: Velocity distribution with bluff bodies and flat deflector (45°).

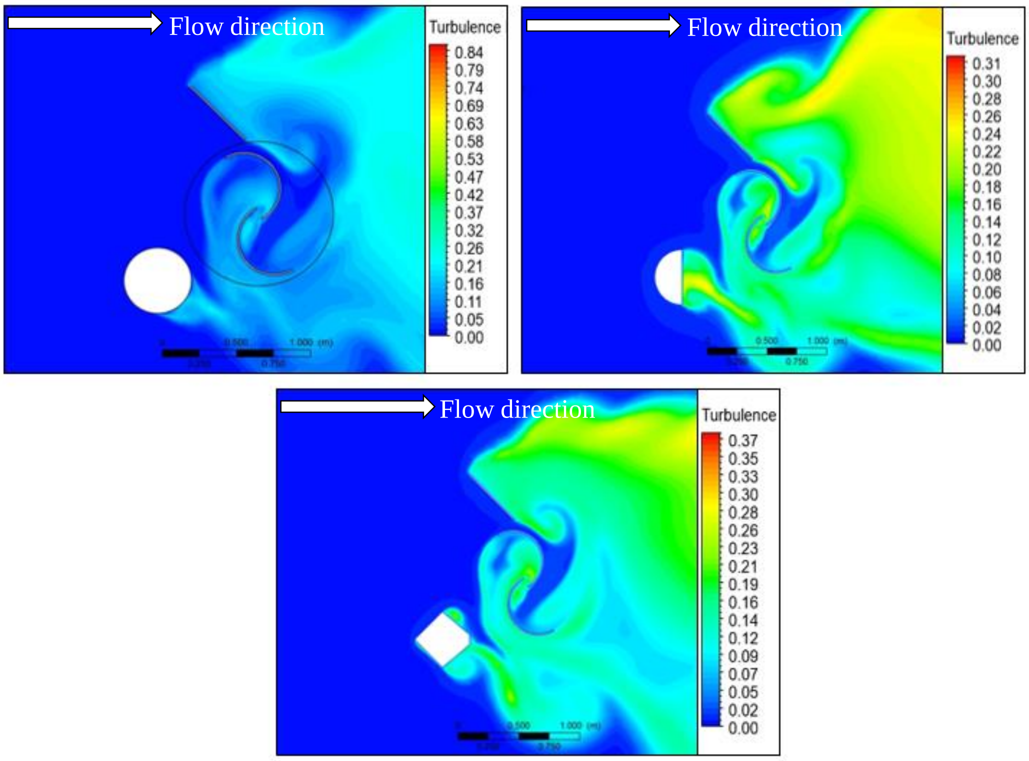

Figure 37: Turbulence Intensity with bluff bodies and flat deflector (45°).

CHAPTER 5: CONCLUSION

5.1 Conclusion:

The present study examines the effects of multiple strategies of augmentation, including the implementation of bluff bodies and deflector plate, on the efficiency indicators of the Savonius Hydrokinetic turbine (SHKT). Through extensive numerical analysis, notable improvements in the turbine's moment coefficient (C_m) and power coefficient (C_p) are observed in comparison to the baseline configuration.

One notable augmentation technique involves the incorporation of bluff bodies, specifically a cylinder positioned upstream. The findings demonstrate a considerable increase in the average moment coefficient (C_m), indicating improved moment generation. The average moment coefficient (C_m) experiences an impressive percentage increase of approximately 17.3% and 14.6% at λ=0.4, when the cylinder is placed at R_y=0.37 and R_y=0.51, respectively corresponding to R_x=1D and d_c=0.5D=. Further optimization of the augmentation technique involves adjusting the horizontal position (R_x) and diameter (d_c/D) of the cylinder. The results demonstrate that fine-tuning these parameters leads to additional performance gains. For instance, at λ=0.8 and with a cylinder diameter (d_c/D) of 0.5 at R_x=0.75 and R_y=0.51, the average power coefficient (C_p) accomplishes a remarkable value of 0.2888, representing a significant percentage increase of 26.7% compared to the baseline design. Moreover, the integration of bluff bodies in alternative shapes, such as half-cylinders and diamond shapes, also contributes to enhanced turbine performance. The diamond shape bluff body, in particular, exhibits substantial improvements over the baseline configuration, achieving a maximum value of average power coefficient (C_p) comparatively and yielding 30.11% at λ=1.2. Furthermore, when combined with a deflector plate, the diamond shape bluff body demonstrates an additional performance boost of 29.57%, and showed maximum gain in average power coefficient (C_p) of 0.416 at λ=1.

In summary, the implementation of augmentation techniques, including bluff bodies and deflector plates, significantly upgrades the operational effectiveness of the Savonius Hydrokinetic turbine. These findings present promising prospects for improving the efficiency and power generation capabilities of hydrokinetic turbines, employing a straightforward and effective design approach. The research outcomes contribute to the advancement of more efficient and sustainable hydrokinetic turbine systems, enabling the harnessing of renewable energy from water currents.

5.2 Future Work:

In accordance with the outcomes of this research, there are a plethora of promising avenues for future practical research on the Savonius Hydrokinetic turbine. Based on this research following future areas can be targeted.

- Optimization of bluff body shapes and positions to enhance turbine performance.
- Investigation of combined augmentation techniques, such as using both bluff bodies and deflector plates, for Synergistic effects.
- Field experiments and real-world testing to validate the findings obtained from numerical simulations.
- Assessment of turbine behavior in different environmental conditions, including varying water flow velocities and turbulence levels.
- Long-term monitoring and performance assessment of turbines in real-world settings to evaluate durability, efficiency, and maintenance requirements.
- Exploration of advanced materials, such as composites, to reduce turbine weight and increase lifespan.
- Incorporation of advanced manufacturing methods, like additive manufacturing, for complex blade geometries and customized designs.
- Economic feasibility studies and techno-economic analysis to assess the cost-effectiveness and commercial viability of turbine installations.
- Evaluation of the levelized cost of energy (LCOE) to determine the competitiveness of Savonius Hydrokinetic turbines in the renewable energy market.
- Market assessments to identify potential applications and opportunities for widespread utilization of hydrokinetic energy systems.

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