Design, modeling, and experimental investigations of the piezoelectric energy harvesting of vortex-induced vibrations by bionic structures

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(2024)

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in

Mechanical Engineering

Supervisor: Dr. Prof. Emad Ud Din

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Islamabad, Pakistan

(2024

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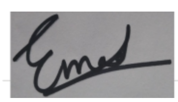
Signature (HOD): 

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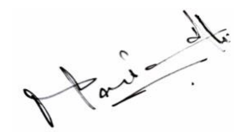

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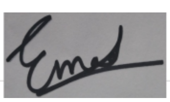

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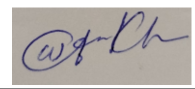
Student Name: Wajid Khan Signature: 

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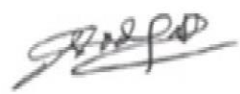
b) External Examiner 2: Name: Sadaqat Ali Signature: 

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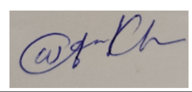

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DEDICATION

I dedicate my research work to my parents for their backup support, my colleagues who assisted me throughout, and my supervisor who helped me a lot in this project.

ACKNOWLEDGEMENTS

I am grateful to my Almighty, Allah, for guiding me every moment and for giving me the strength of research. into my head to help me with this effort. I am especially thankful to my parents and siblings for their tremendous backup and courage they given me. My supervisor Professor Dr Emad Uddin has supported me a lot in technical aspects of the research and hence I am very thankful for his contributions. He has always been great in his supervisory obligations. Moreover, I want to extend my gratitude to Mr. Mahad Shah, my colleague, for all his guidance and collaboration. He helped me a lot during my experimentations and the post processing of the data. He guided me in every phase of the research. I also want to thank the several mentors especially my GEC members for their valuable opinions and suggestions regarding this work and the institute (NUST) for its financial and academic assistance, which has helped me overcome the obstacles I have encountered in my studies. I am particularly grateful for the online help and assistance of Professor Dr Abdessattar Abdelkefi and Dr Usman Latif. Their passion and collective experience have been crucial to our success. I am also very thankful to the whole NUST community concerning my research in either case. The honor of this study is hence not just meant to be for a single person. It is the result of joint support, collaboration, and hard work that we did as a unit.

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ABSTRACT

The study is aiming at the effectiveness of the energy harvesting performance in the wake of various modified bluff bodies through piezoelectric material. These wake dynamics can be correlated to the behavior of high-rise buildings, automobiles, in air and submerged bodies in the water. The applications in the energy requirements include the powering of acoustic sensor, pressure measurement, ultrasonics, and many other industrial electromechanical systems that autonomously operated through sensors and actuators. Hence the need for heavy batteries powering these sensor systems and in turn ensuring a clean environment. Nine modified bluff bodies with 3, 4, and 5 columns of hemispherical protrusions with 9, 11, and 13mm diameters are arranged over the surface of the cylinders and have been investigated for the energy harvesting in their wakes with a piezoelectric membrane. All the bodies are studied at two flow speeds of 0.15m/s and 0.30m/s and compared them the results of the simple circular cylinder outcomes. The findings showed that the 4 columns arrangements have shown a greater output power efficiency with a 41% increase in the power gain following by the 5 column bodies with a 29% increase while the 3 column bodies have shown a power output lagging by about 19%, compared to the simple cylinder output. The power output is greatly affected by the size and orientation of the protrusions, the flow speeds, and the streamwise gaps (Gs). Hemispheres with increasing diameter shown an increasing trend in the power generation. The optimum streamwise gaps range discovered in this study is $2D \leq Gs \leq 3D$. The experimentations have been validated in parallel through the results of the dynamics (frequency and amplitude of oscillations) of the piezoelectric membrane captured by a camera during the experimentations. Particle Image Velocimetry (PIV) technique has been used and validated the experimental findings.

Keywords: *Votrex-induced vibrations, particle image velocimetry, wake dynamics, energy harvesting, fluid-structure interaction, frequency of oscillations.*

CHAPTER 1: INTRODUCTION

1.1 Background

A growing range of renewable performances, sometimes known as energy harvesting items, are being used to extract renewable energy from the environment. In recent years, these systems, which strive to be advantageous and environmentally compatible, have made substantial progress and now include wireless sensor networks. Various transduction methods, including piezoelectric, electromagnetic, and electrostatic, may be used to retrieve these. Pressure and vibration operating energy harvesters are highly sought-after and thoroughly studied kinds of energy harvesters because of their mobility, efficiency, substantial energy utilization, and potential to decrease labor expenses. Our goal is to substitute traditional energy sources with sustainable alternatives considering the increasing preoccupations with resource depletion and the adverse impacts on the environment and human well-being [1] depicted in Figure 1.1.

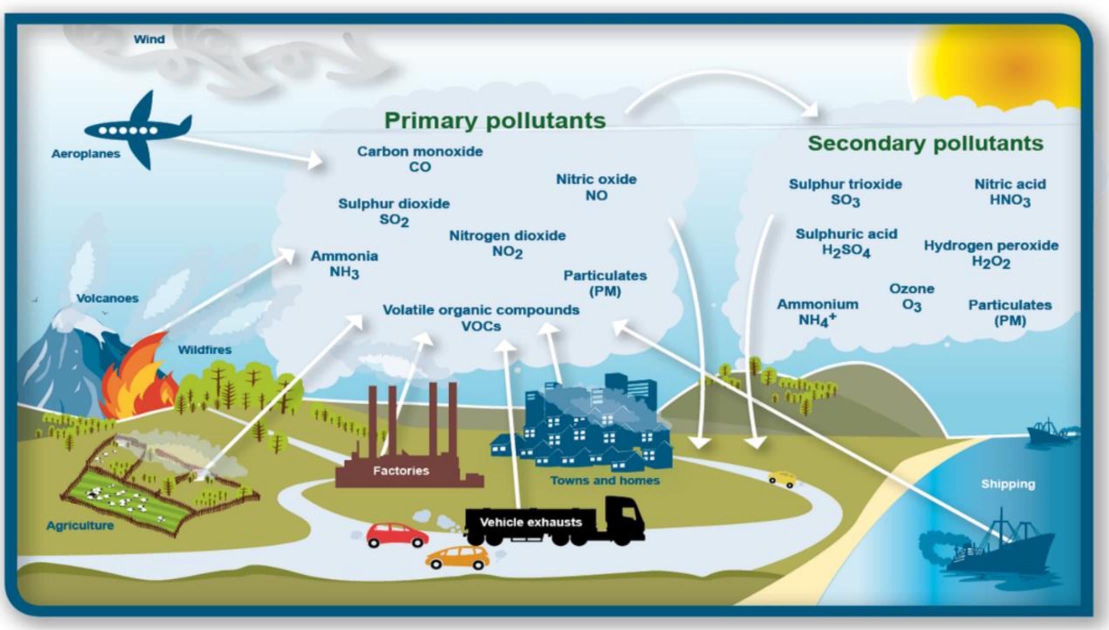

Figure 1.1:The major sources of pollution with the primary and secondary pollutants

Advancing renewable energy means pushing the boundaries to provide inventive solutions and discovering novel methods to develop more efficient gadgets. Although scientists, researchers, and engineers have made substantial progress in the advancement of micro-sensors and other low-power gadgets, more investigation and testing are necessary to ascertain viable solutions in this expansive domain. The energy demand both on a macro and micro scale is progressing day by day. The need for the new systems and techniques to develop efficient utilization of the available recourses is important. The current research and development industry is focusing on the new ways and models to acquire and fulfill the current needs of the energy demand. We acknowledge that more progress in energy harvesting is required for various applications in engineering and medical sciences, since the sensors and equipment involved rely on microwatts of power for operation. Integrating various harvesting systems simultaneously may enhance the development or extraction of more from the existing design devices, thus achieving better and more efficient outcomes. The global community is now progressing towards more practical, diverse, and self-sufficient energy sources and is projected to transition to renewable sources close to 67% by the year 2050 as displayed by [2] in Figure 1.2.

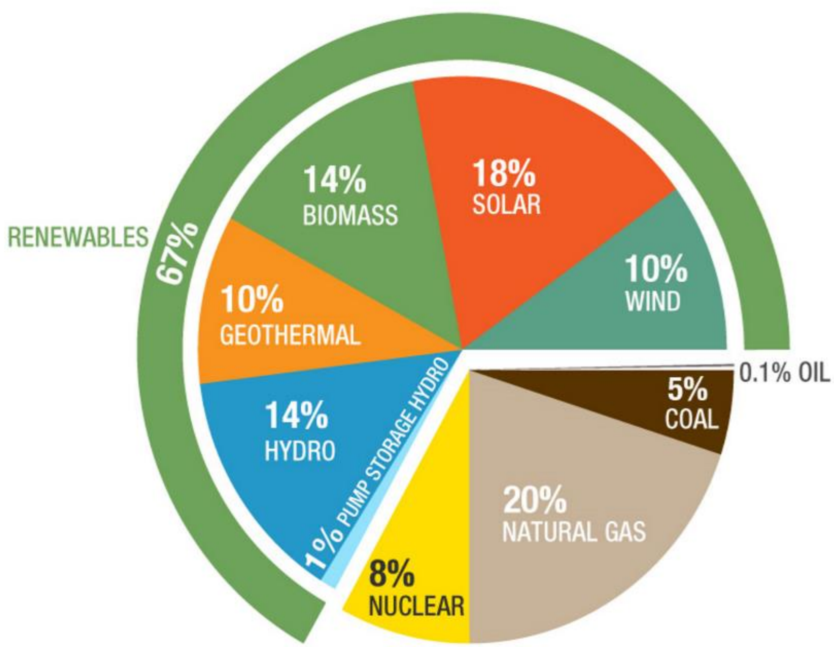

Figure 1.2:The expected shift of the energy sources by 2050.

1.2 Objectives

The present thesis focuses on the investigation of the energy collecting capabilities of the wake-induced vibrations of a piezoelectric flag inside the wake of bluff bodies including hemispherical protrusions. The primary goal of the research is to evaluate the energy production of the suggested structures and compare it to the output of a baseline circular cylinder based on their wake dynamics. The basic goal of this research is to devise an energy harvesting system that revoke increased efficiency, economic, and sustainability to different environmental circumstances. In distant or inaccessible areas where battery replacement is problematic, these devices are especially vital. Furthermore, the process of energy harvesting has the potential to enhance the advancement of autonomous systems, including wireless sensor networks, wearable electronics, and Internet of Things (IoT) hardware, by offering a consistent and uninterrupted power source. The ultimate objective is to drive the development of technologies that promote sustainability, minimize carbon footprints, and facilitate the widespread use of energy-efficient, self-powered devices in many sectors.

The key findings of the research, as compared to a basic cylinder, are as follows:

1. The amount of energy obtained either increases or decreases.
2. The effect of the velocity on the flag flapping frequency, amplitude and hence on the energy output.
3. The effect of the size and number of protrusions on the energy output.
4. The correlation among the energy output, the wake characteristics (frequency, amplitude) and the strength of the vorticities obtained through PIV technique.
5. The optimum streamwise range that contains most of the energy of the vortices in the wake of the bluff bodies.
6. The effect of the fluid velocity on the energy harvesting in a specified low velocity range to give an insight for the normal ocean current and wind flow scenarios.

1.3 Energy harvesting

Optimizing energy harvesting is a crucial aspect, particularly in the sustainable use of energy resources. Modern society is dependent on clean, green energy, yet some specialized applications like communications, signaling, and remote sensing demand a significant amount of energy at the micro level. Considerable challenges emerge in relation to energy providers, with the most prevalent being the cumbersome batteries. Therefore, it is imperative to replace batteries with sustainable alternatives such as energy harvesting using piezoelectric materials and other similar technologies.

Researchers prioritize the optimization of the piezoelectric performance of the material by using methods such as doping, surface modification, and boosting the crystalline phase of the polymer. To enhance the energy conversion efficiency, these developments seek to improve the effectiveness of PVDF harvesters in collecting low-frequency vibrations from the surrounding environment.

Furthermore, PVDF energy harvesting devices has the characteristics of being lightweight, flexible, and readily incorporated into a wide range of surfaces or materials, therefore broadening their possible uses. This study makes a valuable contribution to the advancement of sustainable, self-sustaining systems that decrease dependence on batteries and facilitate the expansion of autonomous, energy-efficient technology in several sectors like healthcare, infrastructure monitoring, and the Internet of Things (IoT).

The field of energy harvesting research encompasses not only the acquisition of ambient energy but also the integration of these technologies into typical applications. The objective of researchers is to develop durable and scalable solutions by enhancing materials such as PVDF and investigating new energy sources like kinetic motion, thermal gradients, and electromagnetic waves. These systems are specifically designed to provide energy to compact electronic devices and sensors in distant or difficult environmental conditions, therefore minimizing the need for battery changes and maintenance. Hence, energy harvesting plays a crucial role in the development of sustainable and self-sustaining technologies that enhance energy efficiency and environmental sustainability in many sectors.

1.3.1 Energy conversion and its types

The basic law of conservation of energy states that energy can neither be created nor be destroyed but it can only be changed from one form to another. The world is consuming energy in various ways and forms as depicted in Figure 1.3. The process of converting one kind of energy into another is known as energy conversion. This procedure is essential to several technologies and systems. Prominent forms of energy conversion include mechanical to electrical conversion (e.g., in generators), chemical to electrical conversion (e.g., in batteries), thermal to mechanical conversion (e.g., in steam engines), and solar to electrical conversion (e.g., in photovoltaic cells). The many forms of energy conversion are essential for certain applications, facilitating the effective utilisation of energy in power production, transportation, and common gadgets.

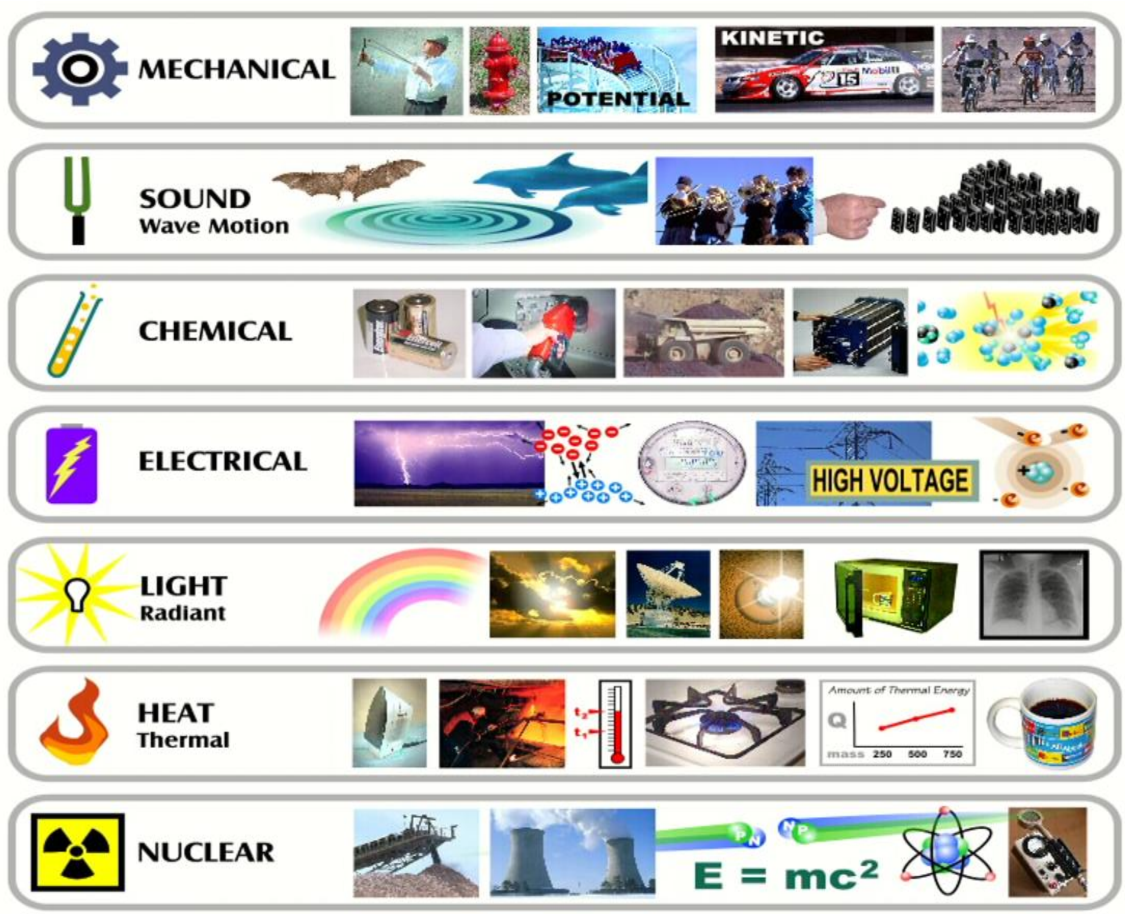

Figure 1.3:The different forms of energy consumption.

1.3.2 Kinetic energy

Kinetic energy refers to the energy present in a body because of its movement. This energy has the potential to be converted into a multitude of different types of energy. The fluid kinetic energy is transformed into rotational energy and then transferred into electrical energy using an electrical generator. Like the conversion of dynamic frictional energy into heat and sound energy in collisions, kinetic energy (KE) is also changed into light energy (photon energy) in some high-energy collisions such as those seen in particle accelerators. To produce power at the microscale, KE harvesting makes use of movements, pressure changes, or vibrations at the nano or microscale. To catch and transform this energy, devices like piezoelectric, electrostatic, and electromagnetic transducers are used. Microelectromechanical systems (MEMS), sensors, and other tiny electronics depend on these devices for power. The development of self-powered, autonomous microsystems is being aided by the increased efficiency of micro-KE harvesters due to the use of advanced materials and construction processes, which allow them to function in low-frequency and low-amplitude situations.

1.3.3 Potential energy

Potential energy refers to the stored energy that is physically capable of doing labor. This energy is linked to the position or condition of an item. Instances of potential energy being released and converted into various types of energy include a weight being lifted, a spring being stretched, or water being stored in a dam [4]. PE is used in novel ways in microelectromechanical systems (MEMS), where precise mechanical motions may transform it into other energy sources, such as electrical or kinetic energy. Next generation microdevices and nano systems need extremely effective energy storage and release mechanisms, which may be achieved by the manipulation of PE at the atomic level made possible by advances in nanotechnology. Potential energy, or PE, is essential to cutting-edge applications, especially when it comes to micro- and nanoscale energy conversion and storage. PE is used in microelectromechanical systems (MEMS) because of an object's configuration or location inside a force field, such as gravitational, elastic, or electrostatic.

These devices use precise mechanical motions to transform PE into either kinetic or electrical energy. The manipulation of PE at the atomic level made possible by advances in nanotechnology provides very effective energy storage and release mechanisms, which are essential for supplying energy to next generation microdevices, nano systems, and creative energy harvesting technologies.

1.3.4 Electrical energy

What keeps modern life going is electricity, which runs machines, lights up our homes, and charges our phones. It is made when electrons move through objects that carry electricity. It can be changed into many types of energy, like heat, light, and motion [3]. It is produced when electrons flow across conductors and is usually captured by means of chemical processes, electromagnetic induction, or photovoltaic effects. Advanced technologies like quantum computing, where electron manipulation and energy levels are accurately regulated for computation and data processing, depend heavily on electrical energy.

Modern batteries, capacitors, or supercapacitors are effective means of storing electrical energy in energy storage systems. Research is being conducted to increase the capacity, efficiency, and longevity of these devices. Furthermore, the administration and distribution of electrical energy are being completely transformed by smart grids and the integration of renewable energy, which is improving sustainability, dependability, and the worldwide switch to cleaner energy sources.

1.3.5 Chemical energy

Chemical processes release chemical energy that is stored in the links between molecules. Living things need energy for metabolism and cell activity, which is what powers biological activities. Chemical energy can also come from fossil fuels like oil, gas, and coal, as well as batteries and other systems that store energy [4]. This energy is essential to many activities, ranging from the biological operations of living things to the commercial uses of energy generation. Advanced chemical energy harvesting techniques include fuel cells, which provide great efficiency and minimal emissions by directly converting chemical energy into electrical energy via electrochemical processes.

Advanced battery technologies, such lithium-ion and solid-state batteries, which are essential for powering electric cars, portable gadgets, and grid storage systems, depend heavily on chemical energy for energy storage. The main goals of this field's research are to increase safety, decrease deterioration, and boost energy density. Moreover, research into sustainable chemical energy sources, such as hydrogen and biofuels, is propelling clean energy technology innovation and supporting international efforts to switch to renewable energy sources and lower carbon emissions.

1.3.6 Thermal energy

Thermal energy, which is also called heat energy, is the energy that a system has inside it because its particles are moving around. It is a part of all matter and can be moved by radiation, convection, or diffusion [5]. Thermal energy is important in almost every industry, such as medical care, food production, air cooling, and making electricity. Thermal energy is essential to many cutting-edge applications and energy conversion procedures since it is a manifestation of the kinetic energy of particles inside a material. Thermal energy management at the micro and nanoscale is essential for creating effective thermoelectric materials, which use the See beck effect to transform heat directly into electricity. These components are essential to waste heat recovery systems because they allow energy that would otherwise be wasted to be captured and reused.

Phase change materials (PCMs) and high-temperature molten salts are utilized in sophisticated thermal energy storage systems to store and release thermal energy, providing a substantial amount of potential for balancing supply and demand for energy in renewable energy systems. Additionally, nanotechnology is boosting our capacity to regulate and control thermal energy at the atomic level, which is resulting in advancements in electronics thermal management that increase efficiency and minimize overheating in small, high-performance devices. The study of thermal energy also includes fusion energy, where using and managing the enormous thermal energy produced by nuclear processes has the potential to transform energy production and provide a clean, almost infinite source of energy in the future.

1.3.7 Electromagnetic energy

Electromagnetic energy includes X-rays, microwaves, radio waves, infrared radiation, ultraviolet radiation, and gamma radiation [6]. Wave-moving types of energy are used in many business processes, as well as in communication, heating, and medical treatments. As a result of the oscillation of electric and magnetic fields, a wide range of energy types, including radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays, are together referred to as electromagnetic energy. Electromagnetic energy plays an important role in many sophisticated technologies. High-frequency electromagnetic waves, for example, are used in telecommunications to provide fast data transfer and worldwide connection via satellite systems and sophisticated wireless networks.

Electromagnetic radiation is used in medical imaging procedures like PET and MRI scans to provide finely detailed inside pictures of the body, which aid in accurate diagnosis and treatment planning. Advances in cloaking technologies, better sensor performance, and increased energy harvesting from electromagnetic radiation are all possible thanks to research into electromagnetic materials, such as metamaterials, which investigate new avenues for controlling and manipulating electromagnetic waves. Future technological landscapes are being shaped by this discipline, which is still driving advancements in spectroscopy, wireless power transmission, and energy-efficient lighting.

1.4 Renewable energy sources (Macro level)

Renewable energy is a huge step toward secure power sources because it cuts down on using limited fossil fuels, protects the environment, and uses resources that naturally grow back. Renewable energy, unlike traditional energy sources like coal and oil, comes from things that don't run out, like plants, the sun, the wind, and water. Adopting green energy technology helps solve the important problem of climate change [7, 8] by spreading out the production of energy. This leads to energy freedom, job creation, economic growth, and social justice. As countries around the world try to switch to a cleaner and more reliable energy model, green energy gives people hope for a better future for the environment. The goal of cutting-edge research in renewable energy is to improve different technologies' scalability and efficiency. The goal of solar energy is to increase energy conversion rates while lowering prices via advancements in photovoltaic materials like perovskites and concentrated solar power systems. Modern turbine designs, such as vertical-axis and floating turbines, optimize performance under a variety of situations and are beneficial to wind generation.

With the development of technologies like tidal energy converters and compact modular hydro systems, which provide scalable solutions for a variety of water sources, hydropower is changing. Research on bioenergy looks at effective ways to convert biomass and the creation of biofuels derived from algae, which are viable, long-term substitutes for conventional fuels. Improved geothermal systems (EGS) and deep drilling methods are further developments in geothermal energy that open new sources of heat to produce electricity. By combining these renewable energy sources with energy storage and smart grid technologies, their dependability is further increased, and thus builds a more robust and sustainable energy infrastructure.

1.4.1 Hydel energy

Hydroelectric power, also written as "hydel energy," is the process of making electricity by using the force of falling or moving water to make electricity. Large dams and lakes make stable, dispatchable energy, but they need to be carefully planned and managed because of worries about ecosystem loss and community uprooting. The goal of cutting-edge hydel energy research is to use novel technologies to increase sustainability and efficiency. Large-scale dams, run-of-river plants, and tiny modular units are all parts of contemporary hydropower systems, each designed with specific environmental and operational requirements in mind. Kaplan and Francis turbines are examples of advanced turbine designs that improve energy extraction and operating flexibility.

Pumped-storage hydropower is a developing technology that supports grid stability and energy storage. It works by pushing water to a higher elevation during times of low demand and releasing it at peak times. Hydrokinetic energy capture technologies also use submerged turbines to gather energy from river and ocean currents without requiring extensive infrastructure. For large-scale power production that minimizes ecological damage and maintains sustainability, hydropower remains a low-carbon, sustainable alternative thanks to ongoing research into fish-friendly turbine designs and environmental effect mitigation.

1.4.2 Solar energy

Solar energy, which comes from sunshine, is the most common and easy to get green energy source. Photovoltaic cells take energy from the sun and turn it into electricity [9]. They can power everything from small solar farms to whole homes. Solar energy has become more widely used and affordable as technology has improved and costs have gone down. This has helped with efforts to shift to clean energy around the world. Photovoltaic (PV) technology is advancing, becoming more cost-effective, and more adaptable to different surfaces and surroundings thanks to innovations like flexible, organic photovoltaics and high-efficiency multi-junction solar cells.

To generate high temperatures that power turbines or thermal storage systems, concentrated solar power (CSP) systems employ mirrors or lenses to focus sunlight into a small area. This allows for continuous power production even when the sun isn't shining. Furthermore, improvements in solar thermal technologies—such as more effective collectors and integrated heat storage systems are improving the capacity to provide reliable heat for both commercial and residential uses. The dependability and scalability of solar energy are further improved by research into its integration with smart grids and energy storage systems, which facilitates the shift to greener, decentralized energy solutions.

1.4.3 Wind energy

Wind machines use the kinetic energy of moving air masses to make electricity. Wind farms, both on land and at sea, use wind energy to make electricity that can be connected to the power grid [10]. As technology has improved, bigger and more efficient wind machines have become able to make huge amounts of clean power. This has led to a lot of growth in the wind energy business. To maximize performance and longevity, modern wind turbines including horizontal- and vertical-axis designs are constructed using cutting-edge materials and aerodynamic advancements.

Offshore wind farms employ floating turbine platforms to explore deeper oceans and optimize energy collection by taking use of stronger and more constant sea breezes. Larger rotor diameters and direct-drive systems are two examples of innovations in turbine technology that boost energy production and lower maintenance requirements. Research on small-scale turbines and distributed wind systems also focusses on energy production in isolated or rural regions. The dependability and efficiency of wind energy systems are increased by improved wind forecasting and grid integration technology, which allows for greater alignment with energy demand and a reduction in unpredictability. These developments contribute to the achievement of global targets for renewable energy by facilitating the shift to a more robust and sustainable energy infrastructure.

1.4.4 Bio energy

It is called bioenergy when biological materials like trash, wood, and farm waste are turned into heat, power, or biofuels. Biomass can be burned directly to make energy, or it can be turned into biofuels like ethanol and biodiesel, or it can be digested without oxygen to make biogas. To keep sustainability and stop bad environmental effects like cutting down trees and competing with food supply, the right management is needed. The creation of second- and third-generation biofuels, which use biomass sources other than food, such as algae, agricultural leftovers, and special energy crops, is a significant breakthrough since it lessens rivalry with food production. Anaerobic digestion and gasification are two techniques used to turn organic waste into biogas and syngas, which may be used as a flexible and sustainable energy source for heating and power production.

The efficiency of turning plant resources into bioethanol and other important biofuels is another goal of research into lignocellulosic biomass processing. Enhancement in production and cost-effectiveness is achieved via advancements in fermentation techniques and enzyme technology. It may be possible to lower greenhouse gas emissions and promote a circular economy by combining bioenergy with carbon capture and storage (CCS) technology.

1.4.5 Tidal energy

Using the moving energy of the ocean waves to make power is called tidal energy. The rising and falling of the waves turn engines at tidal power plants, which make clean energy. Geographically, tidal energy can only be used in seaside areas with large tide ranges, even though it is a steady and reliable source of energy. Underwater turbines are used in tidal stream systems to harness the flow of tidal currents; advancements in material science and turbine design have improved the turbines' endurance and performance in challenging maritime conditions. Utilizing the difference in water levels between high and low tides, tidal range devices, such barrages and tidal lagoons, drive turbines and produce electricity. The goal of improvements in energy capture efficiency and barrage design is to maximize energy production while reducing environmental effect.

New technologies that investigate innovative ways to harvest tidal energy without requiring extensive infrastructure, such as pressure differential systems and dynamic tidal power, have the potential to lessen ecological disturbance. Improved tidal resource evaluations and energy production predictions are made possible by sophisticated computer modelling and monitoring technologies, which also aid in improved grid system integration and the shift to dependable, renewable energy sources.

1.4.6 Geothermal energy

Geothermal energy uses steam or hot water tanks to pull heat from deep inside the Earth and use it to make power or heat and cool directly. In places with a lot of geothermal activity [11], you can find geothermal power plants, which provide a steady source of low-carbon electricity with little harm to the environment. By breaking through deep rock formations, enhanced geothermal systems (EGS) may access previously unreachable geothermal reservoirs, greatly increasing the number of geothermal resources that can be produced.

The goal of advances in geothermal drilling technology is to increase the effectiveness of heat extraction while decreasing costs by improving the depth and accuracy of well drilling. The performance of geothermal power plants is improved by the development of high-temperature materials and sophisticated heat exchangers, especially in regions with intense geothermal conditions. The use of geothermal energy for industrial and domestic heating is expanding thanks to research into geothermal heat pumps and district heating systems, which provide effective and affordable options. Geothermal energy may also be integrated into a varied, robust energy portfolio by investigating it in combination with other renewable energy sources and smart grid technology. This will accelerate the worldwide shift to greener, sustainable energy options.

1.5 Renewable energy sources (Micro level)

To meet the global goal of making power in a way that doesn't harm the environment, small gadgets must be used to collect energy. Wearable electronics, portable sensors, and other small, self-sufficient devices are powered by the very small amount of energy that is taken in, changed, and saved from outside sources [12].

Moving your arms around creates small amounts of current, which can be used to power low-current devices like some automatic watches that use kinetic energy. Photovoltaics (PV) technology based on semiconductors turns sunlight into direct current (DC) power [13]. The possible difference in heat between two materials is also used by thermoelectric generators, or tegs. Small wind machines turn the energy from the wind into electricity, which powers the low-current devices. A standard voltage is made when a piezo crystal is hit physically. In electromagnetic induction, an electric current is made when something vibrates.

1.5.1 Radiation energy

The energy that moves through space as electromagnetic waves or particles is called "radiation energy." It is possible to change this energy into many other types of energy. For instance, thermophotovoltaic cells turn infrared light into electricity, and photovoltaic cells in solar panels use the photovoltaic effect to turn sunlight straight into electricity. It is possible for greenhouses and solar thermal devices to both use sunshine to heat things. Photovoltaic cells, a kind of solar energy technology, use sunlight to generate electricity. As materials like perovskites and quantum dots continue to progress, the goal is to lower prices while increasing efficiency.

Radiation energy is essential to medical technology for both imaging and therapy, with advancements in targeted radiation treatments and high-resolution imaging methods improving the accuracy of diagnosis and effectiveness of treatment. Protection against hazardous radiation in both industrial and medical contexts is being improved by ongoing research on radiation shielding and safety precautions. Furthermore, improvements in radiation detecting technology allow for more precise radiation level monitoring in industrial and environmental settings.

1.5.2 Fluid flow energy

Various turbines and non-turbine sources can be used to collect the potential and kinetic energy that flows through a stream. The most recent wind turbines and aircraft wind energy systems (AWES) are designed to actively seek out and collect wind energy for use in factories [14]. A wind-beam microgenerator was made by Zephyr Energy. It can be used to power small electronics and fill batteries. By putting the heart's kinetic energy inside a spring [15], researchers at the University of Bern have made a new type of pacemaker that is driven by blood flow. With a bluff body as a water-energy collector, Latif U. et al. of NUST University studied how angle, gap, and speed affect the power collected by a piezoelectric flag and the waves caused by vortices [16]. Microelectromechanical monitors are very useful in systems that check the health of buildings. Instead of chemical batteries, piezoelectric harvester eels, also known as flags, can be used to spread these sensors over a large area.

1.5.3 Photovoltaic energy

Photovoltaic harvesting wireless technology is better than old wired or fully battery-powered sensor systems in many ways. It is a source of power that can never run out and has few negative effects on the world. Solar calculators and other indoor solar collecting devices made of amorphous silicon are very popular. One new type of photovoltaic (PV) technology that has come about after years of study is dye sensitive solar cells (DSSCs). The use of numerous semiconductor layers to capture a wider spectrum of sunlight in high-efficiency multi-junction cells and flexible, lightweight organic photovoltaics for a variety of applications are examples of innovations. There is a lot of interest in perovskite solar cells because of their promise for high efficiency and inexpensive manufacturing costs. Furthermore, improvements in tandem solar cells which integrate many photovoltaic materials aim to surpass the efficiency of conventional silicon cells. These advancements help capture solar energy more effectively and increase the use of renewable energy solutions.

1.5.4 Piezoelectric energy

A concept called piezoelectricity was first proposed by [17]. The piezoelectric effect made it possible to turn mechanical energy into electricity. This energy can come from things like movement, weight, sound, and changes in temperature. That's because the milliwatt-level power those piezoelectric devices produce is just too small to be useful in a system. Even so, it works great for small devices like self-winding or automatic wristwatches. The use of the piezoelectric effect is a new and exciting area of technology that has been getting a lot of attention lately. From 2000 to 2005, several industrial uses were launched, such as sensor feed and sound energy gathering. More study shows that piezoelectric technology can turn the mechanical energy that people use to move into electrical energy. A more thoughtful planning process is needed to get the most out of these energy-gathering tools' useful and nice features. To meet the need for small monitors that can be inserted or worn and provide electricity, researchers have been looking into ways to use blood pressure, leg and arm movement, and implant effects [18]. A layer-by-layer method can be used to make three-dimensional nanogels (NGs) that can be put down in places where there are changes in force or pressure, like on shoe pads, under the skin of a ship, or near sources of shaking, like car engines [19]. Wearing a micro-belt is one way to turn the air you breathe in into energy that you can use. Using internal resonance and a piezoelectric stick, you can make a universal energy generator that gets its power from movements caused by people moving, which can come from any direction. Putting piezo elements on streets is one way to collect and use the "people energy" that people walk around with. They can also be used to collect "walking energy" if they are worn correctly. A group of experts at MIT made the first PZT-based micro-scale piezoelectric energy generator in 2005 [20]. A group of experts showed that light from the sun and raindrops can both be turned into energy at the same time using solar panels and a triboelectric gadget [21].

1.5.5 Smart transportation network energy

Piezo-based devices have been used to create and improve smart road technology that is sustainable. We need to make changes right away, like building an electric grid that can fix itself, strengthening buildings that are prone to falling, and using a clever road network system that can predict traffic jams and let drivers know about them. This plan will work to solve the problem of too much data on the network. But because these early systems were expensive, there has been a lack of funding that has kept these technologies from being widely used. But doing things right away, like research and development (R&D) and big investments, will speed up its supply in the industry. But it's important to keep in mind that a lot of the technology is still being worked on and won't be ready for a while.

1.5.6 Electrostatic-capacitive energy

Electrostatic energy harvesters use the idea of changeable capacitance in capacitors to get kinetic energy from moving things. The system's 1mechanical energy is turned into electricity by the vibrations of the charged plates. Things that can renew themselves or batteries that can be charged straight should work well with this method. Enhancing the functionality and uses of capacitors is the main goal of cutting-edge research in electrocapacitive energy, especially regarding supercapacitors and ultracapacitors, which provide higher energy and power densities than conventional capacitors.

The creation of novel electrode materials that enhance energy storage and conductivity, such as graphene and carbon nanotubes, is one example of innovation. To improve operational stability and charge-discharge cycles, researchers are also investigating more sophisticated electrolyte compositions and electrode configurations. The goal of these developments is to provide battery-supplanting energy storage solutions with quick charge and discharge times for regenerative braking systems, electric car applications, and energy grid stabilization. Another important area of research is integration with smart grids and renewable energy systems, which will lead to more responsive and efficient energy storage solutions.

1.5.7 Magnetic induction energy

The idea of magnetic induction says that when a magnetic field is broken, an electric force (voltage) is produced. Two types of motion that can mess up magnetic fields are vibrations and spinning forces. Mechanisms made of cantilevers that have magnets inside them that vibrate are exposed to system movements, which make them produce very little power [22]. In 2007, experts at the University of Southampton made a small gadget that could be inserted in remote areas that did not have direct access to an electricity source [23]. This new feature lets the devices talk to each other and charge themselves even when they were in faraway places that no one could reach. Recently, a wall design was made that uses the idea of magnetic induction to collect energy. The writers have shown that stress causes movements that change the shapes of the microwire walls and the induction. There aren't many magnetic induction power sources that are good for business use. Presently, scientists are working on monitors that can directly pick up structure movements from power lines or transmission lines that are above ground.

1.6 Piezoelectric eel/flag

A lot of energy can be collected with piezoelectric waving flags underwater. This is because they have a unique ability to turn mechanical motion into electrical energy. By moving fluidly, the flag creates electrical charges by deforming the piezoelectric materials that are inserted in it. Because these charges can be collected and kept, they can be used as a long-term power source for many underwater uses. Flapping flags that use piezoelectric technology are a useful and helpful way to collect energy underwater, especially when regular energy sources are limited or not possible. Because piezoelectric energy gathering doesn't need fuel from outside sources, it is better than batteries or fuel-based engines for long-term use in remote or difficult underground settings. Piezoelectric technology can also be used to get energy from waving flags, which is a safe and eco-friendly option. Researchers can lessen the damage that traditional ways of getting energy due to the environment by using the flag's natural tendency to move in response to fluid flow. Because piezoelectric materials are flexible and light, it is possible to make energy-gathering devices that look like they belong with underwater buildings. This makes them more useful and efficient.

1.7 Piezoelectric Principle and energy harvesting

A piezoelectric energy harvester operates by using the piezoelectric effect, as seen in Figure 1.4. It has the potential to function as both a sensor and an energy collector. The piezoelectric effect refers to the capacity of materials to produce an electric charge or undergo deformation when subjected to mechanical stress or electric charge interaction. Molecular electrical neutrality is achieved in the absence of any mechanical tension. The coincidence of the centers of the positive and negative charges in each molecule, as illustrated in Figure 1.5 of the piezoelectric converter of energy, serves to counterbalance the external influences of these charges. Figure 1.5 demonstrates the phenomenon where a molecule, when it is underweight, experiences a displacement of its centers and the formation of a little dipole during the separation of its positive and negative charges. Polarization charge is produced above the surface when the opposing poles nullify each other. Accordingly, polarization leads to the generation of a charged field, which converts mechanical energy into electrical energy. This electrical signal is then captured in the form of an alternating voltage. The voltage signal is then processed and rectified to the desired output. The voltage signal is non-periodic depending on the stress application and the strength of the stress, the orientation or the direction (d_{31}, d_{32}, d_{33}) in which the stress applied. Every direction has its own specific voltage generation capacity but the one we utilized is the d_{31} because of the piezo flag orientation and the vortex shedding transversal nature in the wake region. Most of the energy in the study is extracted in the transverse d_{31} direction.

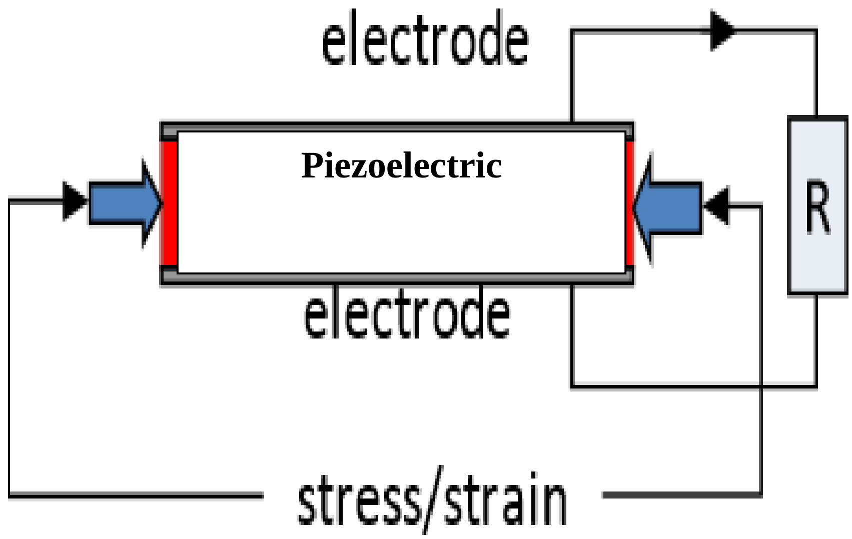

Figure 1.4:Piezoelectric converter of energy

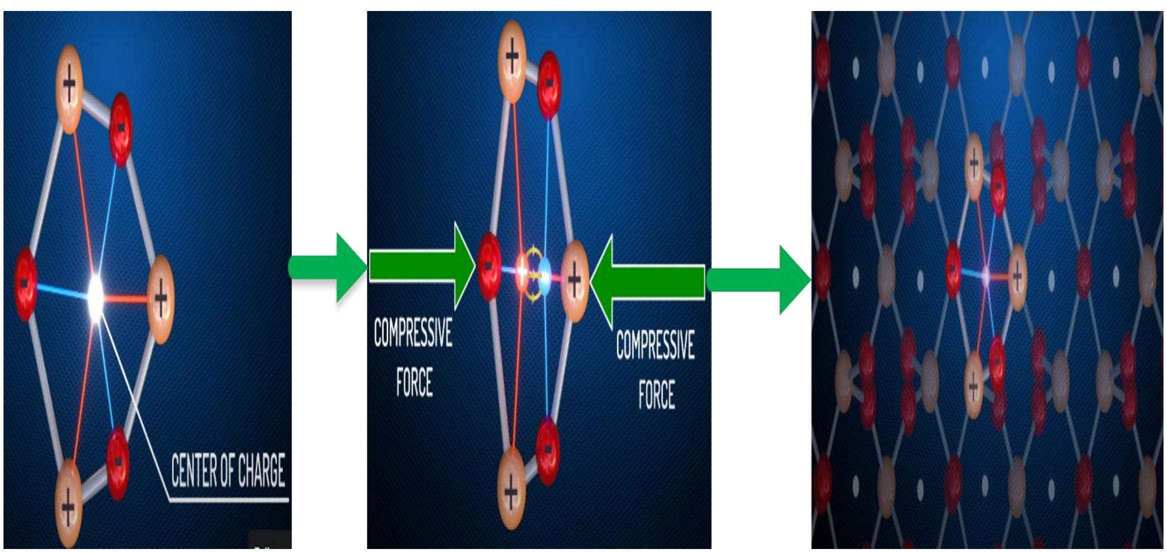

Figure 1.5:The piezoelectric phenomenon.

Because of the reversible nature of the piezoelectric effect, a material may undergo mechanical deformation in response to an applied electric field in addition to mechanical stress producing an electric charge. Because of this dual property, piezoelectric materials are highly valued in many different applications, such as energy harvesting devices, actuators, and sensors. For example, sound waves' mechanical pressure in sensors may be transformed into electrical signals, which are then processed for a variety of uses, including medical ultrasound imaging and microphones. Furthermore, actuators that use the piezoelectric effect to generate exact motions are crucial for a variety of applications, including inkjet printers and precision surgical equipment. Piezoelectric materials' capacity to transform mechanical energy into electrical energy creates opportunities to produce renewable energy, especially in settings with high vibration levels, such industrial equipment or footwear. Innovation in several scientific and technical domains is still being fueled by the adaptability and effectiveness of piezoelectric materials.

CHAPTER 2: LITERATURE REVIEW

Piezoelectric materials are used in energy harvesting for strain measuring sensors, portable electronic devices, and web-based Internet of Things platforms. Effective implementation of small-scale energy harvesting is crucial for powering portable electronic equipment such as laptops, nanorobotic devices, self-power supply, and surveillance devices [24]. Nano-robotic devices are advanced robots capable of self-recognition, adaptation, and execution of very intricate tasks. Nevertheless, it might be difficult to operate these on their own energy sources without diminishing their functionality [25]. Energy harvesting based on vibration is a technique that transforms the vibrational momentum generated by fluid motion into usable electrical energy. In tandem with progress in semiconductor technology and minor technical developments in sensors, it has been more common during the last two decades.

Piezoelectric vortex induced vibration (VIV) is a growing methodology for extracting electrical energy from the mechanical energy of a moving fluid [26]. In terms of their functioning, effectiveness, and capacity as sensor nodes, these piezoelectric energy generation devices exhibit commitment. When placed posterior to the bluff body, the flapping flap exhibits a pattern of movement akin to that of fish in water or birds when their wings flap. This pattern is generated by the vortices that develop when the bluff body is immersed in the flowing fluid. VIV, or vertical internal vibration, is usually caused by Eddie shedding in the downstream area of a bluff body because of fluid flow patterns and pressure variations.

The turbulent pressures exerted by a dynamic stream may enhance the periodic deformations of the piezoelectric flag by causing a cylinder at the free end to mix [27]. The flag undergoes fluttering due to the differential pressure distribution of the fluid, resulting in its rotation. The study conducted by Hu et al. showcased the effects of interposing rods at various angles in proximity to a circular cylinder, resulting in enhanced power production and an enlarged unstable zone. An analysis conducted by [16] on inverted C-shaped bluff bodies with varying cut angles revealed a power increase of 66% at a 120° cut angle, in comparison to a circular cylinder. To enhance efficiency and turbulence, [28] affixed Y-shaped foils across a cylindrical body, resulting in an acceleration of the VIV with a suggested 60° inclination. At a certain velocity, the swirling flag's flapping display generates large amplitude motions that then shift into limited cycle oscillations.

Significant quantities of energy are captured at a consistent or low frequency. Several flow and geometric factors, including angle, bluff body shape, spacing ratio, load resistance, and flow speed, determine the operation of the energy harvester. Through the manipulation of these parameters and the formulation of a sequence of experiments, it is possible to construct the optimal system that can generate the most amount of energy. This investigation included the manipulation of two variables: the velocity of the fluid and the distance of the fluttering flag from the cylinder. The study [29] discovers the effects of the elastic modulus, mass ratio, and shape of the bluff on the energy harvesting. Various bluff body diameters with a range of Reynold Numbers (2000-30000) have been studied [30]. Different meta surfaces are analyzed to study the wake dynamics for energy gain [31]. The spacing effects of the bluff bodies on the wake analysis for energy harvesting are extensively studies [32-34]. Different geometric shapes (conical, polygonal, and extruded surfaces) are examined for the energy harvesting effectiveness [35-37]. A similar kind of study to this work showed both the vibration suppression as well as enhanced energy gain for various bionic attachments to the cylinders [38]. Some low Reynold studies performed on circular cylinders [39]. Traverse galloping geometries (square, triangular and D-shaped) have been studied [40]. Round filleted square bluff bodies with splitter plates, two side by side, and tandem configuration on the energy harvesting are studies [41-44]. The PEH performance of pinned and clamped films in free stream [45] simulated ocean current over a range of Re (6200-131,200) for the performance measure and design of PENG.

In an aquatic context, [46]investigated the energy scavenging capabilities of flexible eels. Through the interaction of fluid dynamics in the water and the flexible flag, its form was modified to resemble the wake of an unimpeded cylinder. Innovative methods using electromagnetic induction and vortex-induced vibrations have been devised by [47] to produce electricity from fluid in motion. The findings indicated a power output (Pins) of 1.77μW instantaneously when subjected to a fluctuating force measured at 62 Hz. A computer study conducted by [48]examined the fluid flow properties on a flexible flag inside a restricted channel. The influence of aspect ratio on energy harvesting efficiency was investigated by [49] using experimental methodology, resulting in reported enhancements of 26.5% and 45.7%. [50] assessed the impact of asymmetric wake flow by using two cylindrical bluff bodies. They demonstrated a remarkable 95% augmentation in energy production when the distance between the cylinders was equal to one unit (N/d).

The tandem arrangement of bluff bodies has been extensively investigated in many studies to enhance energy scavenging efficiency by considering interaction dynamics, fluid drag, and pressure gradients [51]. Alternative methods, such as combining different profiles or modifying the forms of bluff bodies, have shown substantial improvements in performance. [52] observed a 19.6% increase in energy efficiency by using a passive piezoelectric flag in a tandem configuration, operating at a Reynolds number of 8.7 x 104 and a chord length of one. Integrated bluff bodies with diverse profiles were suggested by [53],leading to a significant 380% performance enhancement. [54] investigated the significant increase of 116% in power generation achieved by an arrangement of flags in tandem, operating at a speed of 0.26 m/s. The influence of harvester spacing and flow stream velocity on piezoelectric energy retrieval utilizing two cylindrical bluff bodies in a tandem configuration was highlighted by [55]. Incorporating a cylinder at the free end of a piezoelectric flag may amplify the transient deformations caused by the dynamic forces of a flowing fluid. Furthermore, the harvester undergoes movement because of the unequal pressure distribution of the fluid, which exerts additional stress on it. The effect of introducing rods at various angles around a circular cylinder was shown in reference [56], resulting in the expansion of the unstable zone and an increase in power output. [57] attached Y-shaped foils to a cylindrical object, transforming vertical intensity velocities (VIV) into galloping by introducing a 60° inclination angle to improve performance and induce turbulence. The modified configuration of the bluff body enormously enhanced power generation. Upon reaching a critical velocity, the rippling flag undergoes flutter and then transitions into limit cycle oscillations, which lead to motions of high amplitude. Harvested energy is obtained at a low or constant frequency with broad amplitudes. A computer analysis was conducted to examine the impact of undersea depth on the wake of a circular bluff body, utilizing VIV modelling. The findings show a significant rise in hydropower generation as the depth increased from 0.1 m to 0.5 m. The application of dynamic forces and the installation of a cylinder enhance the strain in the piezoelectric flag, therefore augmenting the movement and strain generation inside the flag [58].

To enhance the efficacy of piezoelectric films, a great deal of research has gone into improving the geometric design of bluff bodies. At a wind speed of 4.0 m/s, the T-shaped bluff body produced 4.0 mW of power [59]. The ideal blade half-angle was discovered to vary from 60 to 80 degrees via theoretical and experimental studies on the voltage output of a three-blade bluff body. [60] looked at the energy-harvesting capabilities of four-cylindrical forms, and at Re = 60,000, the q-trapezoid shape produced the maximum output. In other investigations, resonance was established transversely by synchronizing the shedding frequency with the flag's inherent frequency, which allowed bluff bodies to be used as end masses to create galloping and improve energy harvesting and looked at the effect of a bluff body's cross-sectional design on energy scavenging from the galloping phenomena.

Many studies have been conducted on wake flow properties using piezoelectric cantilever flags for single or multiple bluff bodies; however, few studies have looked at how boundary layer affects power scavenging at different channel widths. Studies on flow dynamics in various channels have been conducted. The performance of an elastically placed circular cylinder in a narrow channel under a buoy was examined by [61] and the findings showed that for smaller channels, the maximum energy conversion efficiency was 37.5% before the viscous effect became noticeable. The study [62] of the gap size's effects on the velocity boundary layer structure revealed that decreasing the gap size limits the formation of the velocity profile and lessens turbulence fluctuations, which in turn affects transverse mixing in the channel gap. Using continuous laser particle imaging velocimetry (PIV), [63] investigated the dynamic response of a zero-pressure gradient turbulent boundary layer (TBL) to an active flow control actuator. The study [64] examined the use of macro fiber composites in an open channel for energy harvesting utilizing triangular prisms and cylinders. The study [65] of hydroelectric power trends in cramped areas took peripheral and inertial circumstances into account. Another study [66] investigate the effects of several piezoelectric flags with Reynold numbers ranging from 2000 to 7500 positioned in various turbulent boundary layer regimes. In the study [67], the attachment of a meta-surface to a height-adjustable cantilever flag enhanced energy harvesting have been investigated.

Prior research has shown the critical impact that channel size variation and the bluff body's form play in flow dynamics. Nevertheless, no thorough investigation of the effects of channel width variation on energy harvesting via adjustments to the energy harvester's streamwise and spanwise gaps has been carried out. The methods covered in earlier research are either bluff bodies for energy harvesting or flow behavior in confined or open channels. Using PIV with greater Reynolds numbers and smaller gap widths, [68] examined boundary layer properties close to fuel rods, affecting channel performance. To provide a performance metric for PENG design, the study [69] has simulated ocean current across a broad range of Re values, from 6200 to 131,200.

2.1 Research Gap

The research is carried out owing to the facts that the current and the literature work that has been done still need to be investigated for some more geometry and flow scenarios. Therefore, the work done before in this domain is domain is still limited and needs to be studied for the possible research gaps. The following limitations of the previous research has been addressed here in this study:

The proposed diameters of the protrusions (9,11,13) have not studied yet.

Only the VIV on PZT (Lead zirconate titanate) has been explored yet in wind tunnels.

Our study aims at PVDF (Polyvinylidene fluoride) WIV performance in water tunnel at Re (3500-11500).

2.2 Future recommendations

The advancement of energy harvesting systems relies heavily on the development of new polymers that exhibit optimal efficiency and exceptional tensile strength. The optimal choice is to use electroactive polymers (EAPs), which are lightweight systems considered to be much more economically efficient than those dependent on piezoelectric materials.

A research team at the Italian NiPS Laboratory is exploring methods to capture and harness energy from ambient noise. Mitigating dependence on batteries or disposable power storage devices is crucial to meet future requirements, especially in remote regions where conventional power networks are unable to provide a comprehensive answer. Implementing hybrid adaptations of existing energy-collecting equipment is an effective approach. Implementing hybrid systems offers a means to enhance the global reliance on autonomous systems. The energy required for various electromechanical devices and some sensors like acoustic sensors, deep sea pressure measurement sensors, ultrasonic transducers, and the sensors used in many modern autonomous industrial systems and automotive and aerospace industries are highly in demand for a sustainable energy source rather than the conventional massive batteries that in turn also pollute the environment. The focus on the research for a more sustainable and long-lasting energy sources deployment and special mechanisms to extract ambient energy is crucial in attaining a sustainable and green industrial future. The impact of the energy development systems on the surroundings of the human being is the pivotal key that deviate the future work in the research industry.

CHAPTER 3: METHODOLOGY

3.1 Water tunnel

The research makes use of an enclosed, slow-speed water channel, as shown in Figure 3.1 from the Department of Mechanical Engineering at the National University of Sciences and Technology (NUST). The water channel's test section has square proportions, measuring 200 mm by 400 mm by 400 mm by 400 mm (L × W × H). The centrifugal pump, which propels the water flow in the channel, has its rotational speed (RPM) controlled by a variable frequency drive (VFD), which runs in the frequency range of 1 to 50 Hz. As determined by the PIV technique, this enables the water velocity to be altered with a 1% intensity of turbulence in the range of 0.1 to 0.5 m/s. A 1.83 m × 0.5 m × 0.0254 m (L × W × H) aluminum honeycomb structure with hexagonal holes is used.

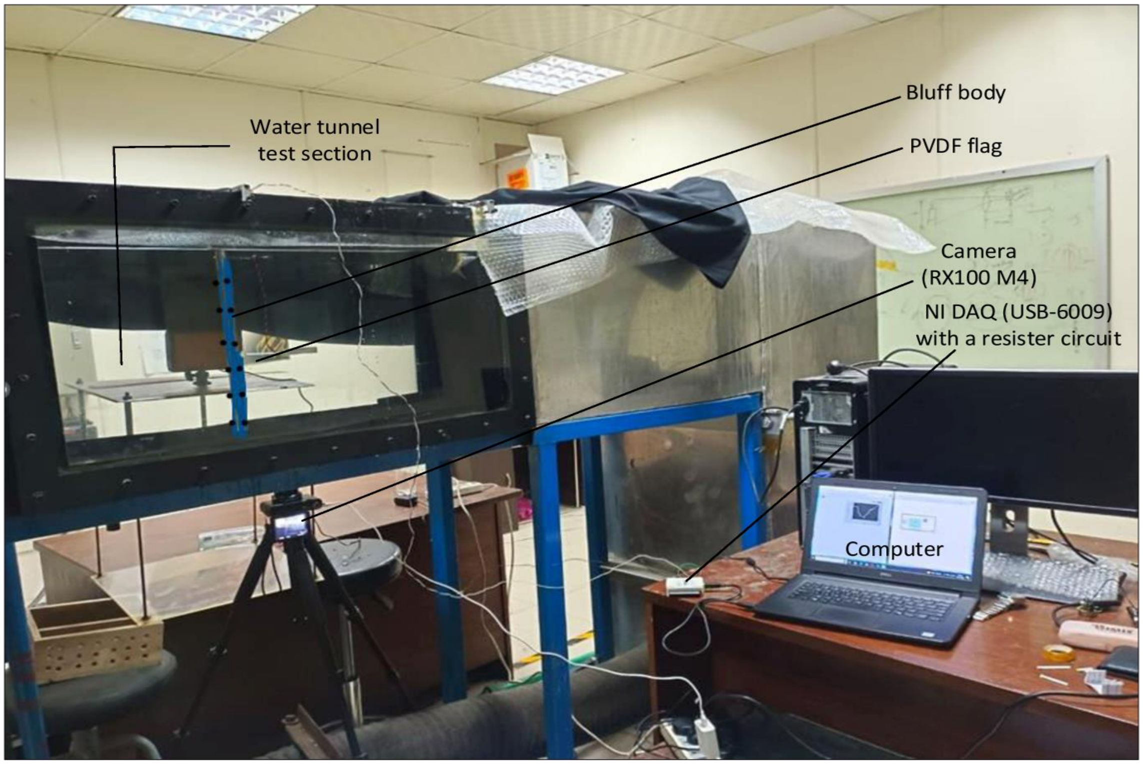

Figure 3.1:Experimental setup of flow lab.

Table 3-1:Piezoelectric flag properties

Specifications	Values
Material	PVDF
Active length (L)	60 (mm)
Total length	72 (mm)
Width (w)	16 (mm)
Thickness (t)	40 (µm)
Mass	0.72 (g)
Capacitance (C)	2.78 (nF)
d31 constant	23 (10-12 C/N)
g31 constant	216 (10-3 m2/C) k31 constant
Young's modulus	2-4 (109 N/m2) Temperature range -40 to 80 (ºC
Mass density	1.78 (103 kg/m)
Material	PVDF
Active length (L)	60 (mm)
Total length	72 (mm)

The piezoelectric material used in this study and its specific material characteristics are listed in Table 3-1. The experimental parameters with their units and values, that are considered in this study are listed in Table 3-2.

3.2 DAQ, camera, and flag arrangement

A flexible flag, a breadboard with the right resistor for the circuit's load, a high-resolution camera to record the flag flapping action from the bottom of the tunnel, and a Data Acquisition (DAQ) device to display the instantaneous voltage generated in the flexible flag because of disturbance are the experimental tools utilized in this work. The voltages generated and recorded under very similar circumstances are analyzed using a digital oscilloscope (UTD-2052CL) to verify the accuracy level of the DAQ device. It is found that the outcomes are rather similar. PVDF flag measurements are 0.072 m x 0.016 m; however, since epoxy gel and adhesive tape are used to hide the connections and fasten the flapping flap end to the cylinder, the flag's operating length is just 0.060 m. The thin metalized coatings covering the 54 μm thick piezo film are linked to integrated terminals for the purpose of transmitting charges produced on the piezo material/film. For protection, a thin layer of transparent plastic is placed over it. Both the pressure and the strain that the flowing fluid imparts to the piezoelectric film determine how much energy is captured. For every micro strain, the PVDF-DT family of piezoelectric films generates more than 10 microvolts. These films have an output voltage range of 10 mV to 100 V, depending on the applied pressure and circuit impedance.

Table 3-2:The study parameters

Parameters	**Specifications**
Fluid	Water
Density	998.6 (kg/m3)
Velocity	0.15, 0.30 (m/s)
Reynold's range	(3500-11500)
Temperature	18 ºC
Cylinder diameter (D)	25 (mm)
Protrusion diameter (d)	9,11,13 (mm)
Bluff bodies material	PVC
Streamwise gap	Gs
Amplitude of vibrations	A (mm)
Test section dimensions (L_t×W×H)	(2m×0.4m×0.4m)

Every experiment's video is recorded for 120 seconds, with a 1920 x 1080-pixel resolution and 50 frames per second. To improve visibility, bright LED lights (Model: Mcopus TTV 204), placed on one side of the flag, are utilized to highlight the piezoelectric film. The test portion of the tunnel is covered with a black cover to prevent interference from background videos. MATLAB is used for post-processing video data to determine the flag's primary frequency and amplitude. Furthermore, LabView and a data collection card (DAQ, National Instruments, NI- USB 6009, multiple purposes I/O) are used to collect data on the energy produced by the PVDF flag for 120 seconds at a frequency of 50 Hz.

The high-resolution camera subsequently records the flag's flapping on video, which is then subjected to MATLAB code analysis. That code initially provides the Microsoft Excel file with flapping flap values that match the amplitude of the flag. Afterwards, this gives the normalized frequency and the A/L value, which helps with data analysis and confirms the power production of the fluttering flag.

3.3 MATLAB Post processing

The experimental setup with a water tunnel test section and a mounting mechanism for the eel and bluff body is shown in Figure 10's design. The NI DAQ data collection system is linked to the eel's terminals, which route the incoming voltage signal via an ideal resistive circuit.

LabVIEW software is then used to process the analog voltage signals. The flag's (eel) fluttering patterns are captured by the camera. In addition, the videos that show the flag's flapping patterns are digitally analyzed using MATLAB software to extract the flag's dynamic properties (eel). The software's image processing features are used to extract the flapping frequencies for each example as well as the amplitude time response of the flag's tip. The Fast Fourier Transformation analysis of the flag dynamics is carried out by the built MATLAB code, which also determines the tip displacements and the prominent flapping peaks in the flag's frequency spectrum. Power production is dependent on both the oscillations' frequency and amplitude. The amplitude and frequency cube have a direct relationship with power. The properties of the piezoelectric material in this example, the eel or flag also affect power. Direction-oriented stress is applied during the fluid-structure interaction between the fluid and the flag. The flag produces a separate voltage signal in each direction. In our case, the d31 direction, which runs perpendicular to the flag's width, is the direction of interest. The frequency of vortex shedding determines the ideal resistance for the flag.

3.4 Schematics

The schematics are represented in Figure 3.2 showing the flag, the bluff body, the flow direction, and test section of the water tunnel to having an idea of the fluid-structure interaction during the experimentation.

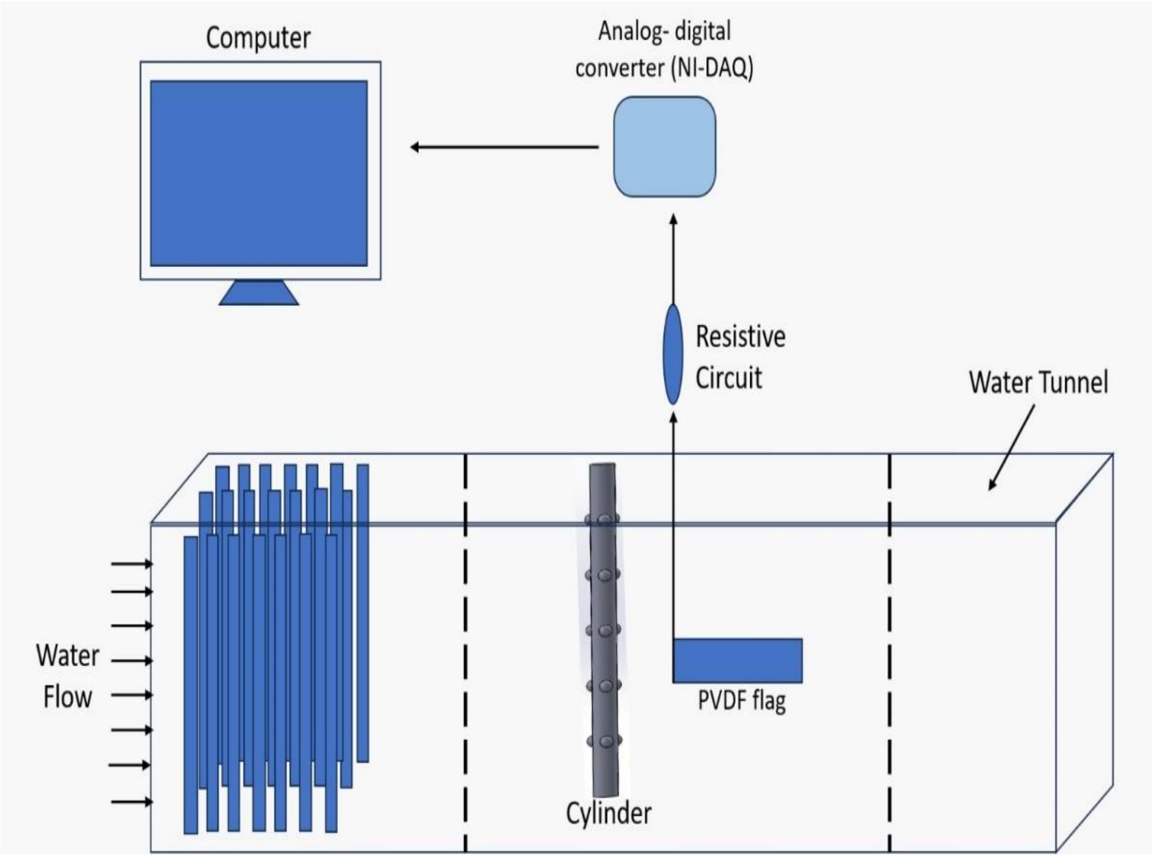

Figure 3.2: Experimental schematic of test section, data acquisition.

3.5 Resistance

In this process of generating energy, resistance is crucial. The ideal resistance for the circuit must be chosen since we are producing energy at the micro level. The circuit's output will be directly impacted by the resistance we choose thus, we won't be able to get the system to produce the most energy possible. Here, I aggressively fluttered the flag underwater as part of my energy-generating experiment, maximizing power generation by using a resistance component. The range of ideal resistance levels is 0.45MΩ–0.6MΩ.

3.6 Particle Image Velocimetry (PIV)

Scientists have created Particle Picture Velocimetry (PIV), an amazing optical method for examining fluid dynamics and flow behavior, especially in the wake zone. The method makes use of tracer particles to provide an image that aids in the explanation of the flow's characteristics. PIV is a technique for stream visualization that is used to get scalar data, such as parameters linked to fluids and instantaneous fields of vectors (velocity). The primary characteristic of this configuration is the introduction of seeding particles into the fluid flow to gather data on flow dynamics. The market offers a wide variety of particles, depending on the use and media. For instance, flow fields for air fluids employ smoke, while those for water fluids use beads, dye, or hollow glass particles. Particle densities are about the same as those of the fluid being investigated. Depending on the application, these particles are illuminated with an optical laser or a pair of lasers to make them visible on the digital camera placed underneath the test area. The successive images taken by the camera while the tracer particles were traveling are then analyzed using a cross-correlation technique to get information about flow velocity (the direction and speed of the particles) on the flow field under inquiry. The processing and analysis of this data shows the distribution of view field parameters, flow vortices, and flow lines, also called speed lines. A typical setup for a particle image velocimetry system consists of a digital CMOS/CCD camera, a laser with an optical arrangement to produce a physical light sheet to illuminate the required/specified flow field, a synchronizer to control the timing of the triggering of the camera and laser, tracer particles, and the fluid under investigation.

3.7 Experimental procedure

To completely investigate the subtleties of bluff bodies in relation to passive flapping processes, 200 well thought-out tests were conducted. The geometric characteristics of the bluff bodies and the flow velocities for each case are listed in Table 3-3. Each kind of bluff included twenty trials, which were thoughtfully set up to provide equitable representation within the experimental range. This systematic methodology enables a detailed analysis of the effects of body shape on the functionality of flapping mechanisms. It is hard to overstate the significance of a procedure this thorough. Since each arrangement would get an equal number of tests, any discrepancies in performance could be attributed to geometric variations rather than bias from the experiment. This meticulous preparation enhances the validity of the study's findings and safeguards the data's accuracy. Careful planning and execution were necessary to ensure the dataset's consistency and reliability. Each experiment was meticulously planned to minimize irrelevant variables and preserve consistency across all trials. The correctness of the results was ensured by meticulously examining every aspect, including the execution of the methods and the calibration of the equipment. The collective outcome of these investigations yielded a wealth of knowledge on the intricate relationships among fluid dynamics, cylinder geometry, and flapping energy generation. After careful investigation, patterns were apparent that showed how little modifications to cylinder design might have a big impact on performance. All the research's experiments yielded data via two distinct channels, which allowed for a thorough understanding of how the flapping mechanism works. Taking a detailed photo of the fluttering flag in action was the first step in the data collection process. A two-minute dynamic action video was also made using a high-resolution camera that meticulously documented every attempt. Researchers were able to see the intricate intricacies of the flapping movement in real time by using this footage. Concurrently, a sophisticated measuring device was used to measure the flying flag's energy generation. The flag's implanted sensors detected the mechanical energy it created as it was flapping, and they transformed that energy into electrical impulses. These signals were then sent to a platform for collecting data, such as the National Instruments platform, which meticulously documented the power output for each experiment. This dual method to data collecting allowed for a comprehensive understanding of both the qualitative and quantitative aspects of the flapping mechanism's operation. A customized MATLAB method was developed to extract meaningful insights from the raw data. This code served as a conduit between the recorded signals and practical metrics such as amplitude and flapping frequency. The acquired data was transformed into understandable values by the MATLAB code using Region Based Object Tracking signal processing techniques, enabling a more in-depth analysis of the dynamics of the flapping mechanism. Using MATLAB, researchers were able to generate key performance indicators that allowed them to assess the flapping mechanism's efficacy in a variety of experimental scenarios. Moreover, the integration of MATLAB into the data analysis pipeline facilitated the process of deriving valuable insights from the vast amount of collected data. Using advanced data visualization tools and automated algorithms, researchers were able to identify patterns, anomalies, and correlations in the data, leading to a more nuanced understanding of the flapping mechanism's functioning. In summary, a comprehensive framework for evaluating the flapping mechanism's performance was made possible by the combination of computer analysis, equipment, and eye observation. With the use of advanced techniques and instruments, researchers were able to extract significant insights that influenced further investigations and guided future research avenues. This integrated approach highlights the critical role that multidisciplinary collaboration plays in advancing the development of innovative renewable energy solutions and deepening our understanding of complex fluid-structure interactions. The study's findings emphasize how important it is to consider cylinder shape in the design and development of active flapping systems for energy production. They not only explain the basic ideas behind fluid-structure interaction, but they also provide helpful guidance for improving the effectiveness and efficiency of renewable energy systems.

Table 3-3:The geometric characteristics of the bluff bodies and the flow conditions.

Bluff body	**Protrusion diameter (mm)**	**No of columns**	**Flow Velocity (m/s)**	**Streamwise gap (Gs)**
b 1	9	3	0.15,0.30	1,1.5,2,2.5,3
b 2	9	4	0.15,0.30	1,1.5,2,2.5,3
b 3	9	5	0.15,0.30	1,1.5,2,2.5,3
b 4	11	3	0.15,0.30	1,1.5,2,2.5,3
b 5	11	4	0.15,0.30	1,1.5,2,2.5,3
b 6	11	5	0.15,0.30	1,1.5,2,2.5,3
b 7	13	3	0.15,0.30	1,1.5,2,2.5,3
b 8	13	4	0.15,0.30	1,1.5,2,2.5,3
b 9	13	5	0.15,0.30	1,1.5,2,2.5,3
sc	-	-	0.15,0.30	1,1.5,2,2.5,3

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Experimental outcomes and dependencies

The optimal circumstances for the flapping flag to produce its maximum power production will be provided by this study. This experiment involves a wide range of variables. The number of columns, the protrusion diameter, the fluid velocity, and the separation between the cylinders with the fluttering flag are these two factors. The range of the fluid velocities is 1D ≤ Gs ≤ 3D, while the distance between the cylinder varies at 1 ≤ Gs ≤ 3D. It created sets of these data ranges, resulting in 10 examples for every bluff body. There were 100 cases completed in all for this study.

Vortex shedding is a natural phenomenon that affects a flying flag when it is positioned behind a cylinder. The flag bends due to the vortices in the higher-pressure cylinder; this strain in the piezoelectric flag then amplifies and generates the electrical charge within the flag. The tension brought on by a flag may be ascertained using the flag structure theory forms. The thickness, peak amplitude, flapping frequency, capacitance, and other characteristics of the piezoelectric flag all influence how much energy it can extract. He and colleagues' study indicate a direct relationship between the deformation of the piezoelectric flag and the generation of electrical energy. Using the same principle of deformation and power production, experimental study is conducted to find the optimal tail placement and electrical generation. Studies reveal that a flexible flag may flap in many ways, such as biassed, periodic, and continuous. P = V^2/R is the formula used to calculate the average power produced. Here, V stands for the voltages recorded using a DAQ during a one-and-a-half-minute period, R for the circuit load resistance found using the maximum power transfer theory, and P for the power produced because of the flag's deformation.

4.1.1 At flow velocity of 0.15m/s

Observing from Figure 4.1 (a) that, for each kind of body, the power gained gradually rises as the width of the protrusions grows along the columns. The protrusion's growing size is the reason for this tendency. Strong vortex development results from early boundary layer separation, which increases wake energy. Additionally, the bluff bodies' wake dynamics are significantly influenced by the direction and positioning of the protrusions. Vibrations may also be reduced by arranging the protrusions across the cylinder surface in certain ways [31]. It is discovered that, in comparison to the simple cylinder (sc) output, the power gain of the three column bodies (b 1 and b 4) has decreased, while the output of b7 is almost identical to the simple cylinder. Noting that the wake in the case of three columns is less severe because of the delay in boundary layer separation. As the protrusion's diameter grows, the boundary layer separates sooner. Therefore, it may be inferred that expanding the diameter even further would increase the three column bodies' energy gain.

The four-column bodies (b 2, b 5, and b 8) exhibit a superiority in power production compared to the five-column bodies (b 3, b 6, and b 9). The energy gain for the b8 is about 12% more than for the basic example, meaning that it can provide the maximal output power of 0.15 m/s. In contrast, body (b1) shows a 19% power degradation as compared to the plain cylinder (sc). The boundary layer separation in the 4 and 5 column bodies (b2, b5, b8, and b3, b6, b9) happens faster than in the 3 columns and simple cylinder (b1, b4, b7, and sc), which is the cause of their dominating wakes. The drag that increases the intensity of the wake vibrations is closely linked to boundary layer separation. Furthermore, the wake dynamics (the VIV) are caused by the pressures that drag and lift forces across the surface of the structures.

Moreover, the streamline range (2D-3D) has the highest power production when examining the streamwise gap Gs. The bodies b8 and b9 have their highest power increase at 3D, whereas the b1 has shown its maximum power output at 2D, b2, b3, b4, b5, b6, b7, and sc at 2.5D. Therefore, the area exhibiting strong vibrations is almost within the range ($2D \leq Gs \leq 3D$). The instantaneous voltage signals and their RMS acquired throughout the experimental method are shown in Figure 4.2. The simple cylinder (sc) is used as a benchmark for comparison with the lowest power producing body (b1) and the greatest power generating body (b8) in the study's figures to demonstrate how much the power output varies.

The amplitude to length ratios that are acquired from the post-processing of the MATLAB results of the videos that were collected during the experiments may be used to evaluate the output power discoveries. According to Figure 4.3 (a), the four columns' (b 2, 5, and 8) overall dominant vibration amplitude is followed by the five columns' (b 3, b 6, and b 9) arrangements. The power outputs shown in Figure 4.1(a) are confirmed by the simple cylinder (sc) and the three column arrangements (b1, b4, and b7), which have the lowest and lowest amplitudes, respectively. Figure 4.4 displays the real-time instantaneous amplitude-time response of the flag's free end oscillations for bodies sc, b1, and b8.

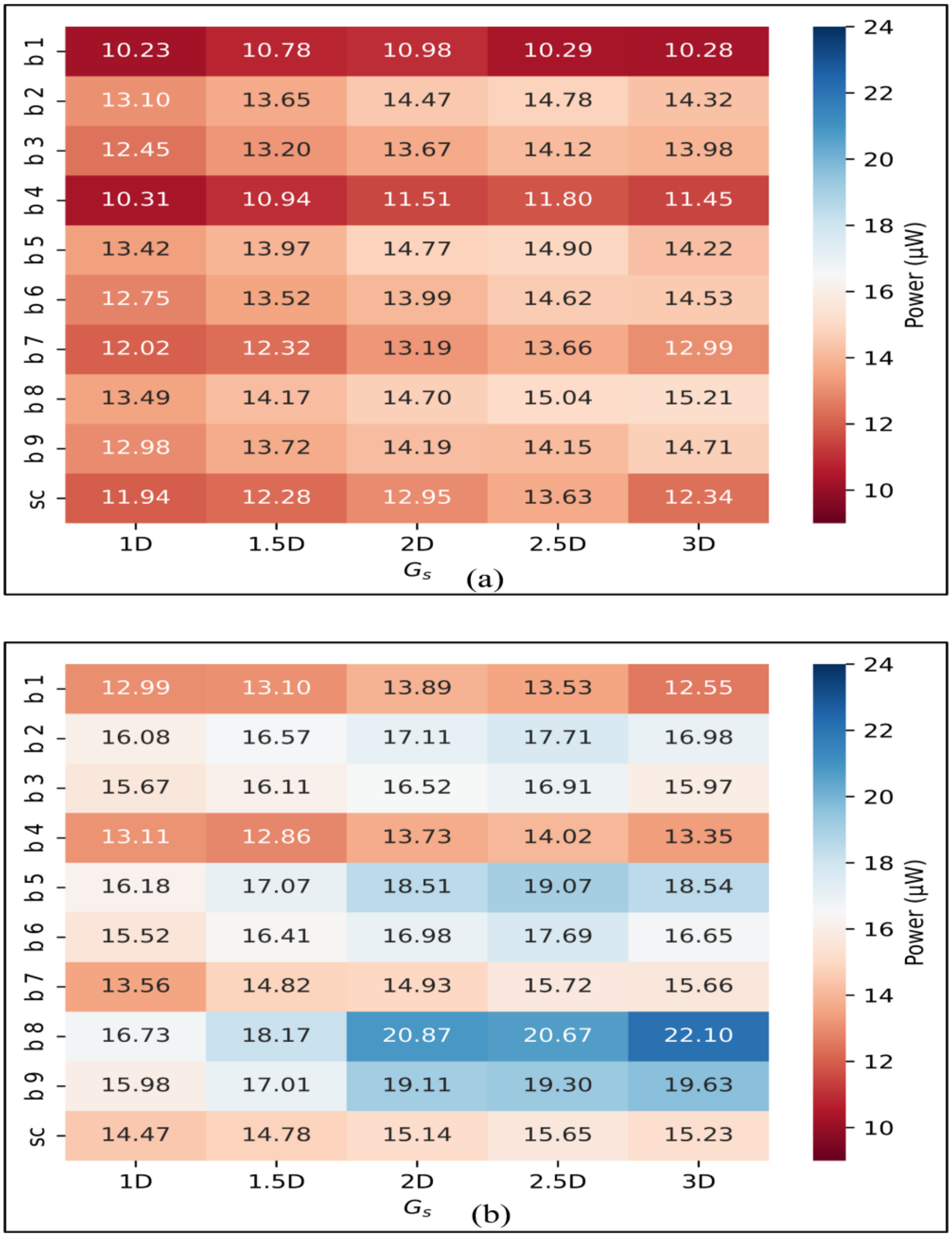

Figure 4. 1:The heatmaps showing the power gain at (a) 0.15m/s (b) 0.30m/s.

One of the main elements influencing the power output is also the oscillation frequency. The power output increases with the flapping frequency. Figure 4.5 (a) illustrates the complex flapping behavior caused by the fluid-structure interactions between the flag and the vortex shedding, which result in certain anomalies in the flag's flapping frequency under various vortex shedding bodies. Still, there is a noticeable difference that indicates the bodies b1, b4, and b7 behave less well generally than the body sc. In oscillations, the bodies b2, b3, b5, b6, b8, and b9 exhibit a collective dominance. The flapping frequency is in direct relation to the power output and hence the greater the flapping frequency of the flag the greater is the power output. The frequency trends are almost agreeing the power outcomes. Although the flapping behavior of the flag is extremely complex due to the cryptic phenomenon of the vortex shedding interactions with the piezoelectric flexible flag in the wake, but still the dominances in the frequency spectrum are almost evident. The conclusions based on their oscillations are therefore significant in this study.

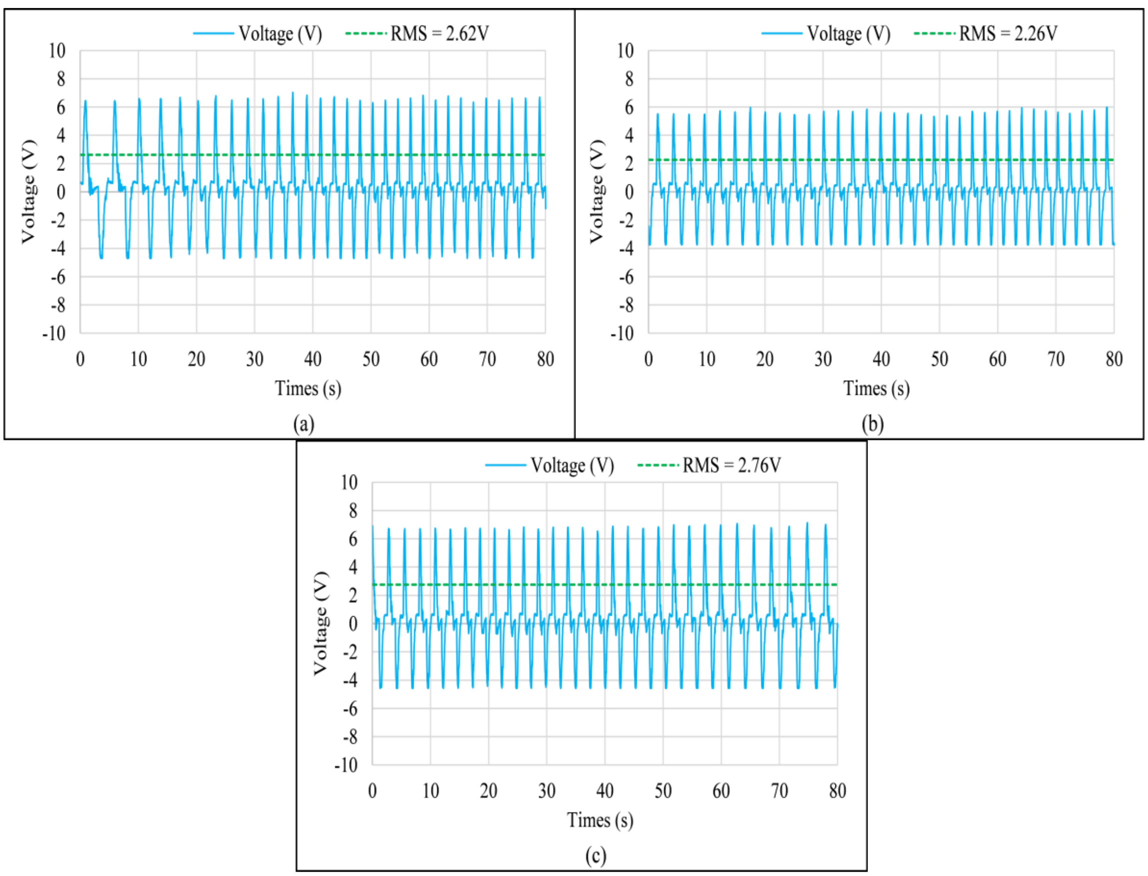

Figure 4.2:The instantaneous voltage at 0.15m/s (a) sc (b) b1 (c) b8.

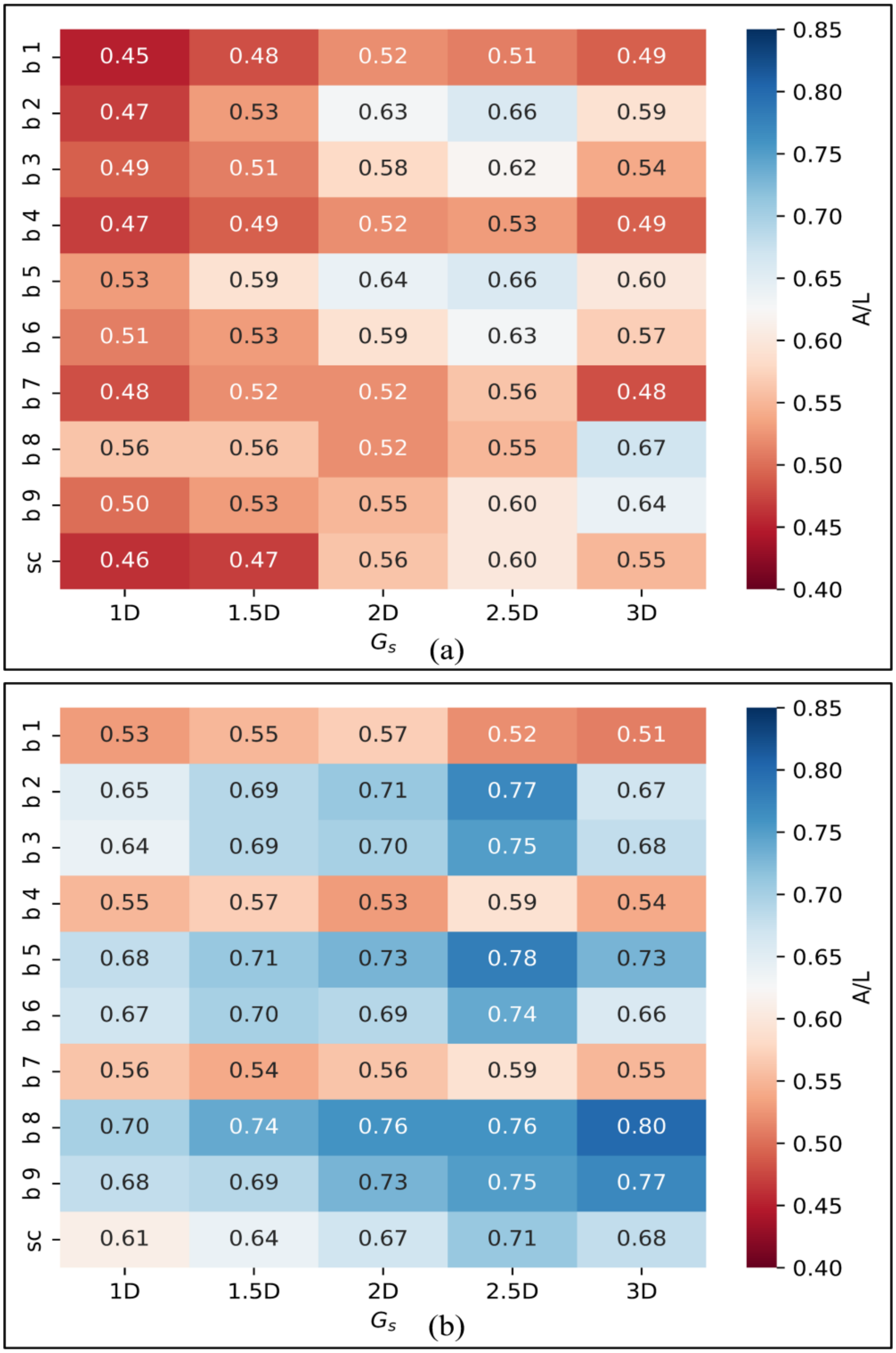

Figure 4. 3:Comparison heatmaps showing the amplitude to length ratios of the flag at (a) 0.15m/s (b) 0.30m/s.

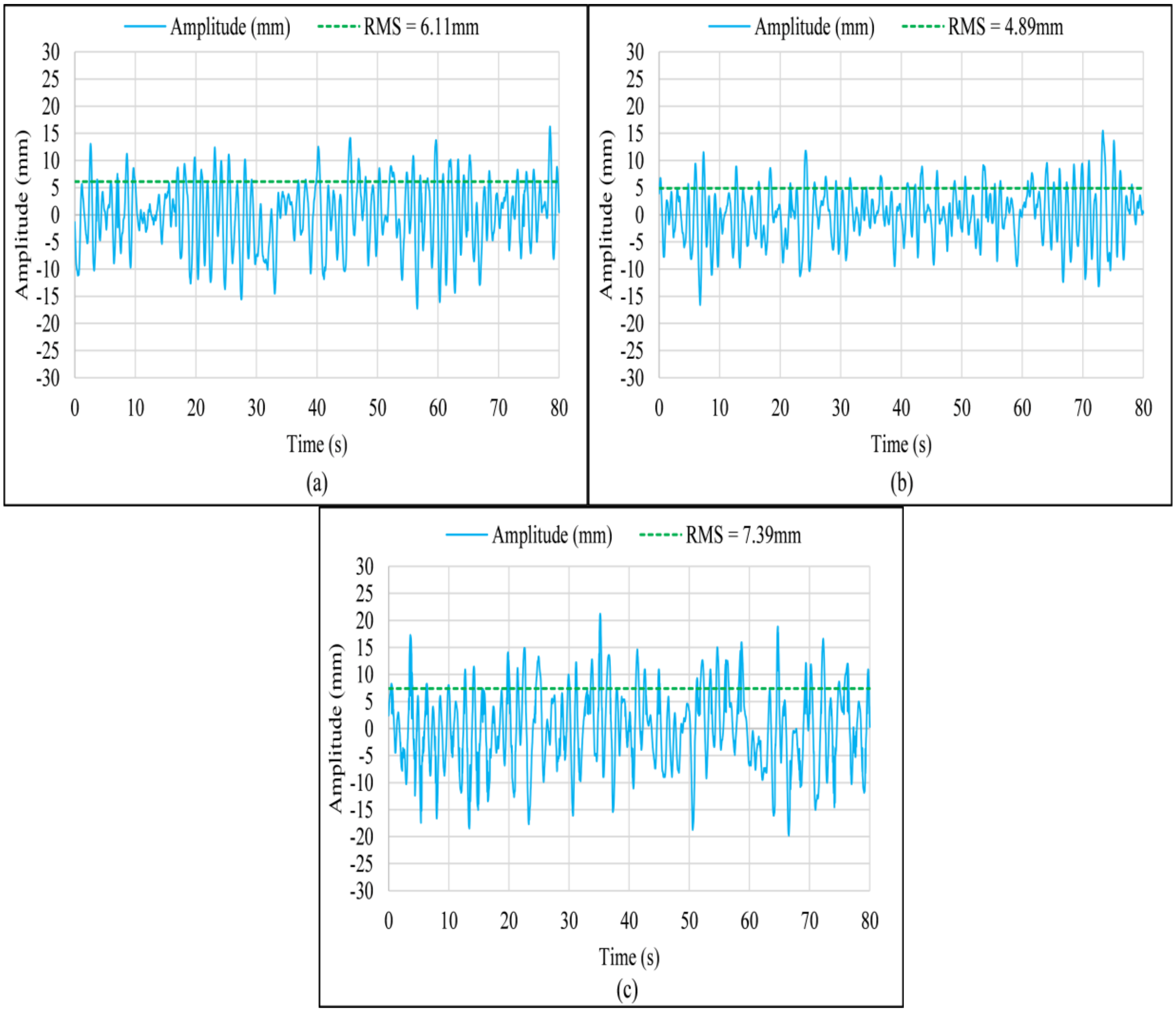

Figure 4. 4:The instantaneous amplitude time response of the flag's free end at the flow velocity of 0.15m/s (a) sc (b) b1 (c) b8.

Therefore, b1, b4, and b7 exhibit a minor leading in the dominant frequency over the simple cylinder (sc), but when comparing their strength (magnitude) in Figure 4.7, the magnitude and therefore the intensity of the oscillations of sc are comparatively more severe than those of b1. Moreover, it should be noted that power is influenced by both frequency and vibration amplitude, with sc exhibiting a notable degree of lead over the bodies b1, b4, and b7. Therefore, it can be said that this difference is not very big. The greatest dominant frequencies of the bodies sc, b1, and b8 at a flow velocity of 0.15 m/s are shown in Figure 4.7.

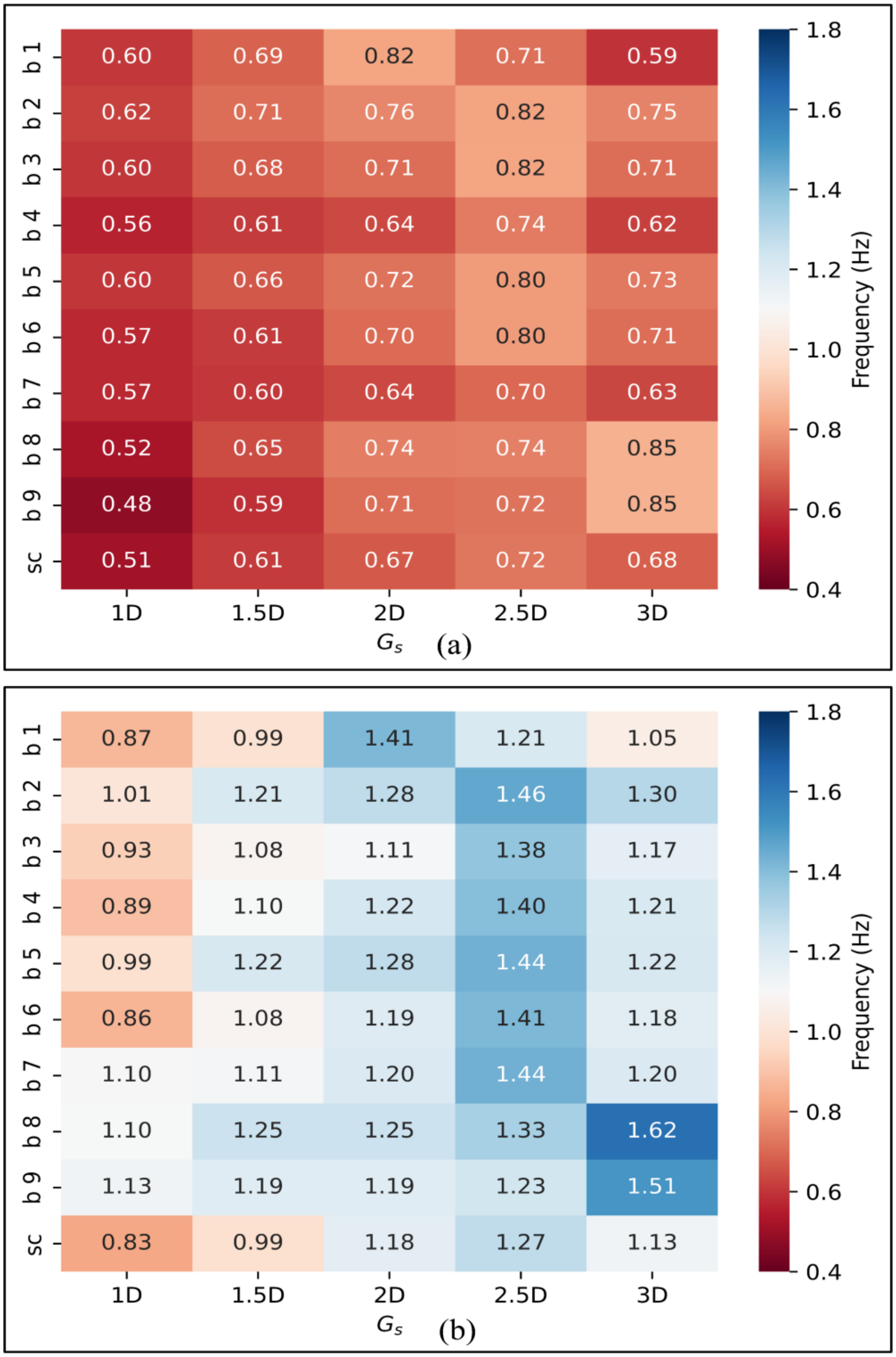

Figure 4.5:Comparison heatmaps showing the dominant flapping frequencies at (a) 0.15m/s (b) 0.30m/s.

4.1.2 At flow velocity of 0.30m/s

The power output exhibits a discernible slant as the fluid velocity increases from 0.15 m/s to 0.30 m/s. Nearly every feature of the bodies' general behavior is identical to that of Figure 4.1(a), which was previously examined. Once again, Figure 4.1(b) shows that although the bodies (b2, b3, b5, b6, b8, and b9) are obviously more efficient than the basic cylinder (sc), the bodies (b1, b4, and b7) are trailing behind in the generation of power. The four column bodies (b2, b5, and b8) in the most efficient arrangement have the maximum power output at b8, which is 22.10μW, or almost 41% more than that of the basic one (sc). On the other hand, the body (b1) has shown an approximately 11% power decrease at a flow rate of 0.30 m/s. In most situations, the optimal streamwise gap ranges in $2D \leq Gs \leq 3D$ are almost identical to those shown in Figure 4.1(a). When comparing Figure 4.2 instantaneous voltage response to Figure 4.7, it is evident that both the voltage fluctuations and the RMS values have increased.

The higher flow velocity causes the amplitude to length ratios seen in Figure 4.3(b) to rise. This validates the higher power output at a speed of 0.30m/s. The A/L ratio of the b8 is around 13% higher than that of the sc. However, b1 has shown a 20% decrease in the A/L in comparison to the sc. As can be seen in Figure 4.3(b), the general trend of the A/L ratios matches the power outputs that validate the ideal streamwise range of $2D \leq Gs \leq 3D$. Figure 4.8 displays the instantaneous amplitude-time responses of the bodies sc, b1, and b8 at a flow rate of 0.30 m/s. The corresponding amplitude of the non-periodic oscillations of the flag in the wake of each body is shown by the RMS, which is obtained.

As shown in Figure 4.5 (a), the oscillations or flapping of the flag are closely correlated with the flow speed. As the flow speed rises, so does the frequency of the flaps. Figure 4.5 (b) displays the same behavioral tendency as Figure 4.5 (a). Figure 4.9 displays the flag's dominating flapping frequencies at a speed of 0.30 m/s.

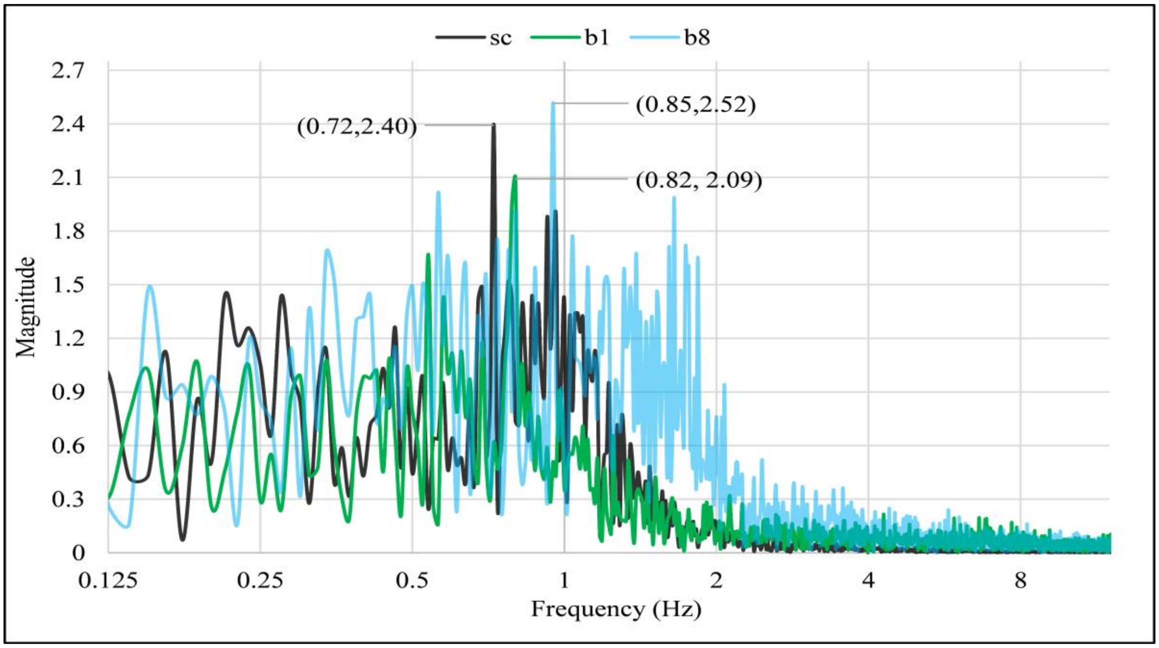

Figure 4.6:Dominant flapping frequencies of the flag at the flow velocity of 0.15m/s.

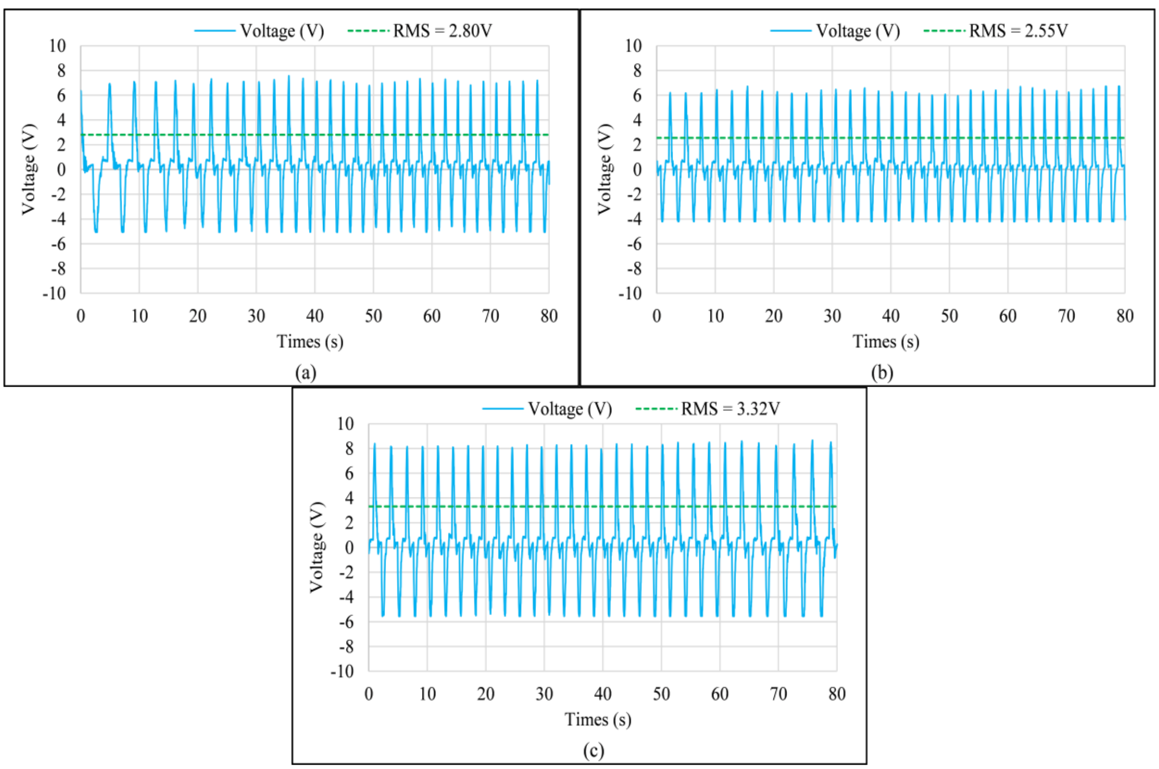

Figure 4.7:The instantaneous voltage response of the flag at the velocity of 0.30m/s (a) sc (b) b1 (c) b8.

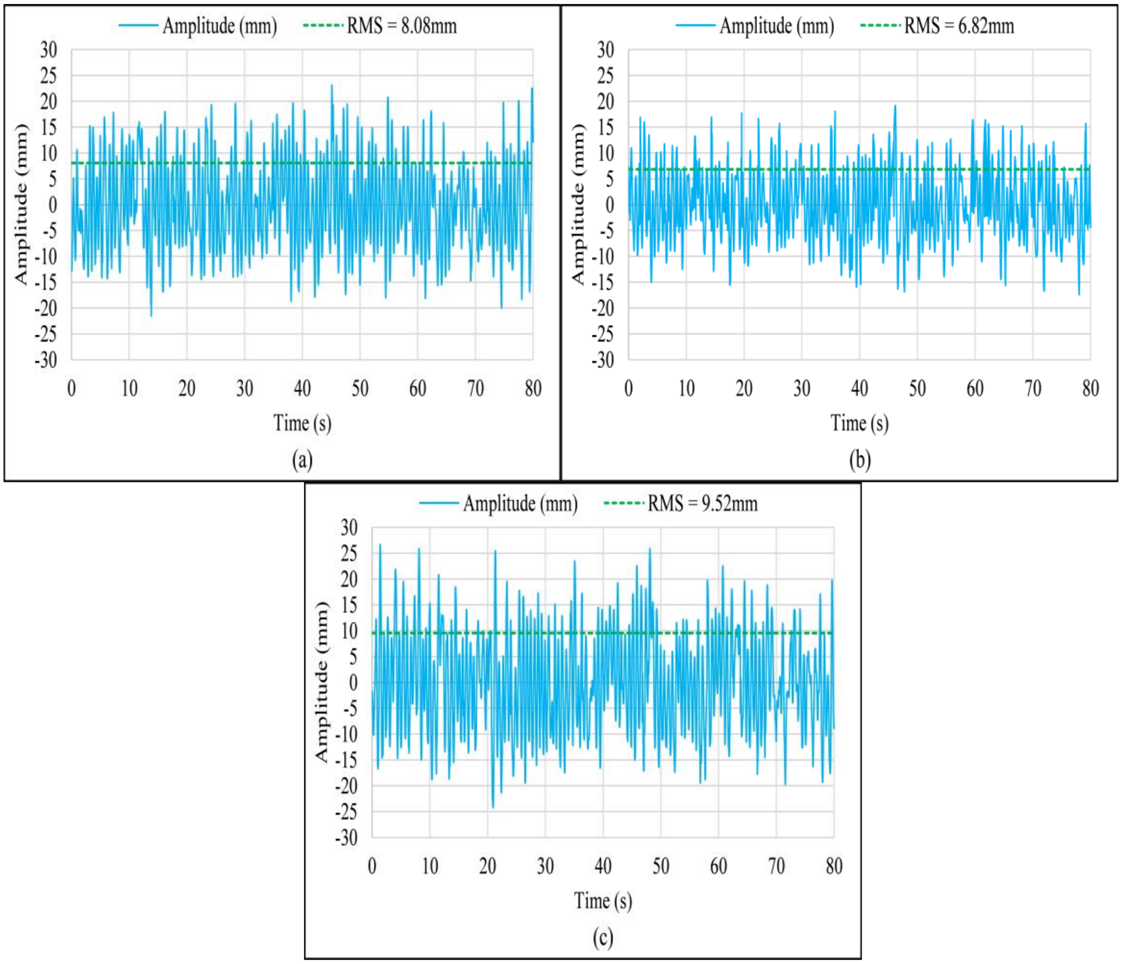

Figure 4.8:Instantaneous amplitude time response of the flag's free end at the flow velocity of 0.30m/s (a) sc (b) b1 (c) b8.

4.2 PIV outcomes

The method extracts information on the wake regime dynamics by visualizing the vorticities in the wake of the bluff bodies. The concept of the displacements created by the fluid particles during time intervals governs this approach [34]. A laser beam is directed in the wake, precisely at the center of the protrusions, and several seed particles (MV-H1020) are injected into the tunnel's water (place of interest).

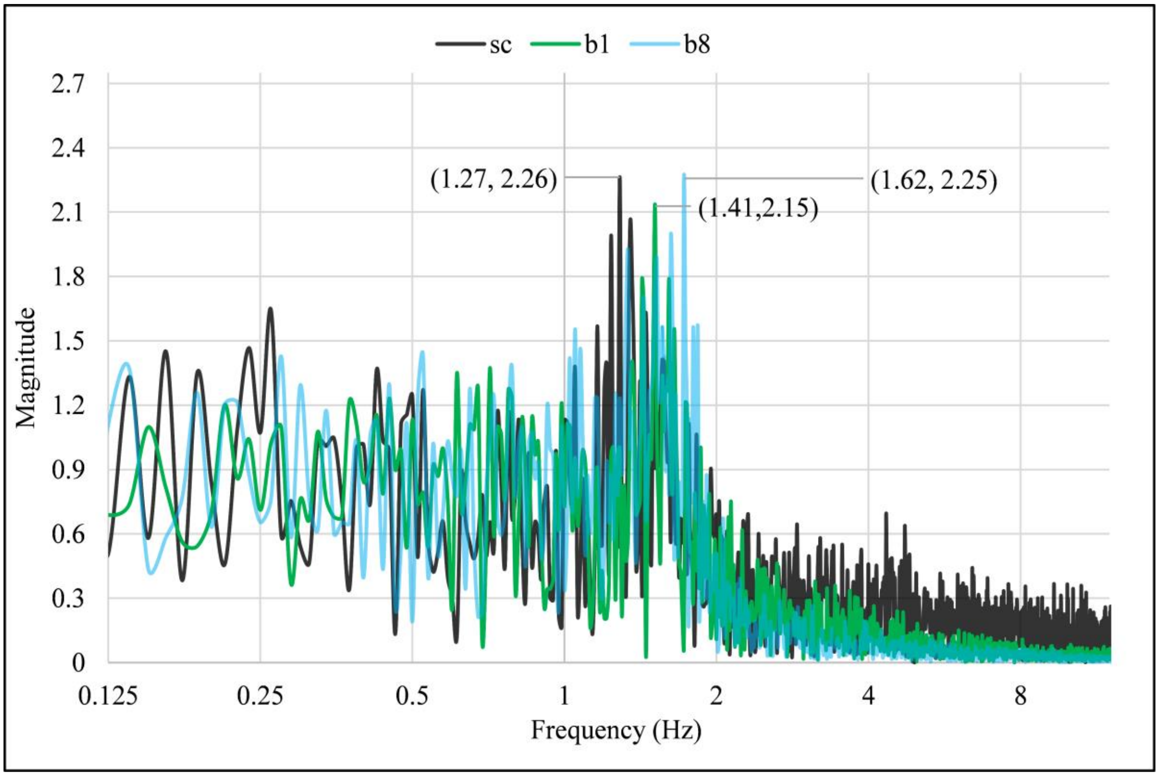

Figure 4.9:Dominant flapping frequencies of the flag at flow velocity of 0.30m/s.

The camera positioned directly underneath the test area records the wake's horizontal cross-section. After that, the data is analyzed using the analysis and visualization program Tecplot 360. The kinetic energy of a vortex is determined by its size, length, wake width (ww), saddle point (S), vortex formation length (Lr), and strength. The PIV gives many dynamics of the wake but the most relevant are the vorticity and the velocities of the fluid particles depicted through the tracer particles that are injected into the flow. PIV Technology supposes the fluid particles behave in the same way as the tracer particles, since it can only capture the velocities of the tracer particles. Therefore, the tracer particles behavior in the fluid flow is crucial. Figure 4.10 shows the PIV setup.

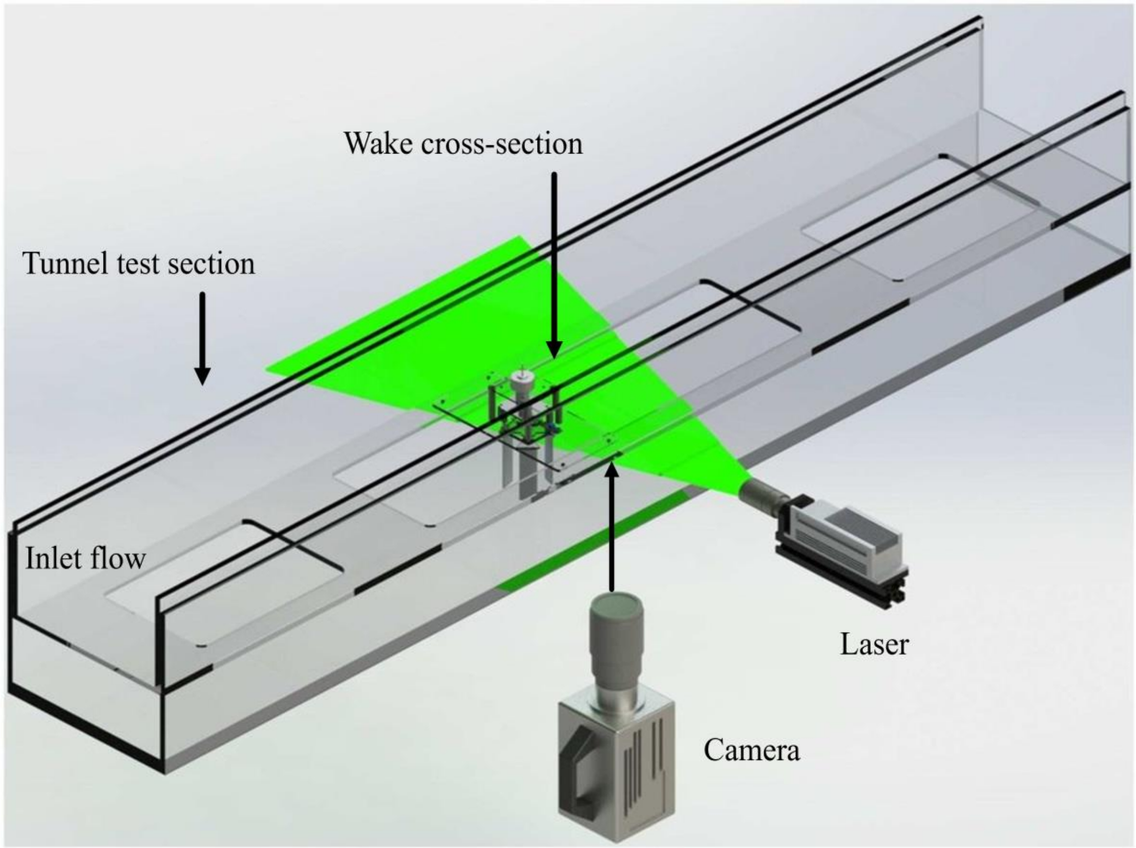

Figure 4.10:The schematic of a PIV setup.

4.2.1 At flow velocity of 0.15m/s

Figure 4.11 presents the strengths of the vorticity contours and its properties in extreme instances. It reveals that the most efficient contour is part (c), which corresponds to the arrangement of four columns (b 8) and has a protrusion diameter of 13mm.The primary indicator of the degree of the vorticity and, therefore, the amount of kinetic energy present in the wake is the wake width (ww). The wake width increases with increasing energy. The body b8 has a wake width of 1.4D at 0.15m/s, which is almost 22% stronger than the simple cylinder (sc), which has a wake width of approximately 1.15D. In contrast, the body b1 has a wake width that is roughly 13% less than the sc's. The percentage gain or loss in power and the % change in wake width are summarized in Figure 4.13. The saddle point (S) in the wake where the most energy is present is indicated by the critical value of the Lr. This configuration is the most efficient for transferring energy to the flag because it maximizes the wake width (ww) and the length of the vortex formation (Lr or S) for the four columns (b 2, b 5, and b 8). The second effective configuration is achieved by the 5 columns (b 3, b 6, and b 9) as they closely resemble the 4 columns in practically all characteristics. Considering how the three column configurations (b1, b4, and c1) behave, it is evident that the wake vorticities lag the basic cylinder (sc). The vorticities of the body (b7) and the simple cylinder (sc) are almost identical. Thus, it can be said that in the situation of three columns, enlarging the protrusion may improve the vortex generation. The separation of the border layer that occurs sooner as the size grows is the most evident cause of the 3-column behavior. Observing that although the boundary layer separates for the five column bodies (b3, b6, and b9) a little sooner than for the four column bodies (b2, b5, and b8), they are trailing behind. The dissipation of kinetic energy caused by the fluid particles' frequent contact with the bluffs is the typical reason for this mismatch. The discrepancy hence can be considered as influential due to the facts stated above.

Figure 4.12 vorticities are clearly stronger than Figure 4.11, confirming the rising power gain with increasing flow rate. Figure 4.12 exhibits comparable wake patterns to Figure 4.11 at a greater speed of 0.30 m/s, as mentioned earlier. Everybody exhibits a uniform kind of output behavior; only the wake characteristics' magnitude varies. The body b8 exhibits the maximum vorticity strength when its wake width (ww) compared to the simple cylinder (sc) increases by around 29%. Figure 4.12 vorticities are clearly stronger than Figure 4.11, confirming the rising power gain with increasing flow rate. Figure 4.12 exhibits comparable wake patterns to Figure 4.11 at a greater speed of 0.30 m/s, as mentioned earlier. Everybody exhibits a uniform kind of output behavior; only the wake characteristics' magnitude varies. The body b8 exhibits the maximum vorticity strength when its wake width (ww) compared to the simple cylinder (sc) increases by around 29%.

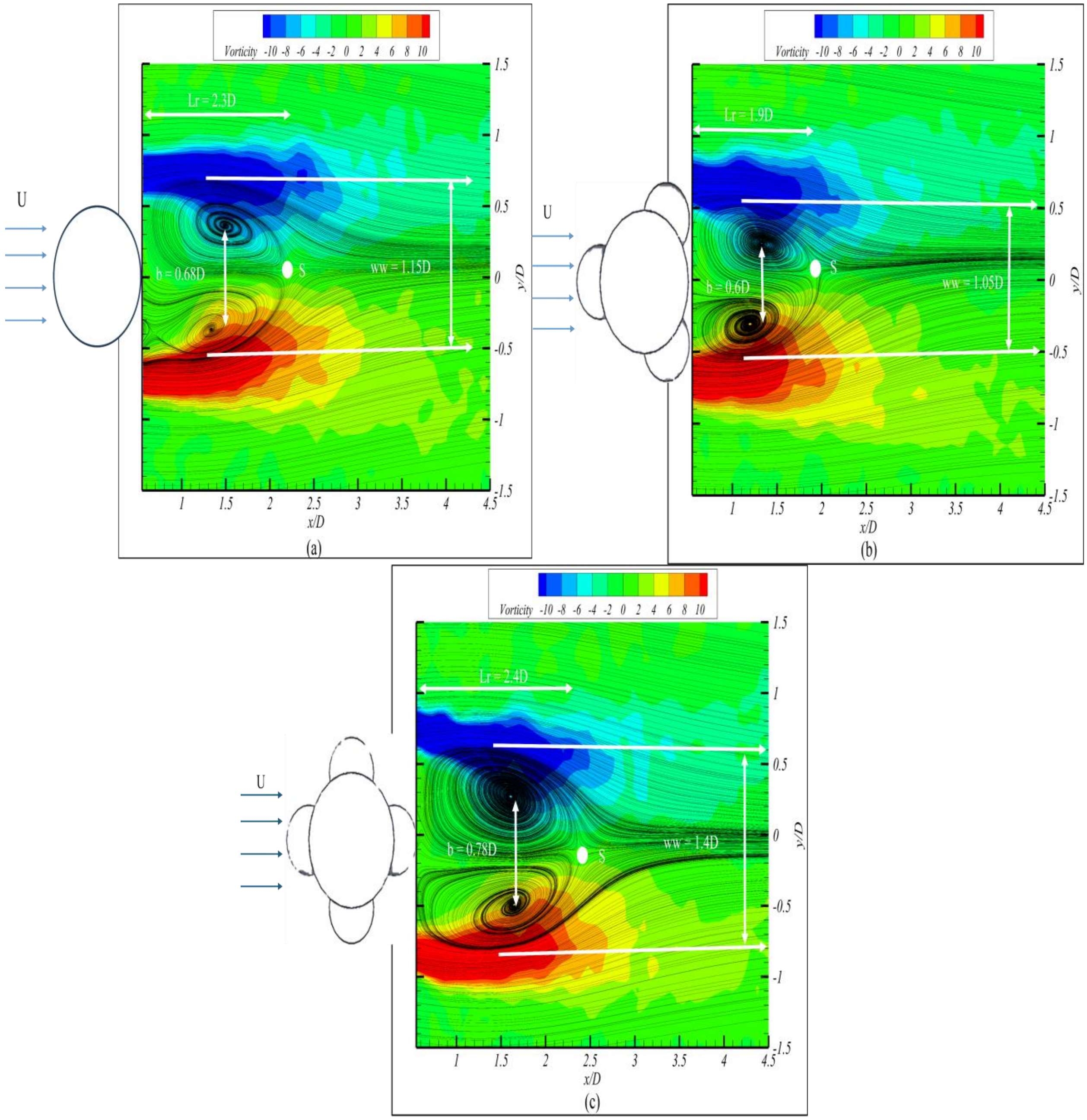

Figure 4.11:Vorticity contours of the bluff bodies at the flow velocity of 0.15m/s (a) sc (b) b1 (c) b8.

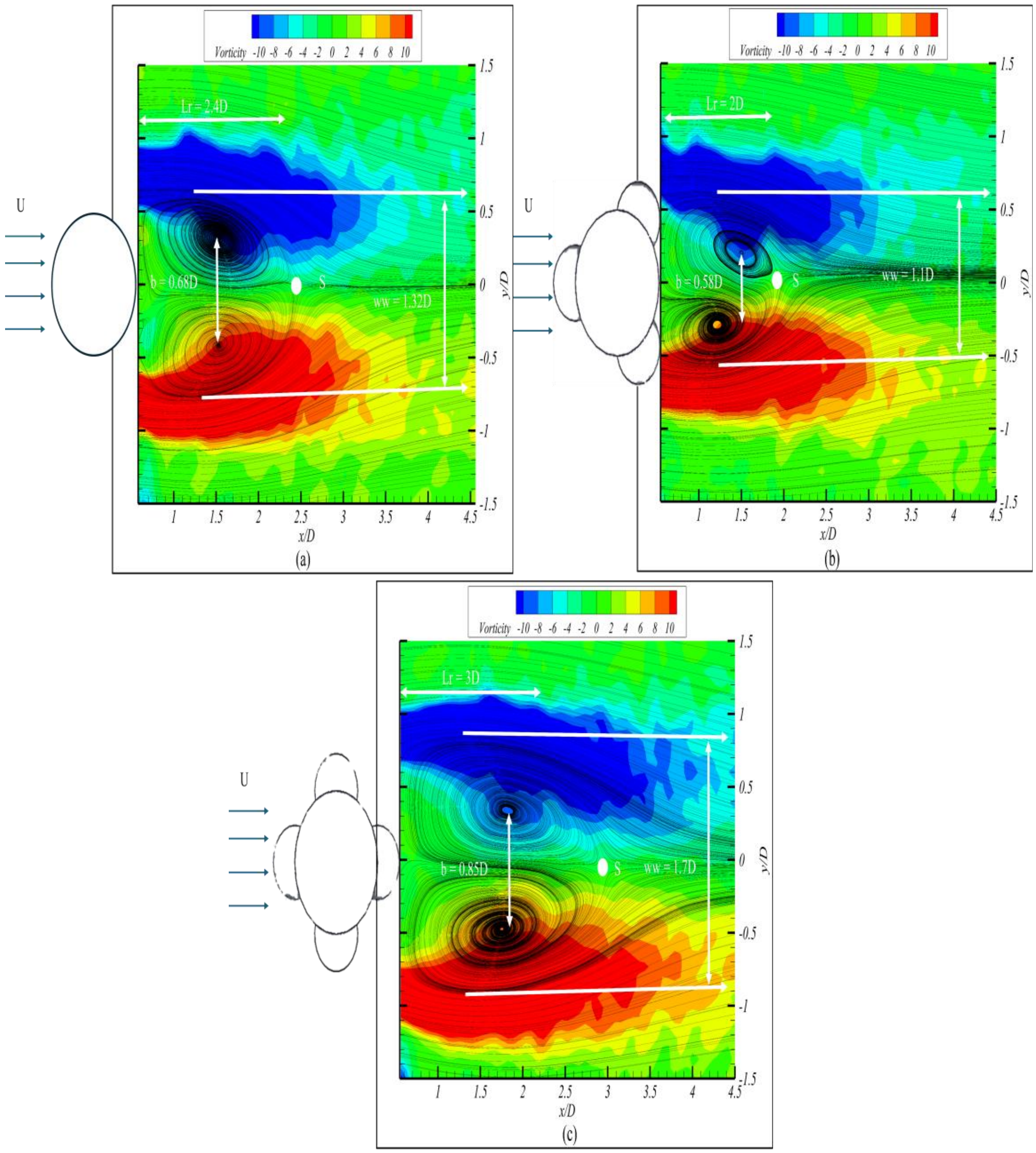

Figure 4.12:Vorticity contours of the bluff bodies at the flow velocity of 0.30m/s (a) sc (b) b1 (c) b8.

The wake width and the saddle points are the two key parameters in the PIV outcomes that reveal the strength, and the point of the highest kinetic energy possessed by the vortices in the wake respectively. The strength is depicted by the red to dark blue transitions in the vorticity contours. The Lr is the recirculation length of the vortices just behind the bluff body. The saddle point can be shown along the horizontal axis pointing to the maximum energy region in the wake and is depicted in each figure for each case. The power percentage change and the wake width percentage change almost having an agreement confirming the flow characteristics and the power findings during the experimentations. The PIV has been performed for all the bluff bodies under the flow velocities of 0.15m/s and 0.30m/s. The contours of the vorticities are depicted in Figure 4.14 of the bluff bodies containing their specific characteristics.

The characteristics include the wake width (ww), recirculation length (Lr), the saddle point (S), the core center to core center distance (b), and the length of the horizontal distance along the stream from the surface of the bluff body to the center of the vortex core (a) for each body are depicted. The most important parameters are the wake width and the saddle point that shows the strength of the vortex and the point of the greatest kinetic energy in the wake region. The greater the wake width of the vortex the greater the energy it possesses. The saddle points confirming the most efficient streamwise length where the greatest of the energy can be transferred to the flexible piezoelectric flag. A broad streamwise range ($2D \leq Gs \leq 3D$) is depicted from the vorticities of the bluff bodies that also align with the power outcomes at these gaps. The amplitude to length ratios as well as the frequency spectrum is also almost in strong agreement with the PIV findings. Hence the study is worth enough for its applications in various systems, like the effectiveness of the bodies can be deployed in providing powering to the sensors and signaling systems of the naval navigations, deep sea explorations, automobiles sensors and actuators, aerospace deployment, and structural health monitoring systems.

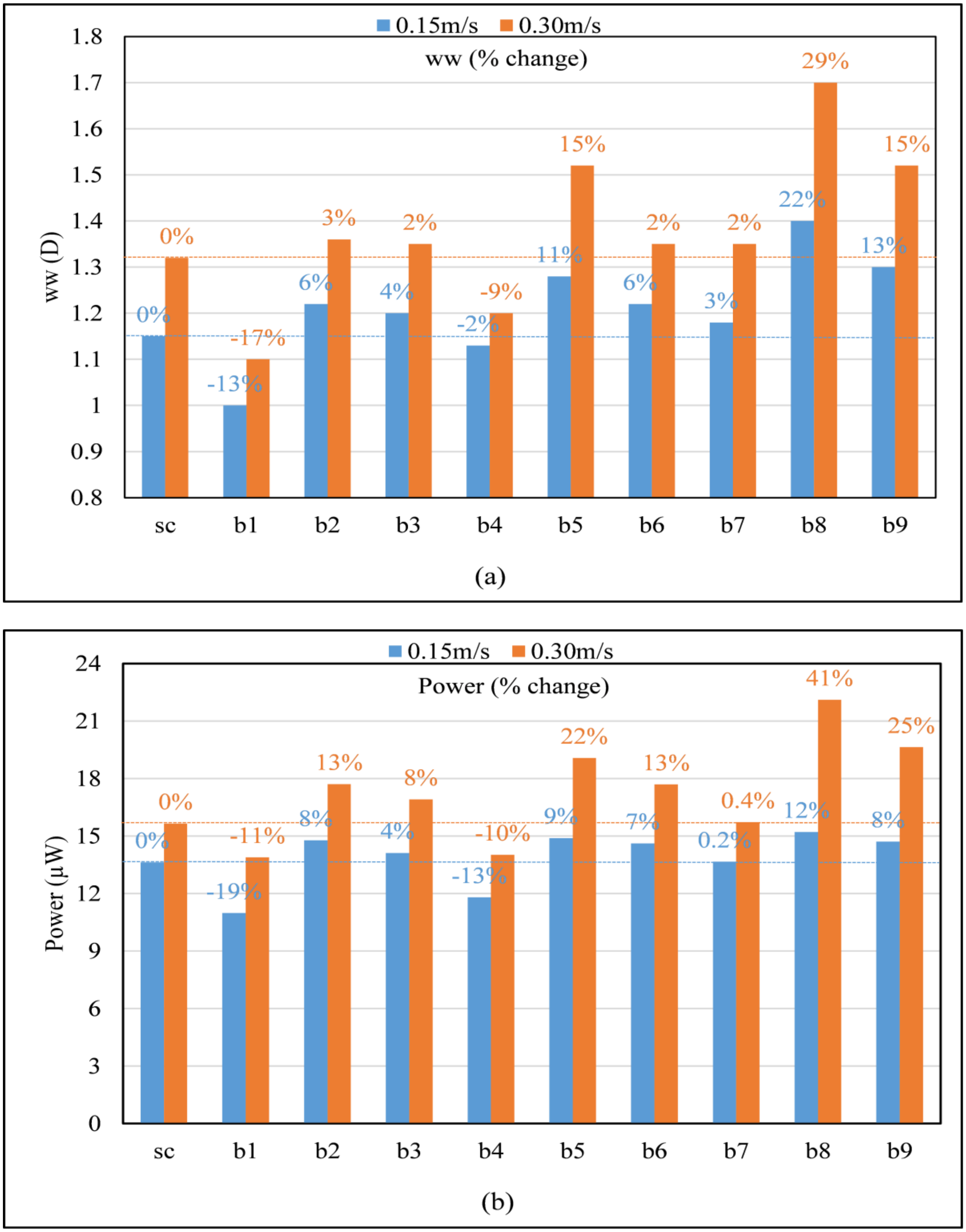

Figure 4.13: Percentage change (a) wake width (ww) (b) maximum power, with simple cylinder (sc).

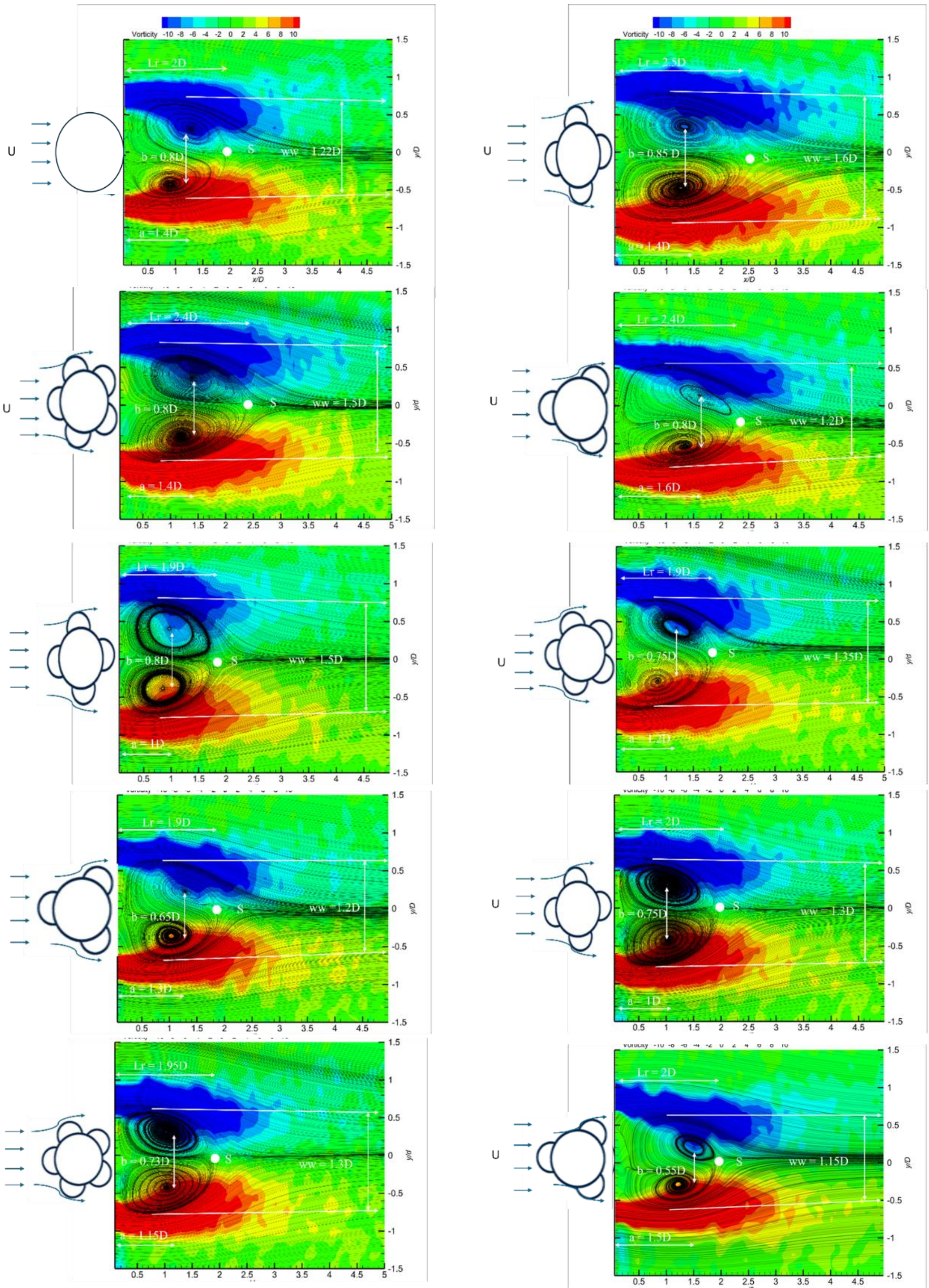

Figure 4.14:The vorticity contours of the PIV of the bluff bodies.

CHAPTER 5: CONCLUSION

The focus of the study is based on the effectiveness of energy harvesting in the wake of geometrically modified cylinders. The hemispherical protrusions have been wrapped over the cylinders because of the lack of specific literature on the proposed bodies in this study. The modified bodies are compared with a simple cylinder and evaluated based on their performance in power gain, amplitude response, frequency spectrums, and the PIV vortex dynamics. The overall behavior of the bodies shows that increasing the diameter of the protrusions the power output increases. The velocity has shown a remarkable gain in the power gain when jumps from 0.15m/s to 0.30m/s. This shows that in this range of velocity the power increases with increase in the velocity. The bodies with 4 column configurations have shown a dominance response in power gain up to about 41% greater power generation than that of the simple cylinder. The highest power gain corresponds to the b8 that has four columns and has the largest diameter (13mm) of protrusion. The second most effective configuration is that of the 5 columns with about 25% increase in the power outcome compared to the simple cylinder. Again, the body corresponds to the 25% gain in power is having 5 columns with the largest diameter (13mm) of the protrusion. The study showed that the 3 column configurations are lagging in the power output compared to the simple cylinder and this behavior is evident from the power output figures, the amplitude responses, the frequency spectrums, and from the PIV vorticity contours. The reason for the power efficiency in the 4 columns is the early boundary layer separation. The boundary layer in 5 columns also separates at the earliest but their lesser efficiency is attributed to the repeated interactions of the fluid with the protrusions, therefore dissipating some kinetic energy. The boundary layer separates later in the 3 columns bodies and that's why they are producing the least severe vortex shedding consequently a lower power generation. This attribute of the 3 column configurations can be utilized in applications where vibration suppression is required, like in high-rise buildings, aircraft, automobiles, and underwater submerged bodies. On the other hand, the 4 and 5 column bodies can enhance the energy gain in applications like the power required for the sensors and electronic systems in the deep-sea explorations and long duration missions. Moreover, they can be deployed in aerospace, autonomous automobiles, and industry 4.0 and onwards. This study also agreed to the most effective streamwise zone (2D $\leq$ Gs$\leq$ 3D) for the energy harvesting depicted in literature. Noting that this study only explored the energy harvesting effectiveness of the three different diameters of the protrusions arranged in 3,4, and 5 columns in orientations that in each configuration the flow strikes the front protrusion at 0° angle of attack. Further insight can be done by altering the angle of attack or the size of the protrusions. Some spiral arrangements of the protrusions over the surface of the cylinders need to be examined for the effects on the vortex dynamics and hence on the energy performance.

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