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Review

Hydrokinetic Turbine Blades: Pioneering Materials for Renewable Energy

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ABSTRACT

Hydro-kinetic technology is a way to get energy from water. It uses the energy of moving water without hurting the environment as hydro-static power does. One of the things about Hydro-kinetic technology is that it is good for the environment. It protects the homes of fish and other animals that live in the water. Hydro-kinetic technology also uses projects that can be built in many places especially in areas where we need to be careful about the environment. The hydrokinetic technology works well if the turbine blades are designed correctly. These blades need to be strong and last a time. They also need to be good at getting energy from the water. The blades have to deal with a lot of forces like the water pushing against them and the spinning motion of the turbine.

To make it better we need to find materials for the turbine blades. These materials need to be strong a long time and not cost too much. We are looking at using materials like carbon fiber and glass fiber. These materials are strong. Can withstand being in the water. We are also looking at materials that are inspired by nature. These materials can make the blades last longer and work better. We want to use materials that can change and adapt to the water conditions. We also want to use materials that're good for the environment and can be recycled.

This review study looks at all problems that affect turbine performance. It shows that we need plans for choosing the right materials and taking care of them to make turbines last longer and work better. The study ends by talking about how to make energy better through improved turbine blade design picking the right materials, for turbine blades and making sure they work as well as possible.

Keyword: *Hydro kinetic, delamination, Turbine materials, Blade Design, Turbine blade*.

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1. INTRODUCTION

Hydro-kinetic technology uses the energy of moving water like rivers and ocean waves to make electricity. This is good because we do not need to build dams or special pools of water. Hydro-kinetic technology works well in places where we cannot use ways to make energy from water. We really need to find ways to make energy that do not hurt the earth. Hydro-kinetic technology is special because it can make energy in many different situations. It is especially useful in places where the land or the environment makes it hard to use ways to make energy from water. Hydro-kinetic technology can provide energy in these situations (1). The good things about HK technology are not about making power. It also helps to not hurt the environment it keeps the homes of fish and other animals in the water safe. It keeps the natural beauty of the land by using the waters own flow. This makes HK technology a better choice for the earth than style hydroelectric plants, which can really hurt the environment by changing the way the water flows and building dams. HK projects are often smaller. Can be put together in different ways, which makes it easier to use them in many different places like in areas that are far away, from cities or that do not have power lines (2). The turbine blade is an important part of this technology as you can see in Fig. 1 and Fig. 2. The turbine blade is the key to making this technology work well. It is what makes the energy collection process effective and efficient. The turbine blade is special because it is designed to work with the water that is flowing. It catches the energy of the flowing water. Turns it into rotational energy. This is important because it lets the turbine make energy using a generator that is connected to the rotating parts. The turbine blade is a deal for HK technology. By changing the design and position of the turbine blades HK technology can get much energy, as possible from the water. This means HK technology can work well in water flow conditions and do a better job overall (3).

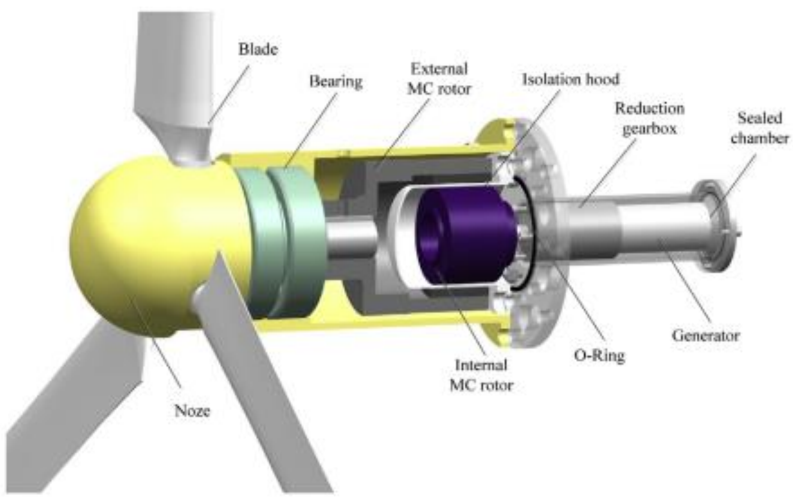


Figure 1. Hydrokinetic turbine profile (4)

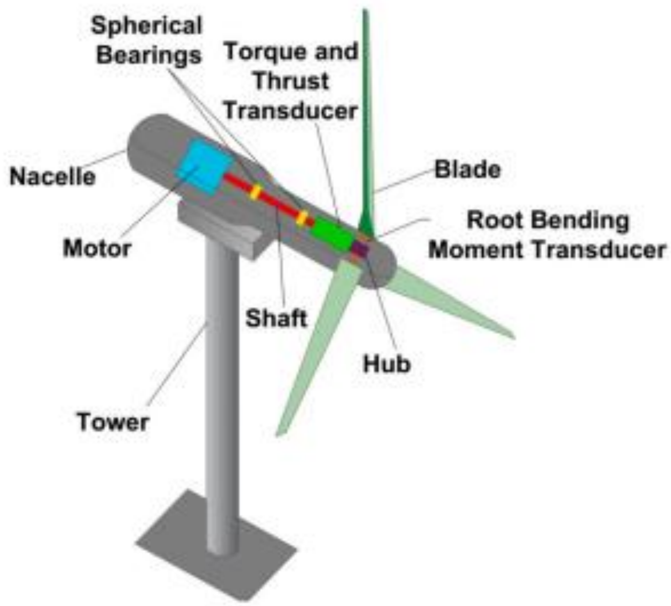


Figure 2. Hydrokinetic turbine model section (5)

The turbine blade is a cool thing that was built very carefully. It is a mix of new technology and old ideas about how water moves. The people who made it wanted to make sure the blades are strong enough to deal with kinds of forces. They also wanted to get much energy as possible from the moving water, which is important, for using energy from natural sources. To make sure the turbine works well and lasts a time the design needs to be just right. Not too weak and not too strong. The materials used to make the turbine blades are very important because these things are often put in places where the water's rough and hard to predict (6). In addition to being very strong and durable the materials chosen must also resist corrosion well. Keep their structure sound.

These traits are crucial for keeping the turbines working at their lasting long even in tough ocean conditions where temperature, salt levels and sediment can vary. The materials need to handle changes in temperature, salinity levels and interactions with sediment, which can be tough on them. The turbines are put in an environment so they must be made to last. Corrosion resistance and structural integrity are key to making sure the turbines keep working overtime. The right materials will help the turbines perform well and last long, in these conditions (7). We take a look at many materials that are good for making hydrokinetic turbine blades. Every material is carefully checked for what makes it special what is good about it and if it can really handle the conditions found in water. The hydrokinetic turbine blades are very important because the materials used to make them have an impact on how well the turbines work. The materials used for the turbine blades can make them last longer and work better. We want to know how the materials used for the turbine blades affect the performance of the turbine designs. The hydrokinetic turbine blades need to be made with materials that can handle the conditions found in aquatic habitats. This study of hydrokinetic turbine blades is important to understand how to make them better. The materials used for the turbine blades are very important, for the overall performance of the turbines (8).

The discussion also looks at the forces that affect hydrokinetic turbine blades when they are working. Hydrokinetic turbine blades have to deal with forces like forces from spinning around. They also have lift which helps them get energy from water. Then there is drag that works against the blades moving. Other stresses on the blades can happen when they are working. We need to understand these forces to see how hydrokinetic turbine blades work and how long they last. This helps us make designs for hydrokinetic turbine blades so they do not break easily and work better overall. Understanding these forces is important, for turbine blades (9). This work is going to help the field of energy by using what we know about materials and how forces work. We think this will make turbine blades better which will help us get energy from water. By studying energy, we hope to make sustainable energy better and make sure it works well with water systems. This will also help hydrokinetic technology get better over time. Hydrokinetic turbines are affected by the forces of water and the environment so we need to understand these forces and how they affect the blades. This is important because it can affect how well the turbines work how efficient they are and how long they last. We are talking about energy and hydrokinetic turbines and we want to make sure we understand the forces that affect hydrokinetic turbines (10). When we are talking about turbines, in water we need to make sure they work well. Hydrokinetic turbines are important because they can turn the energy of water currents into electricity that we can use. To make sure hydrokinetic turbines work properly in water we have to choose the materials and design them carefully. Hydrokinetic turbines need to be able to handle water flow and other things in the water like temperature changes and living things growing on them. This is very important for turbines to work well (11). The composite materials that were studied can handle these loads. Composite materials are made of different things so they can make turbine blades strong and not too heavy. This means the blades can keep their shape when they are under a lot of stress. Composite materials are really good for turbine blades that are used in water because they keep working for a long time. For people who make these turbines picking the composite materials can also mean they do not have to spend as much money to keep them running and they can use less fuel. The composite materials are a choice because they make the turbine blades dependable and they work well. The composite materials help the turbine blades last longer. This is important, for people who use them in the water (12). Delamination is a concern for hydrokinetic turbine blades. It can cause them to break down over time. When delamination happens, it can reduce how well the turbine blades work. Even cause them to fail. This is because of things like bonds between layers of material or just wearing out from being used all the time. Delamination can also make the turbine blades weaker and less able to handle stress. To prevent delamination, we need to understand how the materials stick together and what kinds of stresses they will face over time. The goal is to make sure the turbine blades can last long and keep working under operational pressures. Delamination can be bad, for turbine blades so we have to take steps to prevent it. By understanding the bonding mechanisms and loads on materials we can reduce the risk of delamination. This will help guarantee the long-term endurance and structural integrity of turbine blades (5).

Well, another issue that can really lower turbine efficiency and effectiveness is fouling. This is when unwanted stuff builds up on the blade surface. Algae and barnacles are examples of things that can stick to the blades. This increases. Decreases the turbine's ability to capture energy from water currents. A comprehensive plan is needed to address both delamination and fouling problems. This includes looking into surface treatments and coatings that can make the blades more durable and prevent growth. To get the performance in real-world settings we need to fully understand and deal with these mechanical and environmental stresses. This ensures the functional integrity of hydrokinetic turbine blades, which is crucial for their operation. We have to consider the turbine blades and their performance to make sure they work well. The hydrokinetic turbine blades need to be able to withstand the stresses. So understanding and handling these stresses is key, to performance (13). This article looks at turbines and some big problems they have. For example, things, like fouling and delamination can really hurt how well they work and how long they last. The article says it is very important to choose the materials and take good care of these turbines. It also talks about the problems that happen when we use materials to make hydrokinetic turbine blades. These materials have some limitations. For instance, they can deteriorate quickly because of the environment. They also have trouble withstanding fatigue. It is hard to make them strong and flexible at the same time. Hydrokinetic turbines have a lot of performance issues because of these limitations. The article highlights the importance of turbines and the need to solve these problems to make them work better. Hydrokinetic turbines need to be made with the materials and taken care of properly to make sure they last a long time and work well (5).

To make sure that turbines a long time and work well we need to find a good balance. Using materials that are made from different parts has some good things about it like it makes the turbine lighter it does not corrode easily and we can design it in many different ways. We have to think carefully about these good things. There are also some things about using these materials like they can break apart they can get damaged by the environment and they are hard to make. These problems can really affect how hydrokinetic turbines work over time. When we talk about picking materials we need to think about choosing ones that're strong and can handle different situations like changing water forces and environmental conditions. Hydrokinetic turbines need to be able to handle these things to work properly. We also need to think about things, like how strong the material's how flexible it is and how well it can handle being used a lot. If we think about all these things hydrokinetic turbines will work better (14). By looking at these factors, the study highlights some current challenges. These challenges include difficulties in making materials and how well they last in the environment. The study also suggests that using these materials in hydrokinetic turbine blades could be very promising. This makes it more important to keep researching and developing ways to make renewable energy applications more sustainable, efficient and reliable. If we carefully study these topics, we might find materials and designs. These could greatly improve how hydrokinetic energy systems work making them a better source of clean and sustainable energy. Improving energy systems is important for a sustainable future with composite materials playing a key role. The use of materials in hydrokinetic energy systems could make them more efficient. Hydrokinetic energy systems have a lot of potential, as an energy source.

Hydropower (Hydrokinetic)

Since hydrokinetic (HK) technologies generate power directly from the kinetic energy of flowing water rather than potential energy differences, they are considered "zero-head" renewable energy sources, much like wind energy systems. These devices can be placed in freely flowing rivers or streams without requiring major alterations to the riverbed. As a result, HK power generation avoids many of the challenges associated with conventional hydropower, including the requirement for a sufficient usable head and significant civil works (15). Although hydrokinetic systems were among the first forms of hydropower, their development can be divided into multiple eras. A number of hydrokinetic development projects involving wave energy systems, river currents, and ocean currents are currently at an advanced technological stage. Tidal energy systems have garnered far more attention in hydrokinetic technology research and development than devices used to harness river or ocean current flows. Generally speaking, installations in rivers are more frequent than those in tidal or offshore regions. One of the biggest issues facing ocean current technology developers is developing reliable and affordable mooring devices for deep-water applications (16,17). Among the characteristics that influence a fluid's energy potential are its density, interaction surface area, and flow velocity. However, the production of useable power is limited by the efficiency of fluid-dynamic mechanisms and associated mechatronic systems. Non-turbine alternatives are being looked into more and more in ongoing research, even though turbines are now the most proven and efficient method of harvesting this energy (18). The geometry of hydrokinetic turbine blades has a major impact on how well they convert fluid energy into useable power. Studies show that blades with a parabolic shape outperform alternative types. The torque arm extends from the rotational axis to the respective lift and pressure centers as a result of the advancing blade coming into contact with an area of enhanced pressure drag, which improves performance. The number and shape of a hydrokinetic turbine's blades have a significant impact on its stability, efficiency, and overall energy generation. In small-scale horizontal models, there is a high correlation between the number of blades and performance measures like torque, thrust coefficient, and power coefficient. Additional important factors include susceptibility to fatigue loading and the ways in which pitch angle, thickness, and blade curvature affect conversion efficiency. Because of its simple construction, hydrokinetic turbines can operate without the requirement for reservoirs or spillways. Installation and maintenance are less expensive because to their ease of deployment and manufacturing, as well as their relatively small environmental impact. As a result, they are particularly suitable for usage in remote or off-grid areas (19). Fig.3 illustrates the basic operation of a hydrokinetic turbine.

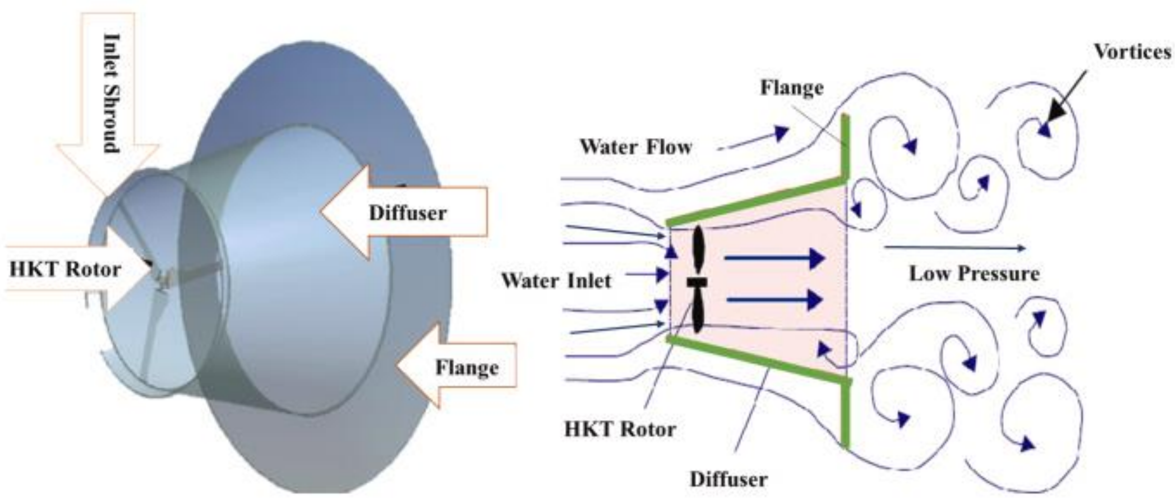


Figure 3 Overview of a hydrokinetic turbine (18)

1. Factors Affecting Hydrokinetic Turbine Blade Performance

As the demand for renewable energy sources continues to rise globally, hydrokinetic energy has garnered considerable attention. Utilizing the kinetic energy of flowing water, hydrokinetic turbines can have a significant influence on the environment while producing electricity. These turbines can use the flowing water in rivers, tides, and ocean currents to produce electricity. However, these turbines' overall performance is significantly impacted by the design and state of the blades they use, which are subject to a wide range of operating conditions. We need to know how flow rates and turbulence and maintenance affect the blades to get the energy, from hydrokinetic sources. These are some things that affect how well the hydrokinetic turbine blades work:

- flow rates
- turbulence
- maintenance

The hydrokinetic turbine blades are very important. So, we have to think about flow rates, turbulence, and maintenance to make the hydrokinetic turbine blades work better. This will help us get energy from the hydrokinetic sources using the hydrokinetic turbine blades.

3.1 Cavitation

In the field of hydrokinetic turbine design hydrokinetic turbine design is an important area and cavitation is a big problem that we have to deal with. It is a problem that's both hard to solve and a chance for us to be creative. As we need renewable energy sources it is more important than ever to understand what cavitation is and how it works so that we can make hydrokinetic turbine blades last longer and work better. So, what is cavitation? It happens when the pressure of a fluid, like water gets lower than its vapor pressure. When this happens the water starts to form bubbles or empty spaces that are filled with vapor. These bubbles might seem harmless at first. They can actually cause a lot of damage. For example, if we look at the pictures in Fig 4 and Fig 5 we can see that cavitation creates bubble structures that do not last long. They burst violently when they move from an area with low pressure to an area with high pressure. When they burst they create shock waves that can be very bad for the surfaces around them, like the turbine blades (20).

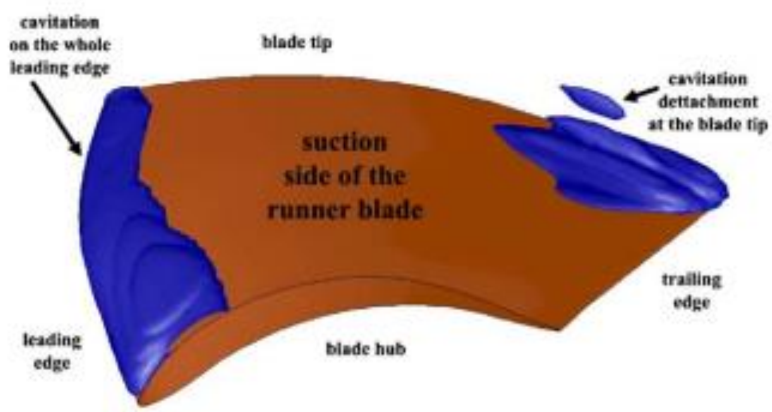


Figure 4. HK in high cavitation operation (21)

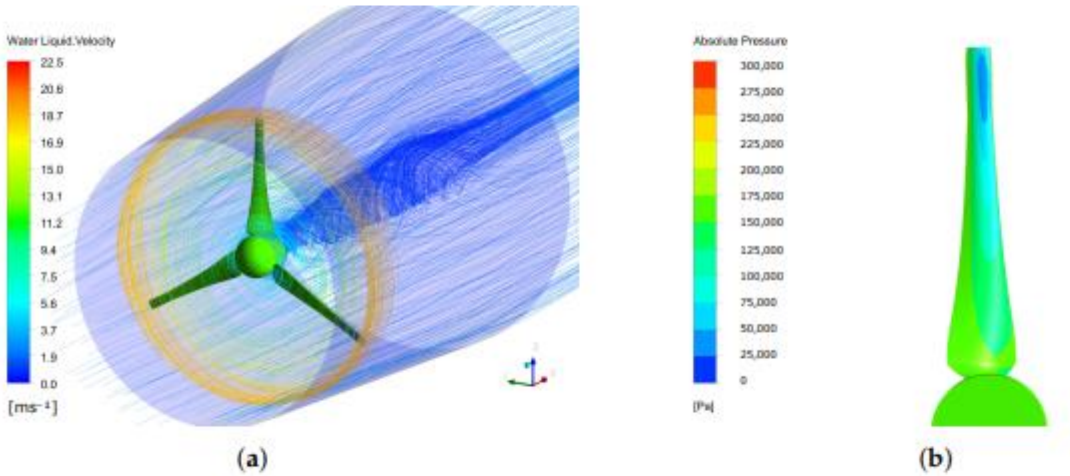


Figure 5. Streamlines colored by velocity magnitude and pressure contour in corrected blades surfaces. (a) Pressure side. (b) Suction side (22).

Cavitation is a deal. When bubbles burst they make shock waves that can hurt the surfaces of the blades over time like you can see in Fig 6. This can affect how well the blades work with water and how strong they are. If the blades get damaged the whole hydrokinetic system will not work well. This means it will not make much power it will cost more to fix and it will not be as efficient. So engineers and designers who make these systems have to think about cavitation when they are designing them to make sure they work perfectly (21).

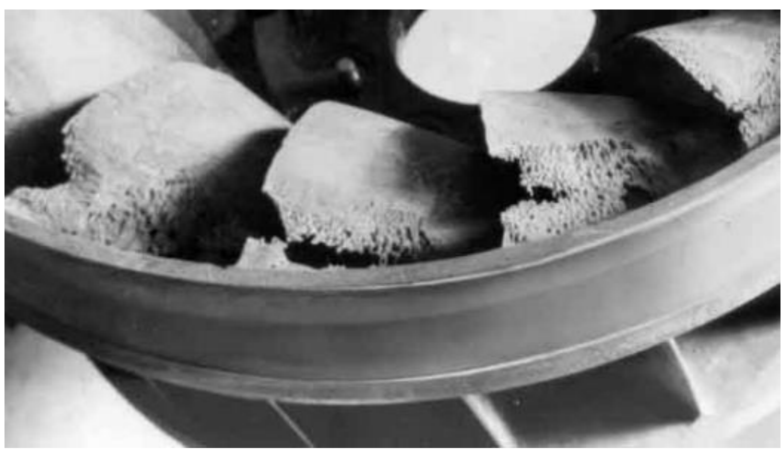


Figure 6. Cavitation damage at the discharge side of the HK turbine blade (23)

The first step to reducing the effects of cavitation is to understand how water moves around turbine blades. The shape of the turbine blades is very important to stop cavitation from happening. We need to make sure the blades can handle changes, in pressure without getting damaged by cavitation. This means we have to change the shape of the hydrofoil profiles to stop pressure from dropping much and causing cavitation. The materials we use to make the turbine blades are also very important. These materials must be strong and able to withstand the damage that cavitation can cause. We can use coatings, treated metals and advanced materials to make the blades last longer and work well even when cavitation is happening. This will help the turbine blades to keep working. Turbine blades are a part of this and we need to make sure they can handle cavitation (24).

Combating cavitation is something that can be helped by design strategies. For example, we can use materials or change the angles of the blades. This can reduce the stress on the blades when they are working hard. The blades can react to the water flowing around them. This can help. These new developments can make the turbines last longer. Reduce the risk of cavitation. Another thing that people are working on is using computers to understand how cavitation works. They want to know what happens when the water is flowing in ways. This can help designers make decisions about where to put the blades and how to design them. They can use simulations to see where cavitation might happen. Cavitation is a problem that needs to be solved. We need to make sure that the blades on the turbines are working well and that they are reliable. To do this we need to deal with cavitation. We can reduce the effects of cavitation by using new techniques choosing the right materials and designing the blades in a special way. As we try to get power from water we need to overcome problems like cavitation. This is important for the future of energy. We want to make sure that we can use water to make power in a way. Cavitation is something that we need to combat to make this happen. Combating cavitation will help us make the most of water's potential for power generation.

3.2 Biofouling

The efficiency and effectiveness of technologies like turbines are really important as renewable energy sources become more popular. Biofouling is one of the factors that can hurt turbine performance. This problem can reduce turbine efficiency. Lead to costly maintenance and operational issues. Biofouling is when microorganisms like bacteria, algae, and small sea creatures build up on surfaces that're underwater. When these organisms attach to wind turbine blades they can change how the blades move through the water, making it harder for them to work. This makes the turbines have to work which reduces their overall efficiency. As a result, operators see energy being produced and more operating costs, which is not good for an industry trying to provide sustainable energy solutions using hydrokinetic turbines. The hydrokinetic turbines are supposed to help us have energy but problems, like biofouling can get in the way. So, finding ways to deal with biofouling on turbines is crucial. It will help keep the turbines working and making clean energy (25). A representation of the main characteristics of the marine biofouling process is shown in Fig. 7.

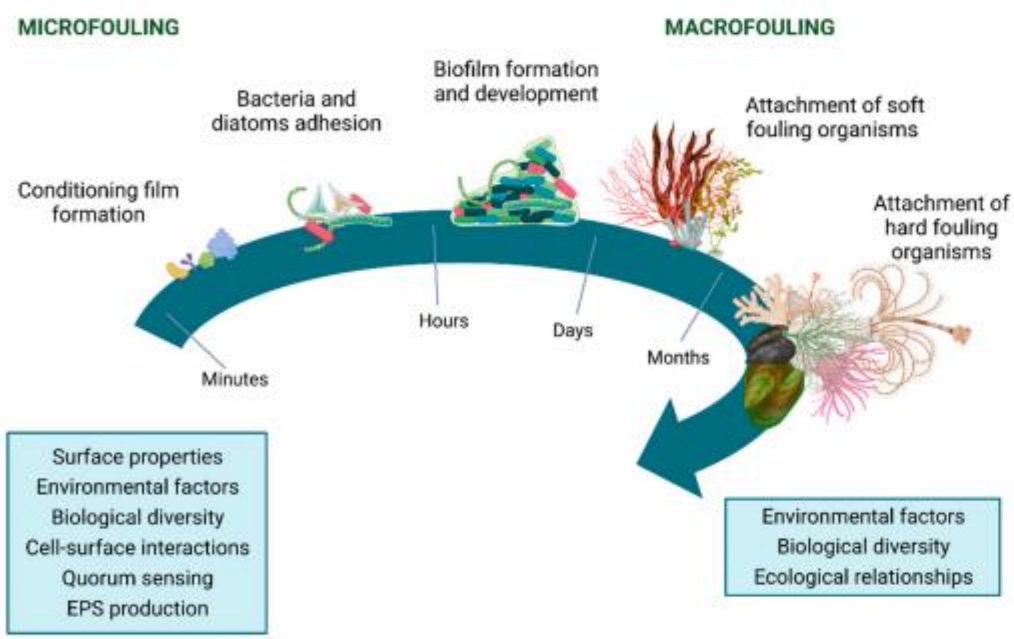
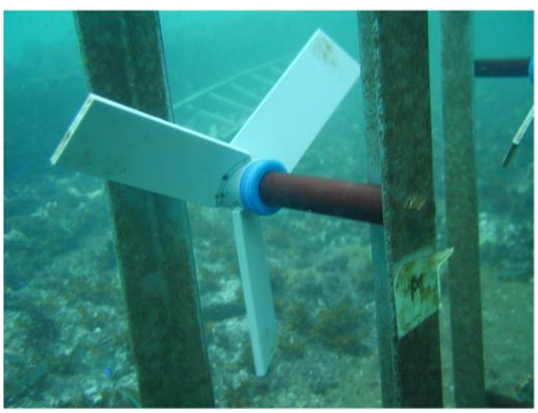


Figure 7. An illustration of the primary parameters of the marine biofouling process (26)

As shown in Fig.8, biofouling can have an impact on turbine component longevity in addition to performance. The accumulation of organic material may eventually cause structural difficulties, necessitating more frequent replacements or repairs. These situations have an impact on HK energy production's financial sustainability as well as its environmental advantages. Therefore, taking proactive measures to address this situation is imperative. Turbine operators and designers are increasingly using creative techniques to fight biofouling.



a)

b)

Figure 8. a) Biofouling inceptions, and b) Highly impacting Biofouling (27)

Using preventative coatings or materials made to withstand biological development is one efficient strategy. By making the surface less attractive to fouling organisms, these specialty coatings can reduce the likelihood of performance declines. There are a variety of anti-fouling solutions available, from slick surfaces to biocidal coatings that prevent organism establishment. Another essential element in the battle against biofouling is regular maintenance programs. Turbine blades can be kept free of bacterial buildup with routine cleaning and inspections. To keep blades effective and performing at their best, maintenance teams may use a variety of methods, such as mechanical cleaning or specific cleaning solutions. In addition to reducing biofouling, preventive maintenance increases the longevity of turbine parts. Additionally, a bright future for turbine efficiency is provided by continuing studies into biofouling and its mitigation. New materials and technologies that can lessen the effects of biofouling are being investigated by businesses and researchers. For turbines, for example, bio-inspired designs that resemble naturally occurring surfaces that are known to withstand fouling could be created, providing an additional line of defense against this problem (26). The techniques for preventing and controlling the consequences of marine biofouling is illustrates in Fig.9.

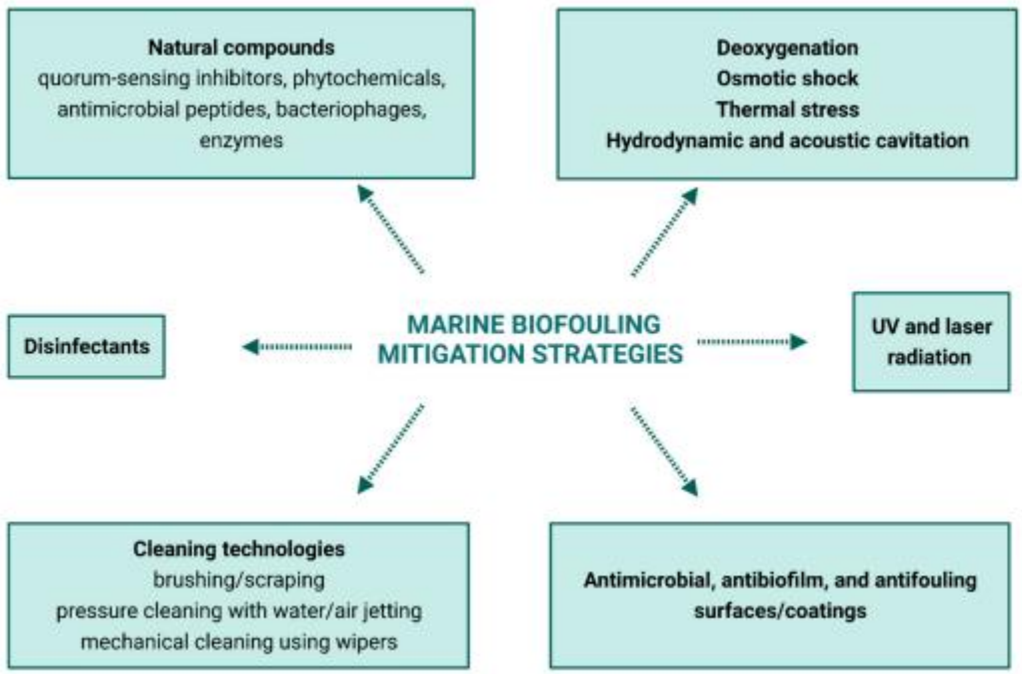


Figure 9. techniques for preventing and controlling the consequences of marine biofouling (26).

Turbine blades have a problem that affects how well they work and that is biofouling. Biofouling is an issue because it affects how long turbine blades last and how well they work. Operators can do a few things to make biofouling not affect turbine blades as much. They can use coatings on turbine blades and they have to make sure they do maintenance on them a lot. The people who make turbines need to think about ways to stop biofouling because it is a big deal. As people learn more about biofouling, they will come up with ways to deal with it. Turbines are very important for energy. Stopping biofouling helps turbines work better. This is important because it helps us get to our goal of making energy in a way that's good for the earth. If we can make turbines work better, we can have a future that's better, for the earth and where we use energy in a smarter way. Turbine blades and turbines are a part of this.

3.3 Erosion

Erosion is something that happens naturally. It is when things like wind or water wear away at a surface. This can be a problem for engineers who are building things that will be near water. When the water is moving it can pick up dirt and other things that can hurt the materials. So, engineers need to understand what erosion is and how to stop it from being a problem. When water moves over a surface it can start to wear it. This is because the water can pick up things like sand or rocks and they can hit the surface and wear it down. This can happen to lots of things like pipes or big machines that use water. It can even happen to bridges or dams.

If the surface of these things gets worn away, they might not work well. This can be a problem if it is not taken care of. It can make the machines work well or even break completely. Engineers need to think about erosion when they are building things so they can make sure they will last a time. Erosion is a deal, for engineers because it can affect how well things work. Erosion can hurt the materials. Make them not last as long (28). Fig 10 shows what happens to the surface of turbines when they break down. This study looks at how the material gets worse and how the water flows around it which is important to know if we want these turbines to last a time. We can use computational fluid dynamics to model what happens in situations and sees how it affects the turbines. The results show that it is very important to choose the material and design the turbines in a way that helps them last longer. When the water flows around the turbines in a way it can cause a lot of damage. This information helps us make hydrokinetic energy systems more sustainable. It also helps us make the turbines work better. Hydrokinetic turbines are very important. This study helps us understand how to make them better. The study of turbines and how they break down is crucial, to making the last longer.

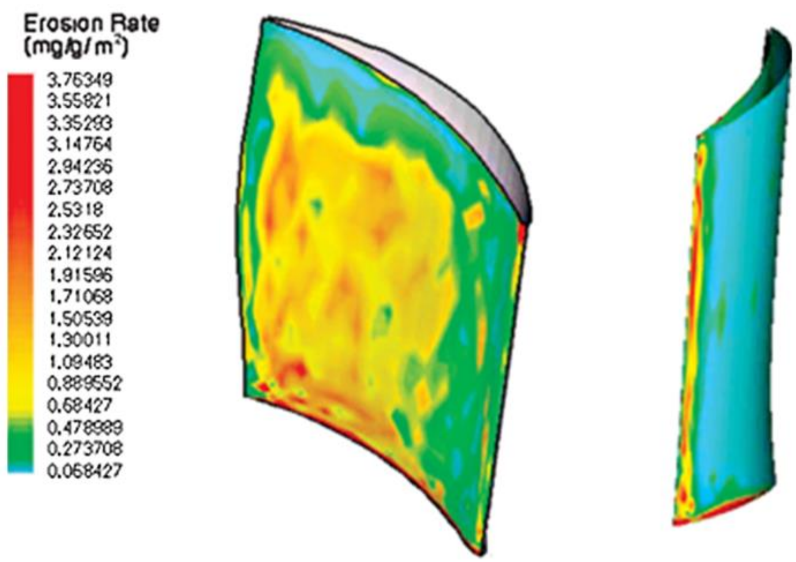


Figure 10. Analysis of surface erosion in hydrokinetic turbines using computational fluid dynamics.

The erosion of parts gets worse over time and that’s a big problem. For example, even a tiny bit of damage to the blades in turbines can make them much less efficient. This means they cost more to run and fix. Erosion in pipelines is also a problem it can make them break and leak which can be really dangerous. Engineers are trying to make materials that're better at resisting erosion. Recently there have been some improvements in material science. These improvements have led to ways to deal with erosion. Engineers are looking into composite materials. These materials are made by combining materials that each have good qualities. They are better than materials at dealing with the forces that cause erosion. This is because they are stronger and more flexible. Another way to protect materials is with coatings. These coatings can be made from polymer materials. They create a barrier that protects the material from erosion. Scientists are also looking into "materials. These materials can change their properties in response to their environment. For example, they might change when they get hot or cold. This can provide protection against erosion. Engineers are using technologies like surface engineering and nanotechnology. They want to create solutions that not resist erosion but also make structural components last longer. They are trying to make materials that can withstand erosion and a long time. Erosion is a problem but with new materials and technologies engineers think they can make it better. Engineers are working on materials that resist erosion and longer. Erosion resistance is key, to making things last (29).

Even though it’s really hard to control erosion in made-made materials there are some solutions coming out because of ongoing research into new and improved material technologies. Engineers can make parts that're stronger and more reliable even in tough conditions by picking the right materials and using smart ways to prevent erosion. How it affects how well materials work is still a big focus as we try to do more with engineering. The fight against erosion can make buildings and structures stronger. Work better in lots of different industries because of new and better materials and coatings. Companies that focus on researching and developing these technologies will make sure their parts last a time. They will also help make engineering processes that're safer and better for the environment, in the future.

3.4 Corrosion

Hydrokinetic turbines are a way to get renewable energy from flowing water. These turbines often work in tough conditions. This can cause problems like corrosion that can hurt how long they last. How well they work. To make hydrokinetic turbines last a long time and work well we need to understand how corrosion happens and find good ways to stop it. The kind of water they are in is a reason why hydrokinetic turbines corrode. The water is different in places. Things like temperature how salty the water is, pH levels and minerals in the water can all make corrosion happen faster. Animals that live in the water can also cause problems. When algae, barnacles and other sea creatures stick to the turbine it is called biofouling. It can make corrosion worse. Hydrokinetic turbines are important, for energy so we need to deal with corrosion and biofouling to keep them working (30). Fig. 11 shows the corrosion profile of the HK turbine. This profile gives details about the type and level of corrosion that has formed over time. The corrosion patterns can help us understand what is causing the damage. The data in this figure points out areas that may need maintenance or further study. By looking at the corrosion profile engineers can make plans to prevent damage and make the turbine last longer. These detailed evaluations are crucial, for ensuring that turbines work reliably and efficiently in environments.

Figure 11 Corrosion profile of HK turbine

Turbine blade corrosion is a problem. The kind of material used to make turbine blades is a factor. Even though turbine blades are very strong the metal they are made of can still get damaged over time. For example, when steel turbine blades are in seawater they can. Become weaker. The same thing happens to aluminum turbine blades when they are in types of water. They can get pits in them. This is a problem because aluminum is usually a choice for turbine blades since it is strong and lightweight. Because of these problems engineers need to find ways to stop turbine blade corrosion. One good way to do this is to use materials that can withstand corrosion. For instance, stainless steel is a choice than regular steel when it comes to turbine blades that will be in seawater. This is because turbine blade corrosion is less likely to happen with steel. Another option is to create alloys that are designed for use in water. These alloys can be used to make turbine blades that will last longer and work better. Turbine blades made with these materials can perform well even in challenging aquatic environments. Using the materials, for turbine blades is important to prevent turbine blade corrosion (31).

Applying sacrificial coatings is another tactic. By corroding themselves first, these coatings the turbine blades can be protected by a coating that shields the underlying metal and maintains the blades structural integrity. This method helps to lower the costs of running the turbine by making the blades last longer and reducing the need for maintenance. Zinc-based compounds are a choice for protecting against corrosion especially in maritime applications because they work really well. It is also important to have a maintenance and inspection plan in place to keep an eye on the state of the turbine's components. By doing inspections you can find out if there are any signs of wear or corrosion and take action before any serious damage is done. There are testing methods that can be used to check the condition of the metal components without damaging them which helps to make sure they will last a long time. Hydrokinetic turbines could be made resilient with new technologies that prevent corrosion. Researchers are looking into materials and coatings such as polymer-based films and nanostructured coatings that can provide better protection, against corrosion. These new developments could completely change how turbine systems last and how they are designed, which would lead to better performance and efficiency when using renewable energy sources like hydrokinetic turbines (32,33).

Although corrosion is a problem for hydrokinetic turbines their operational life can be made much longer by understanding its causes and using effective materials and maintenance techniques. The renewable energy industry can ensure that hydrokinetic turbines keep being an efficient source of sustainable electricity for a long time by focusing on preventing corrosion. To overcome the issues in water environments we need to invest properly in materials, research and regular maintenance procedures. Corrosion issues in turbines must be addressed to make them last longer. By doing hydrokinetic turbines can continue to provide clean energy. Preventing corrosion in these systems is crucial for their longevity and efficiency. The renewable energy sector must prioritize corrosion prevention to ensure hydrokinetic turbines remain effective. Investing in the materials and maintenance can help achieve this goal.

3.5 Structural Loading Strains

Hydrokinetic turbines are a way to get energy from moving water. This is a deal, in the world of renewable energy, which is always changing. The way these turbines are made and how well they work are really important if we want to use them to make energy from water. We need renewable energy sources so we have to make sure these turbines are designed just right. When engineers design the blades for turbines they have to think about the forces that the water puts on them which can cause a lot of strain on the structure. Hydrokinetic turbines are a part of this and hydrokinetic turbine blades have to be strong enough to handle these forces (34). The forces that act on materials when they are exposed to forces are called structural loading strains. When we talk about turbines the main source of these forces is the dynamic contact between the blade surfaces and the water that is flowing. Hydrokinetic turbines have turbine blades that can be severely strained by loads. These variable loads are caused by changes in the rate at which the water flows and the turbulence of the water.

The forces that act on the blades can be very strong when the water velocity is high. If these forces are not taken into consideration the turbine blades may fail. The change in the circumstances in which the turbine blades are loaded is an important issue when designing hydrokinetic turbines. The performance of the turbine blades can be affected by things, including the change in the rate at which the water flows at different times of the year. Other things that can affect the performance of the turbine blades include disruptions to the environment and the patterns of turbulence, in the water. If these things are not well understood and are not included in the design of the turbines the blades may fail completely. This can be very bad because it can require repairs and the turbine will not be able to produce energy for a long time. The energy output of the turbines will be decreased. Hydrokinetic turbines are affected by these issues. The design of turbines is very important. Hydrokinetic turbines have to be designed to withstand the forces that act on them (35).

Engineers are depending more on computer methods to reduce hazards. In this situation computational fluid dynamics simulations are a tool that enables designers to predict how water will flow around the turbine blades. Computational fluid dynamics can assist in forecasting the forces that water will put on the turbine blades by examining how water interacts with the blade surfaces under circumstances. To make the turbine blades better designers need to understand how water flows around them. Finite element analysis, when used with fluid dynamics provides crucial information on how the turbine blades will react to different loads. Engineers can use finite element analysis to build models that show how the turbine blades will behave under stress conditions. By using data from fluid dynamics studies engineers can assess the performance of the turbine blades and find areas that might be weak. This method helps designers make turbine blades that can withstand the demands of operating situations. The combination of fluid dynamics and finite element analysis also makes hydrokinetic systems more efficient and the turbine blades last longer. Engineers can improve the design of the turbine blades to get the energy from water flows while keeping the turbine blades safe. Computational fluid dynamics and finite element analysis are important for designing turbine blades. Engineers need to understand the forces that water puts on the turbine blades to design them well. By using fluid dynamics and finite element analysis engineers can make hydrokinetic systems that are efficient and safe. To make hydrokinetic systems researchers and engineers need to understand how water flows around the turbine blades and how it affects them. They can use fluid dynamics and finite element analysis to forecast and improve the performance of the turbine blades. As the renewable energy sector grows it will be essential to make hydrokinetic systems that are safe and reliable and computational fluid dynamics and finite element analysis will play a big role in this. Hydrokinetic systems can contribute a lot to the energy landscape if they are designed well and computational fluid dynamics and finite element analysis are crucial, for this.

Material Selection

The proper materials must be selected for hydrokinetic energy systems to be efficient and long-lasting. In addition to withstanding continuous exposure to challenging maritime conditions, components must enable effective energy conversion. To do this, a strong resistance to seawater-induced corrosion is required. Options like stainless steel, aluminum alloys, and protective surface treatments are commonly employed to extend service life and maintain system dependability (36). The service life of hydrokinetic devices is directly correlated with the durability of the materials used to make them. For materials to endure the continuous loading from flowing water, they must have sufficient tensile strength and fatigue resistance. Another important consideration in the selection process is cost. Although the initial costs of complex materials are sometimes greater, thorough optimization and resource efficiency can reduce overall costs without sacrificing performance (37). Technical performance and environmental impact must be taken into account when choosing materials for sustainable hydrokinetic systems. Prioritizing eco-friendly or recyclable options lowers the total carbon footprint of these gadgets. Careful material selection not only increases corrosion resistance and durability but also balances cost and environmental considerations. By integrating these features, engineers may design hydrokinetic systems that promote long-term environmental sustainability and operate efficiently (38). The material properties of hydrokinetic turbine blades are currently poorly understood, which makes it challenging to select the appropriate materials, develop reliable design standards, and reduce overall installation and maintenance costs. For a material to be suitable for a specific turbine application, it must meet the functional and operational requirements of the component. The following are some significant factors that affect the choice of materials for hydrokinetic turbines:

- Life cycle cost (e.g. material cost, manufacturing cost, maintenance cost, and installation and removal costs).
- Chemical qualities (e.g. corrosion resistance);
- Required dimensional tolerances;
- Physical properties (e.g. density);
- To start reducing gravitational forces, minimal density is required.,
- The shape of the component;
- Mechanical qualities (e.g., strength, stiffness, hardness, fatigue strength, etc.);
- To keep optimal aerodynamic characteristics, high material stiffness has been required,
- To prevent permanent deformation, higher fatigue life is permitted.

These variables cannot be considered independently since they interact in complex ways to influence the turbine's overall performance. Important characteristics include weight, strength, stiffness, and corrosion resistance. They are especially crucial since mechanical properties have a significant impact on how a blade will respond to structural loading. The perfect material for hydrokinetic turbine blades must balance stiffness, strength, toughness, corrosion resistance, and fatigue life. Many viable materials are now accessible, each with special advantages for different parts of modern hydrokinetic turbine systems.

2. Hydrokinetic turbine blade materials

Hydrokinetic energy generation has become a very viable alternative to assist meet the world's energy needs as the need for sustainable energy sources grows. This cutting-edge technology converts the kinetic energy of flowing water into electrical energy that may be used. The development of materials for hydrokinetic turbine blades is very important, for making hydrokinetic systems work better and last longer. People have been using water to make energy for a time but hydrokinetic systems are still getting better. Hydrokinetic turbines are built to work in places, like rivers, tidal currents and seas where the water is always moving and can give us a steady supply of energy. Hydrokinetic turbines are a part of these systems and they need to be made with good materials so they can withstand the water and keep working well (39). Selecting the materials for the turbine blades is really important for the turbines to work at their best. The materials we pick have to be strong enough to handle pressures and keep their shape in different kinds of water. They also have to be able to withstand everything that can affect how well the blades work. When we use the materials for the turbine blades it helps the turbines last longer and work better which makes them a better choice, in the long run. Hydrokinetic technology and hydrokinetic technology can really help us make a power source, which is something we need as we look for cleaner ways to make energy with hydrokinetic technology (40). We can make energy generation even better by focusing on making better materials, for the turbine blades of hydrokinetic energy generation. This will help us protect the environment and get the energy we need. The number of materials used to make hydrokinetic turbine blades is shown in Fig 12.

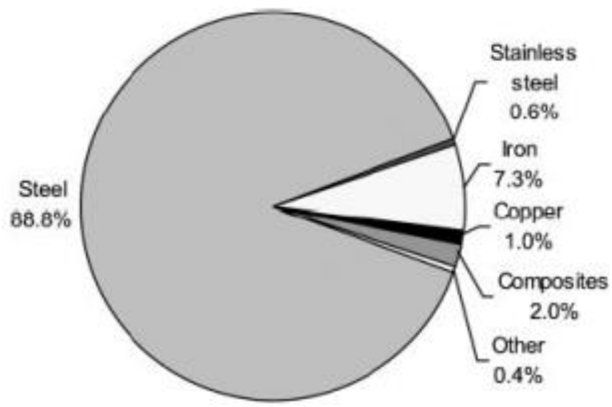


Figure 12. Percentage of various materials used to make hydrokinetic turbine blades(40)

5.1 Fiberglass Reinforced Plastics (FRP): FRP is one of the widely used materials for hydrokinetic turbine blades. The reason for this is that FRP is extremely light in weight, which makes it easy to handle and install. This is an advantage. FRP is also very strong. Can withstand the forces of flowing water. FRP is very good at resisting corrosion. This means it does not rust or break down when it is in the water. FRP is a material for hydrokinetic turbine blades because it is strong and resistant to corrosion. The fact that FRP is light in weight and resistant to corrosion makes it a popular choice, for turbine blades (41). The design freedom of Fiber Reinforced Polymer is another thing about it. This means that engineers can make the turbine blades in lots of ways. The blades can work better in the water because of these shapes, which helps them get more energy from the moving water. A blade with a shape can make more energy and that is very important for hydrokinetic turbines to work well. Fiber Reinforced Polymer is a material for turbine blades but there are some important things to think about. One of these things is how it affects the environment. Even though Fiber Reinforced Polymer is used in things it is made of parts that do not break down easily in nature. This means that when turbine blades get old it can be hard to get rid of them in a way that's good for the environment. Fiber Reinforced Polymer has good things about it for hydrokinetic turbine blades like being strong and light and not getting corroded. It is very important to think carefully about how it affects the environment and if it can be recycled. If we make choices, about the materials we use we can keep getting the benefits of clean energy and also protect the environment at the same time (41,42).

5.2 Carbon Fiber Composites: In the search for better ways to make renewable energy hydrokinetic turbines are becoming a popular choice. They use flowing water to create electricity, which makes them a good option for energy. To get the most out of these turbines and make them last longer the materials used for the blades are very important. Carbon fiber composites are a pick because they perform well especially in tough conditions where hydrokinetic turbines are used. Hydrokinetic turbines can work well in environments and carbon fiber composites help make them strong. The use of carbon fiber composites in turbines is a key factor, in their success. These turbines need to be durable and carbon fiber composites help achieve that. Making energy from water flow is an idea and hydrokinetic turbines are leading the way. They rely on materials like carbon fiber composites to make it happen.(43).

Carbon fiber is really good for making turbine blades. This is because carbon fiber has some good properties. It is very strong, but very light. This means that people who make these blades can design them to handle the forces of fast-moving water. Carbon fiber is better than materials like metal or fiberglass. These materials are heavy. Carbon fiber is light. This means that carbon fiber blades can be made to be light without breaking. When people need something to work well carbon fiber is a good choice. Carbon fiber makes the turbine blades work better and use energy. This is an advantage for carbon fiber. Carbon fiber composites are used for turbine blades because they are good at making energy. They are also very good at responding to the water. This is important, for turbine blades. Hydrokinetic turbine blades made with carbon fiber composites are very good (10).

The hydrokinetic turbine blades need to be really strong. They are always out in the water. That can be very tough on them. The water is moving fast and there are things floating around in it that can hurt the blades. The temperature of the water also changes a lot. The good thing about using carbon fiber to make the turbine blades is that they can withstand all these things. Carbon fiber does not get damaged easily by the water. It does not get tired easily either. This means that the hydrokinetic turbine blades can keep working for a very long time. Because the hydrokinetic turbine blades are made of carbon fiber they do not get broken down by the things in the water. This is really good, for the systems because they can keep working for a long time without needing to be fixed. This also means that it does not cost much to take care of them. Hydrokinetic turbine blades made of carbon fiber are a choice because they are strong and last a long time (44). It is necessary to consider the effects of choosing carbon fiber composites for hydrokinetic turbine blades. One of the problems with carbon fiber composites is that they are more expensive than traditional materials. The processes used to make carbon fiber composites require a lot of labor and advanced technology which means they cost a lot of money. For people who are planning projects and have budgets this can be a big obstacle and it might make it harder to make projects that use hydrokinetic technology work. When making decisions about engineering, people who are planning projects have to think about the good things about carbon fiber composites and the bad things like how much they cost. Carbon fiber composites make blades that work better and last longer which can mean costs for operating and maintaining them over time. So even though it costs more at first using carbon fiber composites can be a choice in the long run. To make decisions people who have a stake in the project need to carefully think about the costs and benefits considering both the money they have now and the good things that carbon fiber composites can do in the long run. The decision to use carbon fiber composites for hydrokinetic turbine blades is about finding a balance between getting good results and staying within a budget. As people want sustainable energy solutions and there is more competition in the market using new materials like carbon fiber can be a key factor in what makes a project successful. By using the characteristics of carbon fiber composites developers can help make sure that hydrokinetic systems meet the energy needs we have now and will be successful in the future with hydrokinetic systems and carbon fiber composites playing a big role. The use of carbon fiber composites in turbine blades can have a big impact, on the success of hydrokinetic systems and carbon fiber composites (45).

The cost of carbon fiber composites is a problem that we cannot ignore. Carbon fiber composites have a lot of benefits. As we get better at making things and new methods are developed, we might be able to make carbon fiber composites cheaper. This would make carbon fiber composites available to hydrokinetic projects. Carbon fiber composites would help us have a sustainable energy landscape, with hydrokinetic projects using carbon fiber composites.

5.3 Aluminum Alloys: People are really interested in energy these days. One way to get energy from water is by using turbines. These turbines can use water from rivers, tides or ocean currents to make energy. The blades of these turbines are very important. They need to be made of a material that works well lasts a time and does not cost too much. For turbines aluminum alloys are a good choice for the blades. Aluminum alloys are being used more and more for turbine blade applications because they are good, for turbines. Hydrokinetic turbines are a way to get energy from moving water (46). Aluminum alloys are really great because they are so light. This is a deal when it comes to hydrokinetic stuff because lighter blades make the whole turbine system lighter. This means the turbine can work better and make energy when the water is not moving very fast. Aluminum alloys make turbines work in lots of places. Also, aluminum alloys are light so they do not put much stress on the things that hold them up. This makes it easier to put them in and fix them when they break, which saves money. Aluminum alloys are great, for this (47). Aluminum alloys are really good at resisting corrosion. This is very important for turbine blades that have to work in tough conditions like when they are underwater in the ocean where the water is salty. Other materials like steel usually need a lot of coating to survive in the water. Aluminum is different because it makes its own protective layer that helps keep it from corroding. This layer is like a shield. However, we still need to do some work to make sure the aluminum lasts a long time. The big problem is making sure we apply the treatments to the surface of the aluminum so it can really withstand the corrosive things it will encounter especially near the coast and in places where rivers meet the sea. We can use things like anodizing and special coatings to add protection to the aluminum. This helps the turbine blades last a lot longer. Aluminum alloys are great because they can resist corrosion. Aluminum alloys are also good, for turbine blades that're in salty water (48).

Another great benefit of using aluminum alloys is that they are easy on the wallet. Compared to materials, which are often praised for their top-notch performance and lightweight aluminum alloys are a more affordable option. The lower cost of materials and simple fabrication process make aluminum a great choice for developers who need to balance performance and budget. This affordability doesn't mean sacrificing quality; in fact, many modern aluminum alloys have been designed to match or beat industry performance standards. However, using aluminum alloys in hydrokinetic turbine applications still has its challenges. One big issue is the risk of corrosion when aluminum comes into contact with other metals, which requires careful design planning. Additionally, while aluminum alloys can deliver on aspects of turbine efficiency ongoing research and development are crucial to improve their performance especially in terms of fatigue resistance and overall structural integrity under repeated stress conditions. Despite these challenges aluminum alloys remain an option for hydrokinetic turbine applications due to their economic feasibility and performance capabilities. The use of aluminum alloys in these applications still requires consideration of their limitations particularly in terms of corrosion and fatigue resistance. Aluminum alloys are a choice for developers who want to balance performance and cost and ongoing research is helping to improve their performance in demanding applications like hydrokinetic turbines. Aluminum alloys have been engineered to meet the needs of these applications. They continue to be a popular choice due, to their affordability and performance (49). Aluminum blades are getting better because of ideas in how we mix metals and treat the surface. This is helping aluminum blades get better in this area. If we focus on making these materials better and using them in the way the people making these things can make renewable energy from water work even better. As the world starts to use energy that's good for the earth aluminum is a good choice for many reasons and it is very important, for hydrokinetic energy systems to keep getting better (50). Aluminum alloys have some problems when we use them to make turbine blades. They are a good choice because they are not very heavy, they can resist corrosion and they are not too expensive. This makes them a great option for people who want to make renewable energy better. We are getting better at treating these materials and making sure they are safe to use. This is helping us to make progress in generating energy from water. It is clear that new and innovative materials like aluminum alloys will play a role in helping us have a more sustainable energy system. Aluminum alloys are going to be very important, for energy generation.

5.4 Stainless Steel: Hydrokinetic turbines are a way to get energy from moving water and they are a really good option for renewable energy. The thing that makes hydrokinetic turbines work well is the materials they are made of the turbine blades. When we think about what materials to use for turbines stainless steel is a very good choice. Stainless steel is strong. Can last a long time and it does not corrode easily. This article is about why stainless steels a good material to use for the blades of hydrokinetic turbines. One big problem with turbines is that they are often in very harsh environments like in the ocean. The saltwater and dirt in the water can really hurt the turbine parts. That can make them break down quickly. Hydrokinetic turbines have to deal with these marine environments. Stainless steel is a choice for hydrokinetic turbines because it can withstand the harsh conditions. Stainless steel does not corrode easily which means that the turbine blades will stay strong for a time even when they are in the water all the time. This is important for turbines because they have to be able to handle the water flowing over them all the time and they have to be able to withstand the stress of being, in a harsh environment. Hydrokinetic turbines and stainless steel are a combination (51,52). Hydrokinetic turbines go through a lot of stress when they're working. They have to deal with water pressure and mechanical stress as they turn the energy of moving water into power. The materials used to make them need to be really strong. Stainless steel is a choice for making turbine blades because it’s very strong and can handle the stress without breaking or bending. It's heavier than some materials like aluminum or plastic but that extra weight doesn't matter much when you think about how well it works. Stainless steels strength means you can make the blades thinner without making them weaker. This can help make the turbines work better and catch energy. When it comes to important uses stainless steel is reliable and that something you can't ignore.

The strength of steel is important for making hydrokinetic turbines work well. It helps them turn water energy into power without breaking down. Stainless steels strength is key, to making turbines that work well and last long (53). Stainless steel is really good for designing turbine blades because it can be made into different shapes. This is important for getting the performance from the turbine. We can use techniques like welding and machining to make complicated blade designs that work well in different environments. This means that engineers can come up with better turbine designs that use energy efficiently and can handle the tough conditions found in waterways. Stainless steel might be more expensive to buy at first compared to materials. It lasts a long time and does not need to be fixed as often which means it is a good value in the long run. Hydrokinetic turbines are meant to run for years so they really benefit from being made with stainless steel. Because they do not need to be fixed often and they last longer the money spent on stainless steel pays off over time. This makes stainless steel a good choice for projects that use energy, like hydrokinetic turbines because stainless steel is a smart choice, for these kinds of projects (54). The need for energy is getting bigger and bigger. So, it is really important to pick the materials for hydrokinetic turbine designs. Hydrokinetic turbine designs need materials that can withstand water and other stuff. Stainless steel is a choice for turbine blades because it does not corrode easily and it is very strong. It is also easy to shape and design with steel. When engineers and developers use steel for turbine blades, they can make sure that the hydrokinetic turbines work well and do not break easily. This helps us have an energy future. Stainless steel is a material for hydrokinetic turbines because it helps them work better and last longer. Hydrokinetic turbines made with steel can really make a difference in the way we make energy. Stainless steel is a choice, for people who make hydrokinetic turbines because it helps them make better turbines.

5.5 Biocomposite Materials: The demand for energy is getting bigger and bigger. People are looking for ways to make energy that do not hurt the environment. One thing that is really interesting is using materials to make hydrokinetic turbine blades. Hydrokinetic turbine blades are important for getting energy from moving water. Usually, these blades are made from manmade materials that can be bad for the environment. Now biocomposites are being made from natural things like fibers and special resins that come from plants. This is a cool alternative to the old way of doing things. Biocomposite materials are a part of this change. Biocomposites can help make turbine blades in a way that is better, for the earth (12,55–57). Biocomposites have a lot of things going for them especially when it comes to the environment. They are made from things that can be grown again like plants so they do not hurt the Earth much as other materials do. These materials can really help lower the things we put into the air, which is a big problem with materials made from oil. Using leftovers from farms or plants that grow fast is an idea because it helps get rid of waste and makes the most of what nature gives us. People have been working hard to make biocomposites better. They have been trying kinds of fibers like flax, hemp and jute and changing the way the resin works. The goal is to make materials that're strong and can bend without breaking. For example, adding things to the fibers and resins can make them stick together better which makes the whole thing work well and last longer. This is especially important for things like turbine blades. Biocomposites also fit well with the idea of making things in a way that does not waste anything. We can design turbine blades that can be recycled or that can break down naturally which is a step towards being kind to the Earth. When these blades are done being used, they can go back into the Earth without making a mess or hurting the environment. That is a good way to make things. There are still some problems to solve. The natural fibers used to make biocomposites can be a little different each time which can make the product not always the same. So, we need to keep working on understanding the materials and making the process better. We also need people from areas of work like science and engineering to work together to make sure biocomposites can be used in the turbines we already have without having to change everything. The use of biocomposites is a step towards a sustainable future. Biocomposites can help reduce waste and make the most of resources. They can be used to make turbine blades that're strong, flexible and good for the environment. Biocomposites are a fit for the circular economy, which is all, about not wasting anything. However there are still some challenges that need to be overcome like making sure the natural fibers are consistent and working well with the resins (58,59).

The move to materials for hydrokinetic turbines is a big deal for sustainable development and renewable energy. People are working hard to make things and biocomposites can really change the hydrokinetic turbine industry. They are strong and good for the earth. The world wants to stop using fossil fuels and biocomposites can help us use resources in a better way. Biocomposites are a sustainable way to make hydrokinetic turbine blades. They are good for the earth. Work well. Scientists are still working to make these materials better so we can use them to make energy. This will help us have technology in the future. Hydrokinetic turbines and biocomposites are important for our planet. Hydrokinetic turbines with biocomposites can make a difference. We need to keep working on biocomposites for turbines to make the earth a better place. Biocomposites, for turbines are the way to go for renewable energy.

5.6 Steel: The search for ways to make energy from natural things is really important. Hydrokinetic turbines are very good at getting energy from moving water like rivers and the currents in the ocean. These turbines are able to catch the energy of the water as it moves and turn it into electricity. This makes them a big part of the way we make energy from things. The blades of the turbines are the parts. They have to be made strong so they can handle the power of the water. This is where steel comes in. Steel is a good choice for the blades because it has many great qualities. The important thing, about steel is that it is very strong. When the water moves over the blades they feel a lot of pressure. Steel is tough enough to handle this pressure so the blades do not bend or break. If the blades were made of a material, they could get damaged easily. This would make the turbines work well and not last as long. So, the strength of steel is very important for turbines to work well for a long time. Hydrokinetic turbines need steel to be strong. Steel makes the blades of turbines strong. The strength of steel is what makes hydrokinetic turbines able to make energy from the water for a time (60,61).

Steel has an advantage when it comes to resisting corrosion. Hydrokinetic turbines are often underwater. A lot of the time they are in saltwater. This can be really bad for the materials because they can start to rust and corrode quickly. Steel can be treated or coated to make it stronger against these things. This helps to keep the blades from getting damaged by the environment, which means they will last longer and need maintenance. So, you get a turbine that's more reliable and better for the environment because you do not need to replace or fix it as often. Also, steel is really versatile when it comes to design. The places where hydrokinetic turbines are used are all very different. The blades need to be specially made for each one to work best. Manufacturers can make steel into all sorts of blade shapes, which lets engineers come up with new solutions that work really well with the unique way the water is moving. This ability to adapt is a part of why turbines keep getting better and better at making energy. Steel is a material, for hydrokinetic turbines because it can be used to make so many different types of blades. Hydrokinetic turbines and steel are a combination because steel can be used to make blades that work well in many different hydrokinetic environments (62,63). The use of steel in turbines is a good idea for many reasons. One of the reasons is that steel is very cost-effective. Other materials like composites or high-performance alloys may be better in some ways. They are also much more expensive. Steel is an option that helps keep the cost of building and maintaining hydrokinetic turbines low. This is important because it helps make renewable energy more affordable for people. Steel is a material for hydrokinetic turbine blades because it is very strong, resistant to corrosion and can be designed in many ways. It is also cost-effective which an advantage is. All these good qualities of steel help to improve technology making it possible to turn water into a useful and sustainable source of energy. As the world needs energy and people want cleaner energy materials like steel become more important for making renewable energy a reality? Using steel in turbines is a big step towards creating a cleaner and more environmentally friendly way of making energy. Steel is a part of making renewable energy from water a practical option. The use of steel in turbines is very important, for creating a sustainable energy future. Hydrokinetic turbines made with steel can help us have a sustainable energy system.

6. Future Directions in Material Development

As the world focuses more on energy hydrokinetic energy is becoming a promising option. This renewable energy uses the energy of flowing water making it a good fit with existing energy technologies. How well hydrokinetic turbines work really depends on the materials used in their blades. With developments in material science researchers are looking for new solutions to make turbine blade materials better more sustainable and stronger. One exciting area of research is self-healing materials for hydrokinetic turbine blades. These materials can fix damages like cracks or scratches on their own. Since turbines work in water and are under constant stress, self-healing materials can make them last longer and be more reliable. Just imagine a blade that can fix itself when damaged which would save money on maintenance and reduce downtime. This could make hydrokinetic turbines more efficient and long-lasting. Another promising area is nanomaterials. By adding particles to traditional materials researchers can create strong and durable materials that are also lighter. This is important for turbines because being lighter means they use less energy to deploy and maintain. Nanomaterials can also help protect against corrosion and growth of living things which are problems for underwater structures like hydrokinetic turbines. Hydrokinetic energy and turbine blade materials are key to making this technology work. Self-healing materials and nanomaterials are being explored to improve turbine blades. Researchers are working hard to develop materials, for hydrokinetic turbines. The goal is to make hydrokinetic energy an efficient and reliable source of renewable energy. Hydrokinetic turbines operate in environments so they need strong and durable materials. New materials can help make hydrokinetic energy more sustainable and cost-effective (64,65). The journey to create the hydrokinetic turbine blade is not just about using new materials. We also need to think about how these materials affect the environment. It's not about finding materials that can withstand water but also about getting them in a way that doesn't harm the planet. Eco-friendly materials are becoming more popular because they come from resources and don't hurt the environment much. When choosing materials for turbines we look at their life cycle to minimize their impact on the environment. In the future universities, companies and government groups will need to work to improve materials for hydrokinetic turbines. By sharing knowledge and resources we can speed up innovation. Solve the many challenges of material development. Projects that encourage sharing and teamwork between experts from fields will help create new ideas. These ideas will combine material science, engineering and sustainable practices to move forward. The goal is to make hydrokinetic turbines better and more eco-friendly. Material research will play a role, in achieving this goal. Hydrokinetic turbine blades need to be strong and eco-friendly. That is why material research is essential (66,67). The hydrokinetic energy sector is. It is very important that we use new materials to make better turbines. If we spend money on research now, we can make improvements in how well the turbines work and how good they are for the environment. This will help the energy sector for a long time. The people who design things and the people who study materials need to work to make this happen. They need to work to make hydrokinetic energy better and more sustainable. This will change the way we use moving water to make power. It will be good for the environment. The hydrokinetic energy sector is ready, for ideas and the future of making turbine blades for hydrokinetic energy is looking very good. Hydrokinetic energy is going to be a part of our energy future and hydrokinetic energy will help us have more power.

7. Future research scope

Researchers are working on making turbine blades better because they can really make a difference in the future. They want to make sure these blades can withstand the conditions of the sea without losing any power. To do this they are looking at materials and designs that can handle the harsh sea environment. The key to getting energy from the ocean in a way that is good for the environment will be to keep making progress in the field of materials. This means hydrokinetic turbine blades will be able to work for a long time and capture energy from the ocean currents. These new developments will also make sure that the turbine designs are strong and can handle conditions like strong currents and salty water. Hydrokinetic turbine blades are very important for this. Researchers are focused on making them better. They are looking at materials and designs to make hydrokinetic turbine blades more efficient and durable (19). The creation of materials that are stronger more flexible and last longer is really important for engineers and materials scientists to keep studying. When you put these materials in the ocean they have to stay strong for a time. This is a place for them because they are always in contact, with saltwater and other things that can damage them. If we can make these materials better than the blades of turbines will be able to withstand all the bad things that happen to them in the water. This is a deal because it means that these turbines will work better and last longer which will make energy production more efficient and cost less money to maintain. When we improve the materials we use, we can make better renewable energy solutions. Composite materials are a part of this. We need to keep working on materials to make them better (68). Hydrokinetic turbines are really interesting. There is a lot to learn about them. One thing that would be great to look into is using coatings to stop them from getting damaged by water. When things like plants and animals build up on the turbine blades it is called fouling. It makes the turbines work less well. This means they do not make much energy as they could. Also, when the blades get corroded, they start to fall and that means they do not work as well for as long. So, it is very important to find coatings that can stop corrosion and fouling. If we can do these hydrokinetic turbines will be able to work for longer and that will make it easier to make energy from the water in a way that is good for the environment. Hydrokinetic turbines will be more efficient and last longer which is great, for making energy from the sea (69). Hydrokinetic turbine blades can be made better by using coating technology. This technology helps the blades last longer because they can resist corrosion and fouling. Manufacturers can make the blades even stronger by using these coatings. This means the blades will work well for a time. They will not need to be fixed often. The blades will also last longer. So, the people who run the equipment do not have to spend all their time fixing it. They can focus on making energy. This can make turbine blades a better way to make energy in the future. Hydrokinetic turbine blades can help us have energy in a way that is good, for the environment and does not cost too much (70). Material scientists and engineers and specialists in energy must work together to make new materials for the blades that will make maritime energy harvesting better and more sustainable. This is important because when people from fields work together, they can handle the tough design and environmental problems that come up in this field. These teams can share what they know from areas and come up with new ideas and solutions. When we combine materials with good design ideas, we can make renewable energy better and reduce the harm it does to the environment. In the future we should focus on making materials that are strong and light and can withstand the conditions in the water. We can use metals that will last a long time and composites that can resist corrosion. We need to test these materials a lot to make sure they can survive underwater. We can also look at materials that're like the ones we find in nature like the ones on the back of a fish or a shell. These materials can help make the blades on the turbines more efficient and last longer. To make this work we need to test these materials in life situations and have material scientists and renewable energy specialists work together. If we focus on making materials and coatings and design methods that are just, for water we can make the systems that use energy from water better and more reliable. We can make these systems capture energy from the water better and make sure they can withstand the environment. This will help us move to energy sources that're better for the environment and cost less. Material scientists and renewable energy specialists and engineers will help us get to a future where energy's clean and does not hurt the environment.

8. Conclusions

The materials used to make Hydro-kinetic turbine blades are very important because they affect how well the turbines work and how long they last. People are still doing research on systems to make them better. To make hydrokinetic systems work better we need to think about the stresses and environmental factors. We need to think about what can hurt the turbine blades and make them not work well. Things like cavitation, biofouling, erosion, corrosion and structural loading strains can all hurt the blades. If engineers know about these things they can make the turbines better. If we keep doing research and making materials and designs hydrokinetic energy systems will get better and better. This will help us make renewable energy. One thing that people are working on is making materials that can fix themselves if they get damaged. This can make the turbine blades last longer. They are also using materials that are light and strong and can withstand being underwater. People want to use materials that're good for the environment.

Future research has focused on making the turbine blades stronger and better at making energy. They will try to make them work well in the conditions of the ocean. They are also working on coatings that can prevent corrosion and fouling.

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