Advancing Hydrokinetic Energy: Composite Solutions for Turbine Blades

BY

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ABSTRACT

Hydro-kinetic technology offers a promising alternative for clean energy generation, especially in areas where traditional hydropower dams are impractical or environmentally undesirable. It harnesses the kinetic energy of flowing water—such as rivers, tidal streams, and ocean currents—without the need for large dams or reservoirs, reducing ecological disruption. This innovative approach not only broadens the potential sites for renewable energy development but also contributes to diversifying the energy mix and reducing reliance on fossil fuels. As research and deployment of hydro-kinetic systems advance, they could play a significant role in sustainable energy strategies worldwide.

The turbine blade, engineered for optimal energy capture, faces significant challenges from environmental factors like salt, sand, and constant flow, making material selection critical. Composites, which combine fibers such as glass or carbon with resins, offer an advantageous solution due to their strength, lightness, and resistance to rust. Several specific studies are examined in this article, which demonstrates that certain composites may withstand high stresses for more than 20 years. However, problems like biofouling and delamination can lower performance, necessitating creative fixes like novel coatings and materials. Composites could improve energy output and sustainability, supporting the drive for renewable energy by 2026, despite high initial prices and repair challenges.

Keywords: Composite, Blade, Energy, tidal, kinetic energy

1. INTRODUCTION

The worldwide search for renewable energy alternatives has quickened due to the combined problems of growing energy costs, depleting fossil fuel supplies, and rising greenhouse gas emissions (1). In this regard, hydropower is frequently highlighted for its dependability and effectiveness as well as its significant global electricity generating contribution in comparison to other clean technologies (2). The two primary categories of hydropower technologies are hydrostatic and hydrokinetic. By holding water in reservoirs, the traditional hydrostatic model produces electricity by converting potential energy into electrical power through the pressure changes that ensue (3). By harnessing the kinetic energy of flowing water, hydrokinetic energy technologies allow power to be generated even in environments with very little elevation change (4). Using tools like canals, wave energy converters, or comparable systems, hydrokinetic (HK) energy conversion converts the kinetic energy of flowing water into useful power (5). As seen in the following picture, a significant difference between hydropower and wind energy technologies is the working fluid: water in the former and air in the latter (6). While wind power harnesses the speed of air (Figure 3) and uses turbine devices to transform its kinetic energy into electrical power, hydropower uses water as its energy source (Figures 1 and 2) (7). When installed in maritime locations, hydrokinetic (HK) turbine blades must withstand harsh circumstances such cavitation, biological fouling, corrosion caused by seawater, and floods. Because seawater is about 830 times denser than air, they must endure far greater hydrodynamic forces than wind turbine blades (8).

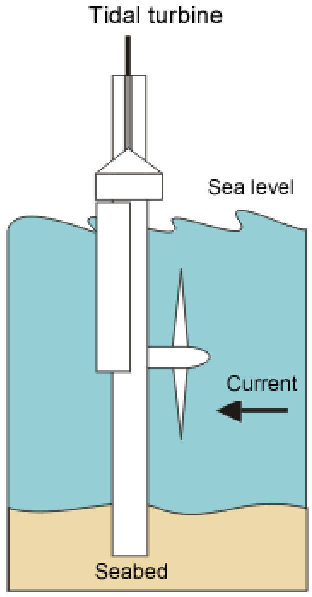


Figure 1 Graphical layout of HK turbine system [6]

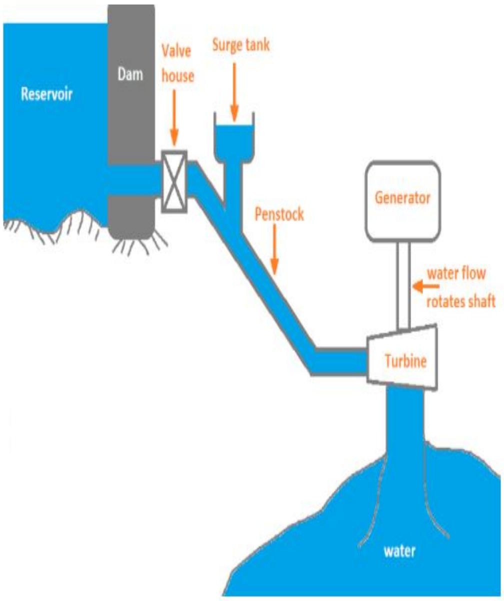


Figure 2 Graphical layout of Hydrostatic turbine system [7]

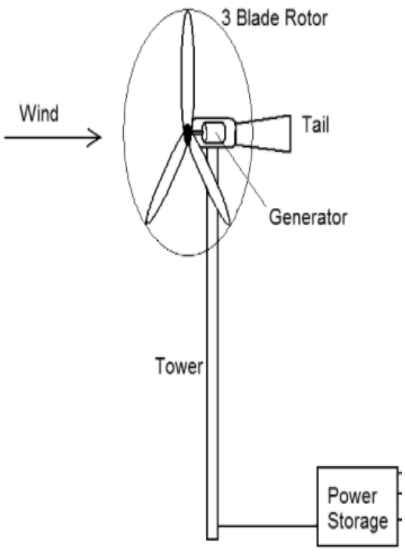


Figure 3 Graphical layout of wind turbine system electric power generation technology [8]

A hydrokinetic (HK) turbine's essential parts need to be planned, produced, and maintained to satisfy sustainability and financial goals. Regardless of their design, turbine blades are a key component of the majority of hydrokinetic energy systems (12). They are constantly submerged in water and subjected to a variety of taxing loading circumstances, such as strong impacts (13). Performance and operational dependability of hydrokinetic turbines are significantly influenced by the material choice of the blades. Selecting the right materials can increase productivity, reduce maintenance needs, and prolong service life. Titanium, aluminum, and stainless steel are often used materials with unique benefits in terms of strength, resilience to corrosion, and longevity (14). These metals are prized for their strength, resilience to corrosion, and durability—elements crucial for turbine blades functioning in watery conditions. Although its high cost frequently prevents its usage in smaller-scale systems, stainless steel is commonly employed because it provides exceptional corrosion resistance and can withstand high mechanical strains. Aluminum is preferred in compact hydrokinetic turbines when reducing weight and expense is a top concern since it offers a lighter and less expensive substitute while maintaining strong corrosion resistance (15).

Another material choice for hydrokinetic turbine blades is titanium, which is valued for its exceptional corrosion resistance, low weight, and great strength. Because of these characteristics, it works especially well with larger turbines where mass reduction is crucial. In addition to metallic alloys, blade fabrication also uses composite materials. Reinforcing fibers, usually made of glass or carbon, are usually placed in a polymer resin matrix to create such composites. This combination produces blades with great strength and stiffness that are also lightweight and resistant to corrosion. Composites' design flexibility, which allows their qualities to be modified to satisfy certain performance requirements, is another benefit for example, a composite blade's stiffness and strength can be precisely controlled by varying the thickness and orientation of the reinforcing fibers. Despite these benefits, composites typically need sophisticated fabrication techniques and are more expensive than metallic counterparts.

Additionally, because environmental exposure can progressively impair their performance, they might have a shorter service life. As a result, the selection of blade material for hydrokinetic turbines needs to take into consideration a number of variables, such as the turbine's size, weight constraints, ambient circumstances, and desired performance results. Designers can increase turbine efficiency and dependability while lowering maintenance requirements and prolonging service life by carefully choosing the materials for the blades. The choice of material directly affects the overall performance of the turbine since different materials have varied mechanical and environmental characteristics. Hydrokinetic (HK) devices, in contrast to wind turbines, run entirely in water, exposing their blades to special difficulties like oxidation, fatigue, material deterioration, and water absorption (16). Because of their advantageous mechanical and environmental properties, composites can help to alleviate many of the drawbacks of traditional metallic materials. High strength-to-weight ratios, resistance to oxidation and corrosion, and the capacity to retain rigidity under demanding loads are just a few benefits of composite blades. They are also highly durable, have a variety of designs, and offer advantages including efficient electrical insulation and a lower petrochemical content (17). Composite materials are frequently regarded as a better option for water turbine blades because of these factors. HK turbine blades are subjected to extremely rigorous operating conditions in river and underwater current situations. Significant thrust, tangential forces, and bending moments are produced by high kinetic energy flux; these factors lead to deformation close to the blade root and high flexural stresses along the core. These elements reflect important design issues that need to be resolved with dependable blade arrangements. A thorough understanding of loading behaviors, structural reactions, and fluid–structure interactions is necessary for effective blade design. Composite blades outperform traditional metallic ones in terms of performance overall. The most prevalent composite materials used in HK turbines are glass and carbon fibre reinforced polymer (18). Composites have been the most widely utilized hydrokinetic material up to this point for a diversity of reasons.

Hydrokinetic Technology

Similar to wind energy systems, hydrokinetic (HK) technologies are regarded as "zero-head" renewables since they produce power directly from the kinetic energy of flowing water as opposed to potential energy differences. Without requiring significant changes to the riverbed, these devices can be installed in rivers or streams that run freely. Consequently, HK power generation circumvents numerous obstacles linked to traditional hydropower, such as the need for a sufficient exploitable head and substantial civil works. (19). Hydrokinetic systems were among the earliest types of hydropower, but their advancement can be segmented into several periods (20). Several hydrokinetic development initiatives in river, ocean currents, and wave energy systems are now at an advanced technological stage (21). Devices intended to capture river or ocean current flows have received much less attention in hydrokinetic technology research and development than tidal energy systems. Installations in rivers are typically more common than those in tidal or offshore areas. Creating dependable and reasonably priced mooring solutions for deep-water applications is one of the main challenges facing ocean current technology developers (22,23).

A fluid's density, interaction surface area, and flow velocity are some of the properties that affect its energy potential. However, the efficiency of fluid-dynamic mechanisms and related mechatronic systems limits the useful power production. Even though turbines are now the most well-established and effective way to harvest this energy, non-turbine options are being investigated more and more in ongoing research (7). The efficiency of hydrokinetic turbine blades in transforming fluid energy into useful power is significantly influenced by their shape. Blades having a parabolic shape perform better than other designs, according to studies. This improved performance results from the advancing blade coming into contact with an area of increased pressure drag, which causes the torque arm to extend from the rotational axis to the corresponding lift and pressure centers (24). The stability, efficiency, and total energy production of a hydrokinetic turbine are greatly influenced by the number and shape of its blades. Performance metrics such as torque, thrust coefficient, and power coefficient are strongly correlated with the number of blades in small-scale horizontal models. Susceptibility to fatigue loading and the functions of pitch angle, thickness, and blade curvature in influencing conversion efficiency are further significant aspects (25,26).

The straightforward design of hydrokinetic turbines allows them to function without the need for spillways or reservoirs. Their ease of deployment and manufacture, along with their comparatively minimal environmental impact, make installation and maintenance more affordable. They are therefore especially well-suited for use in isolated or off-grid communities (27). The fundamental working principle of a hydrokinetic turbine is depicted in Figure 4. These systems are typically used in settings where other renewable energy sources, including traditional river hydropower, tidal and wave devices, or manmade channels, cannot be used efficiently.

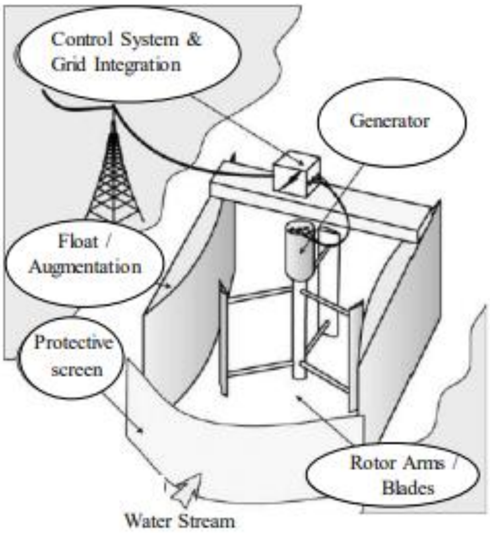


Figure 4 Working principle of inland hydrokinetic turbine (7)

The rotational axis's orientation with respect to the water circulation greatly influences turbine design, as seen in Figure 5. In cross-flow turbines, the axis is placed perpendicularly, allowing operation irrespective of flow direction since rotation can occur in either perpendicular alignment, but in axial-flow turbines, the rotor is aligned with the current to obtain higher conversion efficiency. The main characteristics and differences of the two most widely used energy conversion systems today are presented in Table 1, which also offers a basis for comparison in order to comprehend their working principles. Their structural arrangements and functional parallels are further depicted in Figures 6 and 7, which graphically show how each system accomplishes energy conversion in various applications.

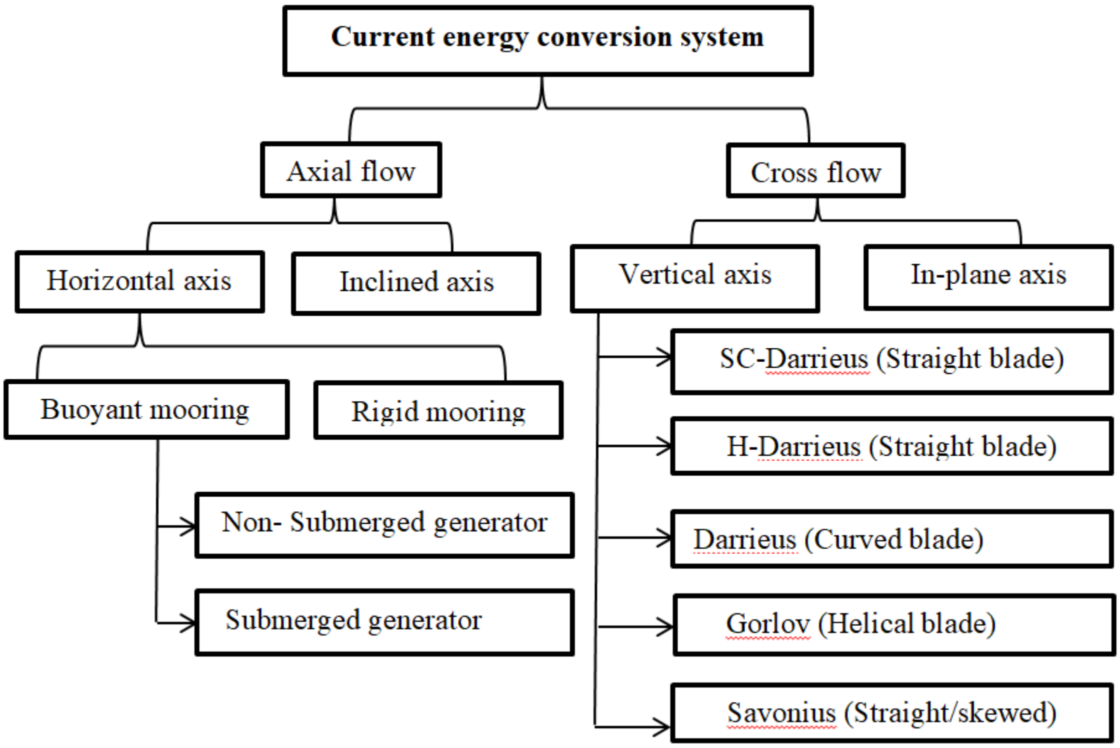
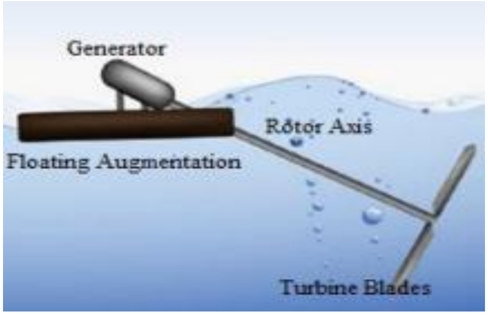


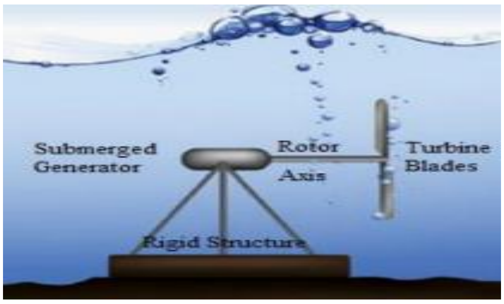
Figure 5 HK turbine classifications (28)

Table 1 correlation of energy production conversion turbine features (28)

Properties	**Turbines aligned in horizontal**	**Turbines aligned in vertical**
Operating current velocity at its lowest	0.5ms^{-1}	1.0ms^{-1} needs a higher velocity to self-start
Operating tip speed ratio(TSR)	Faster (up to 4.5)	Slow (below)
(C_P)	46%	35%
The efficiency of water to wire	25%	26%
Debris resistant	poor	good
Torque ripple	smoother	pulsating
Rotor simplicity	Fairly complex	simple
Potency and material costs	Less	more
Mass	Less	more
Float	Smaller due compactness	Larger
Mechanical power transmission	Complex	simple



a) Inclined axis



b) Rigid mooring

c) Non-submerged generator d) Submerged generator

Figure 6 axial flow turbines (29)

a) In-plane axis b) Squirrelcage c) H- Darrieus

d) Darrieus e) Gorlov f) Savonius

Figure 7 Cross flow turbines (29)

For hydrokinetic devices, the power available per swept area is given by the HK power density (PHK, (W/m2)), density, and device efficiency, as shown in eq. 1 (30).

$$P_{HK} = E \times \frac{\rho}{2} \times V^3$$

(1)

Where, E: device efficiency (%), V: velocity (m/s), and ρ: fluid density (kg/m3).

To govern power output P, the equation can be explained similarly as shown in eq. 2 (31)

$$\mathrm{P} = A \times \frac{\rho}{2} \times V^3 \times C_p$$

(2)

Where A: hydrokinetic turbine swept area (m^2), C_P: power coefficient of specific hydrokinetic turbine taken into account

Factors Affecting Hydrokinetic Turbine Blade Performance

Hydrokinetic turbine blades experience cavitation, biofouling, erosion, corrosion, and a variety of structural loading strains while in operation. The necessity of including preventive measures into the design and optimization of hydrokinetic energy conversion systems is highlighted by the potential for these factors to impair performance and efficiency.

Stress-strain diagram

Experimental stress-strain curves produced under various circumstances are compared to the model's outputs. With pH denoting the acidity or alkalinity of the medium on a scale from 0 (strongly acidic) to 14 (strongly basic), Figure 8 shows both expected and observed responses over a variety of pH values. The model projections and the experimental data showed a high degree of agreement. The degradation patterns seen under conditions of constant load and slow strain rate were faithfully replicated by the corrosion damage model. Damage was modeled as a decrease in the material's mechanical resistance in order to account for the impacts of stress corrosion. Overall, there was a strong correlation between the expected reactions and the room-temperature experimental curves under various acidic conditions (32).

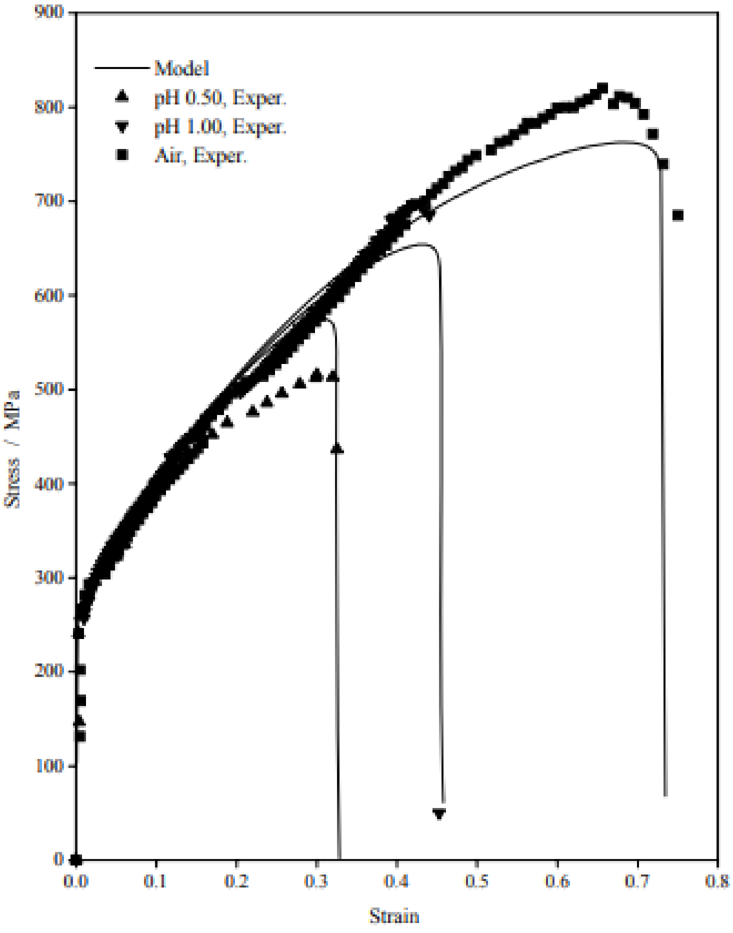


Figure 8 Stress strain diagram for different PH

The mechanical performance of PVC sandwich plates under various pH levels is summed up in Figure 9. This performance includes tensile strength, ultimate strength, elastic modulus, fracture energy, impact resistance, and adhesion shear. In these tests, various adhesive methods were combined with glass fibers. The findings showed that PVC/PVC sandwich plates with 0.95 weight percent glass fiber performed consistently in neutral situations but steadily declined in mechanical qualities in extremely acidic and alkaline environments (33).

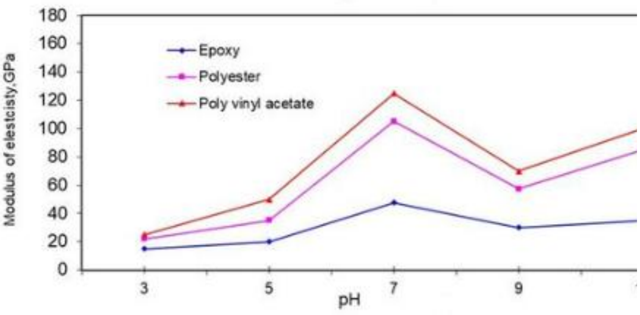


Figure 9 Effect of pH Values at 2 hrs. On the modulus of elasticity Diagram of PVC/PVC Sandwich Plates (h2 = 2.5 mm, 0.95 Wt. % Glass Fiber)

Hydrodynamic cavitation

Because vapor bubble development and collapse in water can result in material degradation and decreased energy conversion efficiency, cavitation must be carefully considered while designing hydrokinetic turbine blades. However, since air does not experience phase transitions under normal operating conditions, wind turbines are not susceptible to cavitation (34). The integrity of turbine blades is seriously threatened by cavitation. The high relative velocity of rotating blades frequently causes it to occur when the local water pressure drops below its vapor pressure (35). Vapor cavities develop on the blade surfaces in these circumstances, and when they collapse, powerful shock waves are released that have the potential to erode and damage structures (15). Rapid fluid vaporization disrupts the flow and causes cavities to form, the size of which is affected by changes in the pressure and velocity fields. Intense pressure pulses are released onto the blade surfaces when these cavities collapse, encouraging material erosion. By decreasing lift and increasing drag, this deterioration lowers turbine efficiency. The cavitation number, which may be obtained from local pressure distributions, is frequently used to express cavitation susceptibility (36). L. M. and A. S. Bahaj claim that if rotor tip speeds are kept close to 7 m/s, which corresponds to the surrounding flow velocity, cavitation can be avoided by first-generation hydrokinetic turbines. Cavitation was only noticeable when tip speeds were higher than about 12 m/s (37). According to research by P. A. S. F. Da Silva, L. D. Shinomiya, and associates, cavitation can be prevented if the relative velocity along the axial direction of all aero-foil sections stays below the turbine blade's critical velocity threshold (38). Pressure dispersals on the cavitation blade in the impeller are depicted in figure 10.

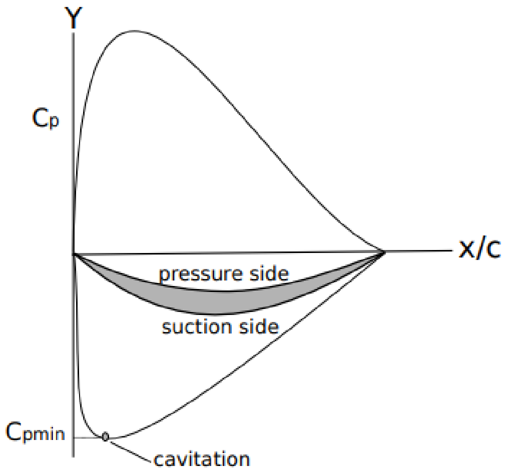


Figure 10 Pressure distributions on cavitation blade in the impeller

Befouling

Because they are always submerged, marine turbine blades are challenging to maintain and monitor. Biofouling—the buildup of microbes, algae, plants, and marine species on blade surfaces—is a major worry. The material integrity may be weakened by this growth, which in extreme cases may result in blade failure (39). Furthermore, biofouling modifies the blades' hydrodynamic properties by increasing their effective area and surface roughness, which increases drag forces. As a result, efficiency decreases ranging from 20% to 70% have been documented, which considerably reduces total power output. By isolating the contributions of shear and pressure, turbine forces were investigated. According to the investigation, surface slagging, which raises surface roughness, reduced pressure torque and increased shear torque, which in turn reduced the power coefficient. In line with the observed drop in pressure torque and rise in shear torque, further analysis of wall stresses verified that dynamic pressure and shear stress decreased on the turbine's upstream and downstream faces (15,40). Figure 11 demonstrates the advancement of plants and other aquatic life on a tidal turbine's supporting framework

Figure 11 A TidGen turbine in Eastport, Maine, North America, has become fouled (41)

Large-scale marine current turbines frequently use antifouling coatings to reduce biofouling, although even at extremely low concentrations, their use may pose environmental risk (42). Carbon nanotubes have been proposed in a number of studies as a way to improve the erosion resistance of antifouling coatings (43,44). By using naturally degrading polymers and replacing dangerous agents with safer alternatives, researchers are investigating greener antifouling methods (45).

Corrosion

Chemical reactions with their surroundings cause metals to corrode, progressively compromising their structural integrity (46).

Uniform attack, galvanic action, localized pitting, intergranular deterioration, crevice corrosion, and stress-related cracking that can result in brittle fractures are some of the ways that corrosion can appear. The service life of hydrokinetic turbines is decreased by these deterioration routes, which also degrade structural elements, promote crack initiation, and hasten blade failure (47). The corroded hydrokinetic turbine structure is portrayed in Figure 12.

Figure 12 Support structure for Open Hydrokinetic turbine with sacrificial anodes (15)

One of three techniques is usually used to protect metals from corrosion: cathode protection, galvanizing with a zinc layer, or providing protective coatings (like paint). The cathode approach involves electrically connecting the metal to a more reactive substance, usually magnesium, aluminum, or zinc, which corrodes in place of the metal that is being protected (48). According to the principles of galvanic corrosion, a more reactive substance, like zinc, acts as the sacrificial anode and corrodes in its place, forcing the protected metal, like iron, to operate as a cathode. The sacrificial anode eventually needs to be changed, especially in marine turbine installations. Cathode protection systems have been effectively used in documented examples, such as the steel support structures of the Open Hydro and Sea Gen devices. This technique has been demonstrated to cut corrosion rates to about 0.1 to 0.2 mm annually when combined with protective coatings, which is about an order of magnitude less than those of unprotected steel (49). Because aluminum alloys are lightweight, corrosion-resistant, and have a high tensile strength, they are employed extensively. To increase its endurance even more, protective coatings are occasionally applied. Aluminum components have a superior strength-to-weight ratio, which makes them excellent for making Horizontal Axis Turbine (HAWT) blades in river-based hydro-kinetic power systems, despite the fact that they can become fatigued in turbulent conditions. In situations where both mechanical strength and conductivity are necessary, aluminum alloys' inherent corrosion resistance and superior electrical conductivity enhance efficiency, while their lightweight characteristics also offer value. Conversely, stainless steel offers better durability and long-term resistance against corrosion. Given that stainless steel can withstand hostile aquatic environments, it is frequently utilized in turbine blades. However, overall turbine efficiency may be impacted by its comparatively high density in comparison to lighter materials. Notwithstanding this disadvantage, its remarkable durability and great tensile strength guarantee structural dependability in a range of climatic circumstances. Stainless steel is cost-effective for long-term underwater use because of its resistance to corrosion, which also lessens the need for frequent maintenance and replacement. Turbine blade design uses composite materials, such as fiberglass-reinforced plastics, in addition to metals. These composites are a viable substitute for heavier metallic alternatives because they combine low weight, high strength, and resistance to water-induced breakdown. Because the imbedded fibers improve structural strength while maintaining the material's lightweight nature, fiberglass-reinforced composites are frequently employed in the production of turbine blades. They work especially well in situations where buoyancy and reduced bulk are crucial factors because of their advantageous strength-to-weight ratio. Furthermore, fiberglass can withstand corrosion caused by water, which enables it to function dependably in damp or flooded conditions (14).

Material Selection

Regarding hydrokinetic energy systems to be effective and long-lasting, the right materials must be chosen. Components must facilitate efficient energy conversion in addition to withstanding constant exposure to harsh sea environments. Strong resistance to corrosion caused by seawater is necessary in order to accomplish this. To increase service life and preserve system dependability, options like stainless steel, aluminum alloys, and protective surface treatments are frequently used (50). The longevity of the materials used to manufacture hydrokinetic devices is directly related to their service life. Materials must have good tensile qualities and fatigue resistance in order to endure the constant loading caused by flowing water. Cost factors are also a major factor in the choosing process. Even while sophisticated materials frequently have higher beginning costs, overall costs can be decreased without compromising performance through rigorous optimization and resource efficiency (51). The selection of materials for sustainable hydrokinetic systems must take into consideration both technical performance and environmental effects. Making recyclable or eco-friendly choices a priority reduces these devices' overall carbon impact. In addition to improving durability and resistance to corrosion, careful material selection also strikes a balance between cost and environmental factors. Engineers can create hydrokinetic systems that support long-term environmental sustainability and function effectively by combining these characteristics (52).

There is currently little information available on the material characteristics of hydrokinetic turbine blades, which makes it difficult to choose the best materials, create trustworthy design standards, and lower overall installation and maintenance expenses. A material must satisfy the component's functional and operational requirements in order to be appropriate for a particular turbine application. The selection of materials for hydrokinetic turbines is influenced by a number of important aspects, which are as follows:

- ✓ 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 factors interact in intricate ways to affect the total performance of the turbine, therefore they cannot be taken into account separately. Strength, rigidity, weight, and resistance to corrosion are important factors. Since mechanical characteristics play a major role in determining how a blade will react to structural loading, they are particularly important. Stiffness, strength, toughness, corrosion resistance, and fatigue life must all be balanced in the ideal material for hydrokinetic turbine blades. Today, a variety of potential materials are available, each with unique benefits for various components of contemporary hydrokinetic turbine systems.

Hydrokinetic turbine blade materials

Since material choice has a direct impact on the turbine's overall cost, performance, and durability, it is essential to establishing cost-effective designs for hydrokinetic turbine blades (53). Studies have looked at a variety of materials, including carbon fiber, fiberglass, bamboo fiber, and reinforced polymers, for the production of hydrokinetic turbine blades (54–56). However, many of these materials are not readily available or affordable for small-scale hydrokinetic applications. For example, [Author(s)] investigated the feasibility of producing low-cost wooden blades with minimal fabrication expenses. While the approach appeared economically viable, the long-term durability of the wooden core under continuous operation was not confirmed (11). Fiberglass composites and wood are frequently utilized as affordable materials for the production of tiny wind turbine blades in underdeveloped nations like Chile (53). One novel strategy in renewable energy technology is the use of bamboo fiber composites in hydrokinetic turbine blades. Because bamboo is strong, lightweight, and biodegradable, it provides a sustainable substitute for traditional synthetic composites (57,58). Integrating this material into turbine blade design may enhance operational efficiency while minimizing ecological impacts. Such an approach highlights the potential of natural resources in advancing environmentally responsible energy technologies (59,60). In contrast to wind turbine blades, hydrokinetic system blades function completely underwater, posing problems including biofouling and accelerated material deterioration. Furthermore, changes in rotor speed and water flow produce varying hydraulic stresses, which can lead to fatigue failure by creating demanding conditions. In this situation, composite blades are frequently preferred because to their superior strength-to-weight ratio, which combines low weight and great strength (61).

In light of their ability to withstand corrosion in submerged conditions, fiber-reinforced polymers, including glass fiber-reinforced epoxy, present a viable material alternative for hydrokinetic turbine blades. However, a significant obstacle that needs to be taken into account during blade design and manufacturing is the potential decrease in tensile and compressive strength that might happen as water seeps through the material. Furthermore, considerable bending moments and shear forces are produced by the varying loads acting on hydrokinetic rotor blades, necessitating meticulous structural research to guarantee dependable operation (13). There is a lot of promise for increasing the production of renewable hydropower with hydrokinetic turbines. Designing lift-based rotor blades is crucial for rivers with comparatively low flow velocities in order to optimize the available kinetic energy. Axial-flow turbines can self-start thanks to low-inertia rotors, which guarantees that the system can efficiently capture the energy of the river. In this situation, rotor performance can be maximized by customizing hydrofoils made of composite materials (62). Reinforced thermoplastic composites can be used to create turbine rotor hydrofoils, which combine high strength and low rotational inertia. Important design factors, such as fiber orientation, layer count, stacking configuration, and overall laminate thickness, affect how well these fiber-reinforced systems operate (63).

Because carbon fiber's electrical conductivity makes it more vulnerable to galvanic corrosion when utilized with metallic fasteners and connectors, glass/epoxy composites were chosen in its stead. This problem is particularly significant in marine situations, where glass fiber is a better substitute due to the acceleration of galvanic reactions (64). Studies have shown that unidirectional CFRP composite blades outperform conventional blade configurations under high loading conditions, offering extended service life compared to alternative layup orientations (52).

The beam's merit index $M_b = \frac{E^{1/2}}{\rho}$ is symbolized by curving lines with M_b values of 0.003 (lower line) and 0.006 (upper line). The absolute stiffness principle, E = 15 GPa is represented by the horizontal line, where E is the material stiffness and ρ is the density of the substance. Materials that gratify the are on the alignment and to the outer left of the line, and constant M_b lines are overlaid on the diagram (65). Designing an optimal rotor blade involves balancing multiple factors, including material properties, performance requirements, and cost considerations. The purpose of this overview is not to examine the full system design in detail, but rather to emphasize the role of material selection in meeting the performance demands of hydrokinetic turbine blades.

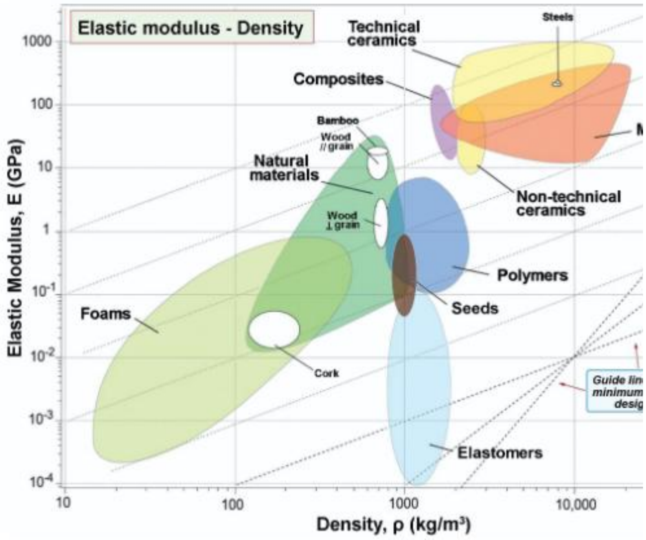


Figure 13: Elastic Modulus versus density diagram for HK materials (66).

Plotting two reference lines versus density and Elastic modulus on a materials selection chart for a cantilever beam is shown in Figure 13. Composites, porous ceramics, metals, and conventional ceramics are examples of materials that fall close to the bottom line and satisfy the baseline requirement, which is equivalent to a merit index of Mb = 0.003. A twofold merit index value (Mb = 0.006) is shown in the upper line, where ceramics and composites continue to be among the best options. Another important factor is a material's elastic modulus: stiffer materials have less cantilever beam deflection than more flexible ones. This criteria is shown on the materials selection chart by a horizontal line that shows the lowest amount of permissible stiffness. Furthermore, when assessing material performance, the fracture toughness of composites—their capacity to withstand overload, fatigue damage, and crack growth—is a crucial factor (47).

Composite materials

Metals, polymers, ceramics, and composites are the four general groups into which structural materials fall. Because they integrate two or more of these material types into a single designed construction, composites are unique. Composites can provide performance attributes that are not achievable with the individual materials alone by combining several parts (67). Reinforcing fibers and a surrounding matrix are combined to create a composite material. The quality of the interface between the fibers and matrix, in addition to their individual qualities, determines the composite's overall attributes (68,69). The characteristics of the resin matrix and reinforcing fibers, as well as how they are positioned within the structure, have a significant impact on a composite's performance. The fiber volume fraction and fiber orientation are the two most important of these variables. The composite's elastic modulus (E_c), which may be calculated using well-established micromechanical models, is determined by these properties taken together.

$$E_c = \eta V_f E_f + V_m E_m \tag{3}$$

Where., E_f is elastic modulus of the fiber, E_m elastic modulus of the matrix; V_f is the fiber volume fraction; V_m is the matrix volume fraction; η is the composite efficiency factor (orientation factor for the fibres); f is the fibre index, and m is the matrix To obtain an exact, porosity-free composite, $V_f + V_m = 1$. For parallel fibres that are aligned and loaded in the fibre orientation, the orientation factor is 1; The orientation factor for a randomly oriented fibre arrangement in two dimensions (in a plane; commonly referred to as a fibre-mat) is 1/3 (70,71).

One of the most popular materials for producing hydrokinetic turbine blades is composite. They are superior to metals in a number of ways, including lower inertial loading during operation, enhanced fatigue resistance, a favorable stiffness-to-weight ratio, and the ability to produce intricate aerodynamic forms (72). Hydrofoil blades in tidal stream turbines need to be extremely rigid since too much deformation can change the hydrodynamic behavior and lower power output. Because carbon fibers are less prone to biofouling—a benefit that has been emphasized in previous research—they are especially beneficial in this situation (73,74). Fortunately, blade failures have not completely disappeared despite the adoption of composite materials. The precise failure causes of hydrokinetic turbine blades are currently poorly understood, which makes this a crucial subject for additional research. Furthermore, when combined with steel components, the electrolytic effects of carbon in composite structures can cause galvanic currents, which could result in corrosion issues if proper precautions are not taken (49). After six years of testing in seawater, the Kobold prototype turbine with carbon fiber/epoxy blades showed successful operation (75). Blades can be treated with antifouling paint to lessen these problems, and the steel support structure can be shielded by a combination of techniques such sacrificial anodes, impressed current systems, and surface coatings. Studies conducted more recently have brought attention to the mechanical deterioration of fiber-reinforced composite materials under prolonged exposure to maritime settings (76,77). To fully comprehend how seawater absorption affects composites' mechanical performance, more investigation is required. Once frequently used because of their accessibility and well-established production methods, glass fiber-based composites only offer mediocre performance. On the other hand, carbon fiber composites have better mechanical qualities, which has made them increasingly used in sophisticated and large-scale hydrokinetic turbine blades. Modern turbine blades are frequently made from hybrid composites, which blend carbon and fiberglass fibers. While hybrid designs may also integrate both materials at the microstructural level—either by intermixing within layers or merging fibers directly—carbon fiber is frequently applied to the weight-sensitive outer sections of the blade. A balance between the superior performance of carbon fiber and the more affordable fiberglass is provided by this hybridization. Consequently, blades made entirely of carbon fiber are still rather rare [77]. When it comes to hydrokinetic turbine applications, composite materials provide a number of benefits over traditional metals. Carbon fiber composites are becoming increasingly popular in larger and more sophisticated blade designs, but glass fiber composites are still utilized extensively because of their accessibility and well-established manufacturing procedures. Fully carbon fiber blades are still somewhat uncommon because to their greater cost; instead, hybrid designs that blend glass and carbon fibers are becoming more and more popular. It is anticipated that the use of these hybrid and high-performance composites in turbine blades would increase further due to continuous advancements in materials engineering. Considering materials like glass and carbon show significantly more strength and stiffness when treated into fibers than in their bulk form, fibrous reinforcements are very useful. The lamina, the fundamental building block of composite constructions, is typically composed of particular fiber–matrix configurations, as seen in Figure 14. Among these, the unidirectional lamina, which is made up of parallel, continuous fibers, offers a useful starting point for a lot of composite designs [78].

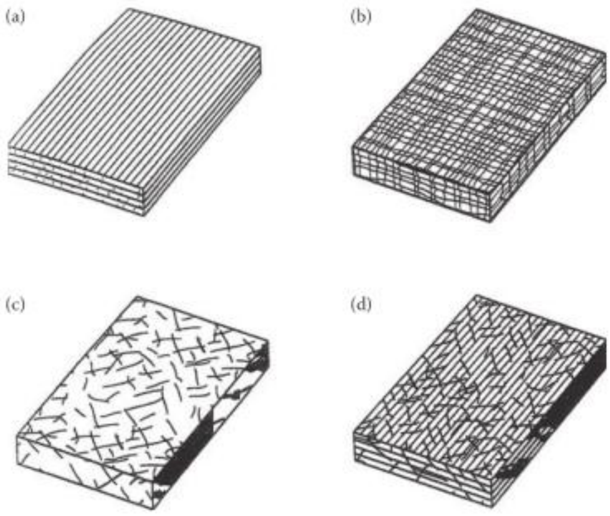


Figure 14 types of fiber-reinforced composites. (a) Continuous fiber composite, (b) woven composite, (c) chopper fiber composite, and (d) hybrid composite.

Three perpendicular planes of symmetry in the mechanical properties of an orthotropic material, like a unidirectional composite lamina, are characteristic; these planes usually correspond to the 1–2, 2–3, and 1–3 planes, as shown in Figure 15.

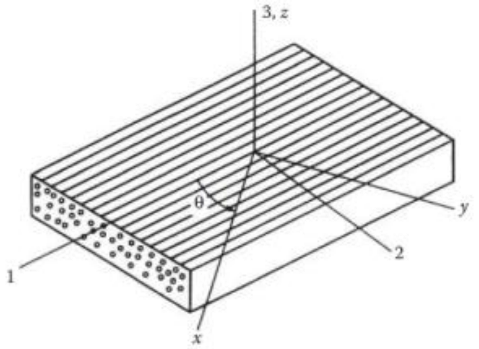


Figure 15 Orthotropic lamina with principal (123) and non-principal (xyz) coordinate system.

Take a look at a straightforward uniaxial tensile test where a longitudinal normal stress, σ_1, is applied along the 1-axis, or fiber reinforcement direction. Depending on whether it pulls the piece apart or forces it together, this stress acts along the specimen's length and can put the material in either tension or compression, as shown in Figure 16a. Such loading is essential for evaluating the strength, deformation behavior, and probable failure modes of components subjected to axial forces since it directly influences the material's elongation or contraction.

A transverse normal stress is applied perpendicular to the longitudinal axis of the material, as shown in Figure 16b. This kind of loading may result in transverse deformation and lead to bending, buckling, or lateral strain, depending on the boundary conditions and material qualities. In-plane shear stress, when shear forces act parallel to the material surface, as shown in Figure 16c. In addition to offering information on shear strength, possible failure modes, and the material's overall mechanical response, an understanding of this stress state is essential for assessing how components react to shear-dominated loading, such as torsion or coupled multi-axial loads.

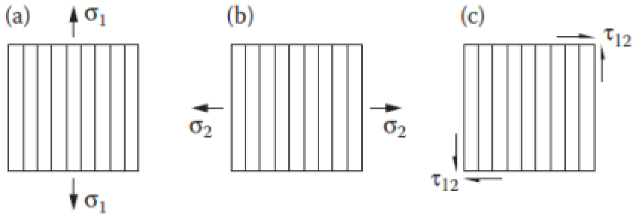


Figure 16 Simple states of stress used to defined engineering contents. (a) Applied longitudinal normal stress, (b) applied transverse normal stress, and (c) applied inplane shear stress

Hybrid composites

The usage of basalt and E-glass fibers as substitutes for full carbon reinforcement has been investigated recently. According to research, total substitution may result in an 80% reduction in structural weight but a 150% increase in material prices. In a similar vein, replacement parts made with these substitutes have been shown to cost roughly 90% more even if they may weigh about 50% less (81). The strength properties and failure mechanisms of hybrid composites have been studied. According to numerous research, glass fibers increase impact resistance and strain-to-failure in carbon fiber composites. On the other hand, it has been demonstrated that adding carbon fibers to glass fiber composites increases the overall failure strain. According to numerical calculations, there is a V-shaped tendency in the link between composite strength and the glass-to-carbon ratio. Additional research has shed more light on these characteristics through the use of micromechanical multi-fiber simulations and probabilistic fiber bundle models (82).

Siu (Alfredo) reported on studies using a hybrid composite made of glass fiber (GF) and carbon fiber (CF) intended for turbine blade spar caps, as seen in Figure 17. Five plies, two CF layers and three GF layers, all aligned at 0°, made up the laminate. Since the exterior surfaces of the laminate are subjected to the largest bending loads and carbon fiber provides more mechanical resistance than GF, the carbon fiber plies were placed there (83).

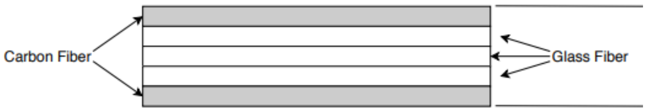


Figure 17 the hybrid material laminate's cross-section.

The mechanical characteristics of the hybrid specimens examined at fiber orientations of 0° and 90° are summarized in Tables 2 and 3, respectively. When these data are compared, it can be seen that the hybrid laminate performs well longitudinally (0°), but its strength and strain capacity are severely constrained when loaded transversely (90°).

Table 2: Mechanical properties of hybrid composite laminates at 0°(83).

Property	Value	Unit
Ultimate tensile strength	1076.1	Mpa
Tensile elastic modulus	56.13	Gpa
Ultimate compressive strength	418.7	Mpa
Compressive elastic modulus	4	Gpa
Shear strength	68.56	Mpa
Shear modulus	4.57	Gpa
Poisson’s ratio	0.295	

Table 3: Mechanical properties of hybrid composite laminates at 90°(83)

Property	Value	Unit
Ultimate tension strength	46.83	Mpa
Tensile elastic modulus	12.78	Gpa
Ultimate compressive strength	111.53	Mpa

Shear strength	68.56	Mpa
Shear modulus	4.57	Gpa
Poisson’s ratio	0.295	

Material mechanics of composite materials

The mechanical performance of composite materials is influenced by a number of elements, but production quality and consistency are particularly important. Fiber rupture, interfacial failure, or resin cracking are examples of vulnerabilities that can be introduced by flaws like stretch marks, material irregularities, or porosity. Damage mechanisms include micro-buckling, translaminar fracture development, and delamination may be triggered by these defects. These processes have a major impact on mechanical behavior, which means that the material quality and the beginning and course of damage have a large influence on the observable attributes and their variability.

Damage

The concepts of damage mechanics have advanced significantly during the last 20 years, based on a basic understanding of material failure and deterioration (84). Different damage mechanisms predominate in composite materials based on the load level: delamination tends to start under lower load conditions, frequently influenced by stress concentrations, matrix cracking and interfacial failures are more common at intermediate loads, and fiber breakage usually occurs under high loads. Extrapolating test results from one regime to another can result in inaccurate conclusions since these mechanisms are different within the different S-N fatigue curve regimes (85).

An efficient way to evaluate damage buildup in a polymer matrix composite is to track the decrease in elastic stiffness over the course of its service life (86). Three stages can be distinguished in the normal evolution of the stiffness–cycle relationship (S–N curve). The first is a brief initial phase characterized by a significant decrease in rigidity. After then, there is a somewhat stable area where the modulus drops off at a pace that is almost constant. Lastly, as catastrophic failure develops in the ultimate stage, stiffness rapidly decreases. The location and kind of failure inside the loaded material determine the rate of stiffness loss and overall fatigue life at every stage. Therefore, the pace at which stiffness deteriorates over time can be used to characterize the rate of damage progression (87–89). The rate of stiffness reduction has been verified in order to resolve these problems, demonstrating that it is possible to assume a linear relationship between normalized stiffness and cycle number. Predicting stiffness degradation over a predetermined number of cycles under specific loading circumstances is made possible by this correlation. Since stiffness evolution is independent of the material's previous loading history, a prediction model has been put forth (87,90).

Mechanical properties

Advanced, high-performance materials are required for hydrokinetic turbine blades because they must be designed to endure high loads and resist fatigue (91). Composite materials are particularly suitable due to their favorable stiffness-to-weight and strength-to-weight ratios, combined with superior fatigue resistance (76). Equation 3 illustrates how the properties of a composite's ingredients (fiber and matrix) as well as lay-up parameters like fiber orientation and volume percent can be used to determine the material's elastic qualities. The rule of mixtures or more sophisticated laminate analysis techniques can be used to approximate these qualities when more accuracy is needed. Static tests are conducted to assess tensile, compressive, and shear behavior in order to validate such computations (92). However, because stiffer materials are frequently more sensitive to cyclic loading, increased stiffness affects fatigue performance. As a result, fatigue life is a crucial performance criterion, and fatigue constraints are often the primary limitation in composite design (15). Standardized coupons or representative components are usually tested in order to assess stiffness, static strength, and fatigue behavior. The information obtained from aeroelastic simulations of the blades under expected loading circumstances is used to confirm material performance and design criteria. While fatigue testing are performed under varied cyclic loads, uniform static tests are performed under quasi-static loading. Material properties can be described under shear, compression, tension, or mixtures of these loading modes, depending on the testing goal.

Progress and challenges

Thermoplastic composites

Numerous fiber-reinforced thermoplastic composites, including glass fiber/PP and carbon fiber/PEEK systems, have been created since the 1980s. Benefits like increased toughness, quick processing, infinite semi-finished material shelf life, cleaner handling during manufacture, and increased possibilities for recycling and remanufacturing are what are driving their acceptance. Their use in hydrokinetic turbine blades has been constrained, nonetheless, by issues with sophisticated processing specifications and the difficulty of obtaining dependable adhesive bonding (65,93).

In traditional thermoplastic manufacturing, the polymer is heated until it melts, then consolidated under pressure to create the required composite structure. Finally, the matrix is re-solidified by cooling. Processing calls for substantially higher temperatures, usually between 180 and 390 °C, for high-performance thermoplastics that can function continuously at high temperatures (usually between 80 and 250 °C). To account for thermal expansion and provide sufficient thermal resistance at these levels, great care must be taken in the design of the tool and the choice of auxiliary equipment (93). With its extremely low viscosity at processing temperatures, a recently developed cyclic thermoplastic poly-butylene terephthalate (PBT) resin is especially well-suited for resin infusion techniques. The resin changes from a low-viscosity liquid to a solid thermoplastic polymer at a processing temperature of about 180 °C (94,95).

Environmental Impact

There are significant environmental ramifications when choosing between traditional metallic materials and composite substitutes for hydrokinetic turbines. Because of their energy-intensive extraction and manufacturing processes, metals frequently have larger carbon footprints. Composites, on the other hand, are usually more resilient and lighter, which lowers maintenance requirements and increases service life. By reducing resource consumption, emissions, and waste over the turbine's lifecycle, these characteristics can lessen the total environmental effect. Therefore, choosing materials should carefully weigh the need to maximize performance and efficiency against ecological factors (96–101).

The choice of material for hydrokinetic turbine blades has significant effects on the environment. The environmental costs of extracting raw materials for conventional metals like steel and aluminum, which can lead to habitat loss and water contamination, as well as industrial methods that release large amounts of greenhouse gases, are causes for worry. Composite materials, on the other hand, may have environmental benefits. Over time, their increased durability and decreased weight can reduce resource use by increasing turbine efficiency and extending operational life. Additionally, end-of-life recovery of some composites is becoming possible due to advancements in recycling technologies, which lessens the impact of disposal. Hydrokinetic turbines that use composite materials can also require less maintenance, which lessens the environmental impact of operation. This benefit results from their increased resilience to wear and corrosion, which lowers the need for maintenance and component replacements. Thus, the selection of materials has a significant influence on the total ecological impact of hydrokinetic systems. By choosing composites over traditional metals, the environmental impact can be reduced at every stage of the lifespan, from production and operation to end-of-life care (102–105). Additionally, hydrokinetic turbines' extremely aquatic surroundings can hasten the deterioration of their blades. Long-term exposure to the sea can harm even the most sophisticated composite materials. Although composites typically have a lower carbon footprint during production than metals, there are environmental concerns regarding how they are managed after the end of their useful lives. The materials themselves are not biodegradable, and incineration may produce hazardous byproducts. It is crucial to create environmentally friendly recycling and disposal methods in order to lessen these effects (13,106,107).

New structural design

One of the main goals for manufacturers is to lower the rotor blades' weight-to-length ratio. In addition to being physically required, this objective has financial benefits since lighter blades can help reduce the cost of energy production (cost per kWh). Significant advancements have been made in structural design in addition to material choices. Due to constraints related to material strength, aerodynamic performance, and design specifications, rotor blade weight often rises with blade length, frequently in a nonlinear fashion, as seen in Figure 18. This scaling relationship may be depicted in the picture as measured data or a trend line, highlighting the necessity of optimizing blade design and construction to guarantee structural dependability and efficiency in systems like wind turbines and helicopters.

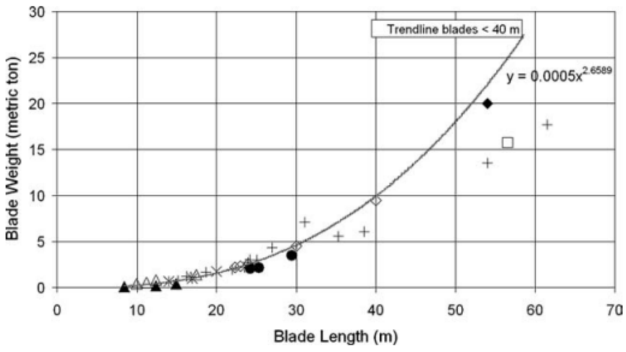


Figure 18 Rotor blade weight versus length (65).

When exposed to severe loads, composite blade structures can experience coupled bending and twisting due to the unique behavior of anisotropic, non-symmetrical laminates. This characteristic allows a rotor blade's aerodynamic profile to self-adjust, increasing efficiency at low flow rates and twisting out of the water at higher speeds to lessen structural loading. Conventional pitch control, which mechanically rotates the blade about its axis, reacts somewhat slowly to abrupt fluctuations, which offers an additional advantage in stormy situations. On the other hand, under extremely variable flow circumstances, bend-twist systems, whether passive or active, can improve the performance of the blade and rotor.

New structural well-being/Health

The continuous effort to increase the cost-effectiveness of hydrokinetic energy necessitates that blades be constructed within safe but optimum bounds, avoiding both under- and over-weight configurations, in addition to meeting the aerodynamic and structural demands placed on rotor blades. A better comprehension of the long-term deterioration of composite materials under cyclic fatigue stress is necessary to accomplish this. For dependable functioning, predictive models that calculate blade longevity in challenging aquatic settings must be developed. In order to continually record important markers of material deterioration, structural health monitoring (SHM) techniques have recently been developed. This allows for real-time evaluation of blade condition and supports preventive maintenance plans.

The degree of material deterioration can be a crucial determinant for calculating the remaining service life and facilitating precise lifetime forecasts after trustworthy models have been developed. Rotor blade inspection, repair, or replacement may be necessary in response to notable changes in deterioration behavior. Large-scale rotor blades are becoming more and more outfitted with sophisticated monitoring systems to enable this, including embedded optical fibers and sensor technologies that can record loads, temperature changes, damage initiation, and even extreme environmental occurrences like powerful storms (108).

Markets and trends

Hydrokinetic power has emerged as one of the most promising sources of renewable energy, which has grown rapidly in recent years. The endurance and design of the rotor blades have a significant impact on the efficiency of hydrokinetic turbines, which use the kinetic energy of water currents to generate power. As a result, improved blade materials that can withstand the harsh marine environment while enhancing energy conversion efficiency have become the focus of more and more research and development. The use of composite materials is one of the most noteworthy developments. These are made up of two or more separate components, each with unique physical or chemical properties that together produce better mechanical and environmental qualities than the parts alone. Due to their high rigidity, low density, and potential for extended service life, composites are appealing for hydrokinetic rotor blades. Their characteristics, like high strength, fatigue resistance, and durability under cyclic loading, can be adjusted to satisfy certain performance needs. The advent of intelligent blades is a more recent development in this area. These blades have inbuilt sensors that can track variables including strain, loads, and vibrations. Predictive maintenance, real-time health evaluation, and turbine performance improvement are made possible by the data gathered, which lowers the possibility of unplanned breakdowns. Likewise, the structural demands on materials in next-generation hydrokinetic turbines increase in tandem with the continuous increase in blade lengths. This change emphasizes the necessity for cutting-edge materials that guarantee structural safety in the severe and variable circumstances of marine environments, in addition to offering mechanical resistance. Extending the performance limits of hydrokinetic turbines requires ongoing research into new materials. The creation of efficient maintenance and monitoring plans is equally crucial. It gets harder to guarantee operational safety and dependability as turbine systems get bigger and more complicated. New structural health monitoring (SHM) measures are being put into place to address this. Numerous manufacturers of turbine blades have already incorporated sensor technology into their designs, allowing for the ongoing gathering of data on fatigue behavior, degradation causes, and blade stresses. By supporting predictive maintenance techniques and improving knowledge of service life performance, this data lowers downtime and increases turbine longevity. All things considered, the selection and advancement of hydrokinetic blade materials are essential to the advancement of rotor blade technology. In order to improve turbine efficiency, dependability, and safety, composite materials and sophisticated blade systems are leading the way. To satisfy the growing demand for renewable energy worldwide, more research into next-generation materials is still necessary. Long-term operating performance also depends on strong monitoring and maintenance plans, and new structural health monitoring programs offer helpful answers to this problem. When combined, these developments point to a bright future for hydrokinetic energy, one in which cutting-edge blade materials and intelligent technologies will continue to be essential to the industry's long-term, steady expansion (109).

Future Trends in Materials Selection for Turbines

A key component of renewable energy production, hydrokinetic turbines (HKT) are being explored more and more for integration in a variety of applications. The selection of materials utilized in their construction is essential to attaining long-term performance, durability, and efficiency. The choice and development of turbine materials are constantly changing to address new operational and environmental concerns as a result of developing technology and rising demands for higher energy output.

Advanced Alloys:

The use of advanced alloys is one of the newer trends in the selection of materials for hydrokinetic turbines. These materials are designed to withstand high levels of stress, varying loads, and corrosive environments. For example, super alloys based on nickel are used extensively in gas turbine engines due to their exceptional mechanical strength at high temperatures. At the same time, scientists are looking into cutting-edge substitutes such ceramic matrix composites (CMCs), which offer a viable solution for upcoming turbine applications by combining low weight and high temperature tolerance (110–112).

Additive Manufacturing:

Hydrokinetic turbine component manufacturing is changing as a result of additive manufacturing (AM), also referred to as 3D printing. Engineers may improve designs for efficiency and performance because to this technology's ability to fabricate complicated shapes with extreme precision. In the future, it is anticipated that additive manufacturing methods will become more prevalent in the production of hydrokinetic turbine components, opening up new possibilities for creative material choices, specialized blade configurations, and robust yet lightweight designs (113,114).

Sustainable Materials:

The use of environmentally friendly materials in the construction of hydrokinetic turbines is becoming more and more significant as sustainability and environmental responsibility acquire more attention. Bio-based composites, recycled metals, and other environmentally friendly substitutes for traditional materials are being investigated in current research. These choices may result in cost savings and, in certain cases, improved performance in addition to lowering the carbon footprint connected with the manufacture of turbines (115–117).

Smart Materials:

Another encouraging trend for further advancement is the incorporation of smart materials into the design of hydrokinetic turbines. Smart materials have adaptive functionality because they can react dynamically to changes in the environment, such as variations in temperature, pressure, or mechanical loads. Shape memory alloys, for example, are ideal for dampening vibration in turbine components because they can return to their original shape after deformation. The integration of these materials into turbine systems holds promise for improving overall operational performance, efficiency, and dependability (118,119).

Nanomaterials:

The mechanical, thermal, and electrical characteristics of nanomaterials—engineered at the nanoscale—make them attractive options for hydrokinetic turbine applications. Materials with remarkable strength-to-weight ratios, low densities, and superior thermal conductivity include graphene and carbon nanotubes. By increasing durability, decreasing total weight, and enhancing heat dissipation, their incorporation into turbine components may improve operational lifespan and efficiency. It is expected that nanomaterials will be used more widely in turbine design and manufacture as nanotechnology research advances (120–122).

As engineers and researchers continue to progress the subject, there are a lot of opportunities for the future of turbine material selection. The creation of high-performance alloys, the use of additive manufacturing, the acceptance of composites made of natural and sustainable fibers, the incorporation of smart materials, and the investigation of nanoparticles are some of the major trends. When combined, these developments should result in turbines that are more effective, long-lasting, and perform better overall. Further developments in material science and design are anticipated to influence the next generation of turbines in various industries as technology develops, hence enhancing their contribution to the production of sustainable energy.

Future research scope

There is a lot of innovative potential in the future of hydrokinetic turbine blade materials, and researchers are concentrating on finding solutions that maximize structural durability and energy conversion efficiency. Continued developments in material science and engineering will be crucial to the development of sustainable and effective marine energy harvesting, as they will guarantee that turbine designs can endure challenging conditions while optimizing long-term performance (27). The creation of composite materials with improved strength, flexibility, and durability is a crucial subject for further study. Under the harsh circumstances of marine environments, such materials must be able to retain their structural integrity. Developments in this field would guarantee that hydrokinetic turbine blades can withstand the deterioration brought on by ongoing exposure to saltwater, biofouling, and other environmental stresses, increasing overall reliability and service life (123). Using cutting-edge coating technologies to reduce corrosion and fouling is another exciting avenue for future study. By interfering with hydrodynamic performance, fouling—the buildup of marine creatures and detritus on blade surfaces—can drastically reduce energy conversion efficiency. On the other hand, corrosion gradually weakens the blades' structural integrity, reducing how long they can operate. Therefore, creating specialized coatings that can withstand both of these phenomena would be essential to improving the long-term robustness and effectiveness of hydrokinetic turbine systems (124). It is possible to create hydrokinetic turbine blades with improved corrosion and fouling resistance by integrating cutting-edge coating technology. In addition to increasing blade longevity, these enhancements would sustain peak performance over time, lowering the need for maintenance. In the end, these developments might enable marine energy harvesting a more economical and environmentally friendly way to provide future energy needs (125). The development of next-generation blade materials that provide effective and sustainable maritime energy harvesting will require cooperation between material scientists, engineers, and renewable energy experts. Interdisciplinary teams address complex design and environmental challenges by bringing together a variety of expertise, which facilitates the creation of creative solutions. The development of strong, lightweight materials that can endure the mechanically demanding and corrosive conditions of aquatic environments should be the main focus of future research. The application of corrosion-resistant composites and sophisticated metals made for long-term performance are promising avenues.

Furthermore, bio-inspired materials that mimic the surface and structural adaptations of marine animals can present new strategies to increase turbine blade efficiency and prolong operational life. Realizing these breakthroughs will require extensive testing under real-world operating settings and tight coordination between material scientists and renewable energy experts. The effectiveness, dependability, and durability of hydrokinetic energy systems can be greatly increased by giving priority to research into cutting-edge materials, protective coatings, and creative design techniques. We will get closer to a robust and carbon-neutral energy future with such advancements, which will quicken the shift to more sustainable marine energy alternatives.

Conclusions

In order to maximize energy conversion efficiency and guarantee long-term dependability in marine energy harvesting, hydrokinetic turbine blade development is essential. Composite materials, especially those reinforced with glass and carbon fiber, present a promising avenue because of their high strength, resilience, and natural ability to withstand corrosion. To protect blade performance and operational longevity, however, important issues including cavitation, fouling, and extended exposure to corrosive marine conditions must be taken into consideration during the material selection and design process. The usage of advanced alloys, additive manufacturing, sustainable materials, smart materials, and nanomaterials are among the emerging trends in the selection of materials for hydrokinetic turbines. These developments have the potential to greatly improve the overall performance, durability, and efficiency of turbines. The creation of composite materials with increased strength, flexibility, and durability as well as cutting-edge coating methods to reduce corrosion and fouling should be the main focus of future research. These developments will guarantee that turbine blades retain their structural integrity even under the harsh conditions of maritime environments. Material scientists, engineers, and experts in renewable energy will need to work closely together to develop next-generation blade materials for effective and sustainable maritime energy harvesting in order to meet these targets.

Recommendation

Hydrokinetic energy has become a potential method for generating power from the natural motion of water as the world's shift to renewable energy increases. Hydrokinetic turbines are at the core of this technology, and the materials employed in their construction have a direct impact on its lifespan, dependability, and efficiency. Further research on turbine blade materials is crucial to maximizing energy conversion and guaranteeing long-term endurance in harsh aquatic environments. The performance and sustainability of hydrokinetic energy systems can be greatly improved by researchers by investigating novel material solutions and tackling issues like corrosion, fouling, and fatigue. The creation of materials that are both strong and lightweight is a top objective for further study. Because heavier blades require more energy to start and maintain rotation, blade weight has a significant impact on turbine efficiency. Lighter materials can perform better, but in hostile aquatic environments, they are frequently more prone to breakage. Therefore, striking the correct balance between durability and weight reduction is crucial. The use of corrosion-resistant composites, which combine strength and low density, and the investigation of new alloys designed especially to withstand prolonged exposure to maritime environments are promising options.

The creation of bio-inspired materials is another exciting area for further study. Numerous marine creatures have developed unique adaptations that enable them to remain effective in aquatic conditions, withstand corrosion, and avoid biofouling. Researchers could develop novel ways to improve the endurance and performance of turbine blades by imitating these natural characteristics. For example, materials inspired by the hardness and protective properties of barnacle shells could help avoid biofouling and prolong blade lifespan, while coatings designed after shark skin microstructures could reduce drag and increase hydrodynamic efficiency. Naturally, creating new materials is just one aspect of the problem. Verifying their long-term performance, safety, and efficacy through extensive testing in real-world settings is equally crucial. The intricate problems of marine habitats, such as shifting water velocities, salinity, and biofouling, cannot be adequately captured by laboratory data alone. Therefore, cooperation with specialists in engineering, material science, and renewable energy will be crucial. Researchers can speed up the creation of technologically sound, financially feasible, and environmentally sustainable solutions by combining knowledge and experience from several fields.

Ethics approval and consent to participate

The authors confirm that they respect the publication ethics and consent to their work's publication

Consent for publication

The authors consent to the publication of this work.

Availability of data and materials

The availability of data and materials is available upon request

Funding

The author state that they do not have any known competing financial interests or personal relationships that could appear to have influenced the work reported in this paper.

Conflict of interest

Furthermore, the authors stated that there is no inherent contradiction with the publication of this manuscript or its data.

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