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Review on the characterization and selection of the advanced materials for tidal turbine blades

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Abstract- In the past few years, tidal turbines have been developed to exploit the kinetic energy of seawater currents to generate electrical energy. The blade is the more critical part of the tidal turbines. It is designed according to hydrodynamic science in order to capture the maximum energy from marine currents and supposed to withstand the environment marine conditions for long periods. The material selection of the tidal turbine blades in such a severe environment plays a vital role in the efficiency of the tidal turbine. This paper discusses essential factors that affect the performance and the durability of the tidal current turbine such as cavitation, biofouling and corrosion. This paper intends to present a short review of the characteristics of available materials for tidal current turbine blades. Apart from the traditional materials, new alternative materials undertaken are discussed.

Keywords- Tidal energy, tidal turbine, blade, composite material, corrosion.

I. INTRODUCTION

Tidal Current Energy is a clean energy source and utilizes kinetic energy available in currents. Tidal current energy can be converted into renewable electricity with tidal current turbines placed directly in streams. The rotating movement of turbine blades due to tidal currents can generate electricity. Due to their high predictability and regularity tidal current energy is an attractive source of renewable energy, compared to wind energy which is intermittent and variable. Many developers have started the research of tidal current energy at the end of the last century, such as Open hydro (owned by DCNS), Marine Current Turbine (SeaFlow, SeaGen), Andritz Hydro Hammerfest (HS1000), Voith Siemens Hydro, Atlantis Resource Corporation, and Alstom, etc. [1]. The tidal current turbines market is young, compared to the offshore wind, oil and gas and no full-scale commercial marine current energy farm has been deployed so far. The tidal turbine developers must soon pass from prototyping to production scale; the first pilot farm of tidal turbines will be installed soon at Raz Blanchard (Alderney Race) located on the West coast of Normandy (France). OpenHydro is currently progressing with a tidal array project in Brittany, France aiming to deploy four tidal turbines. One major barrier to the implementation of tidal turbine farm is the cost of maintenance which is critically dependent on the environment conditions [2]. Some tidal turbine developers have connected successfully their turbine prototypes to the electric grid. For example, Open Hydro (in 2008), became one of the world's first grid connected tidal turbines in Scotland, SeaGen turbine, developed in 2008 by Marine Current Turbines, was the world's first grid connected megawatt size device at 1.2 MW in Ireland [3]. Recently, Sabella D10 (in 2015) was the first prototype tidal turbine connected to the French electricity grid [4].

Tidal turbines should be deployed at sites with strong conditions (high currents, turbulence, waves and storms). Moreover, the tidal turbine elements will be exposed to various marine aggressions such as biofouling, erosion, and corrosion. The blade is the more critical part of the tidal turbine. It is designed according to hydrodynamic science in order to capture the maximum energy from marine currents and supposed to withstand the environment marine conditions for long periods. Blade failures were reported during in situ tests due to the unexpected high loading from the marine current, pointing out the importance to design the turbine. Therefore, choosing adequate material for tidal turbine blades in such a severe environment is crucial to reduce the risks of failure, to minimize the costly maintenance load and to prolong their service periods (more than 25 years) [5-8].

This paper will first describe some recent developments on the tidal current turbines design, and then discuss in more general terms the challenges in developing tidal turbine comparing to wind turbines. This work focuses on reviewing the most important factors affecting tidal turbine systems. Furthermore, a review of the fundamental characteristics required for selecting the alternative materials undertaken for each component of the turbine and especially for the blades will be presented.

II. Tidal Current Turbines Design

Tidal current turbine designs are often inspired from earlier developments in the wind turbine industry. The rotor blades of tidal turbine convert the tidal current kinetic energy into the shaft mechanical energy and a generator converts this mechanical energy into electricity [9]. The tidal turbines have different designs and technology. Horizontal and vertical axis tidal turbines have been widely developed in the last 10 years [10-11]. Based on an overview of existing tidal current projects, most tidal turbine projects are based on horizontal axis technology [12]. Several companies (e.g. Marine Current Turbine, Verdant Power, and OpenHydro) have developed horizontal axis tidal turbines prototypes that are currently undergoing testing. Figure 1 shows a few examples of Horizontal axis tidal current turbine configurations.

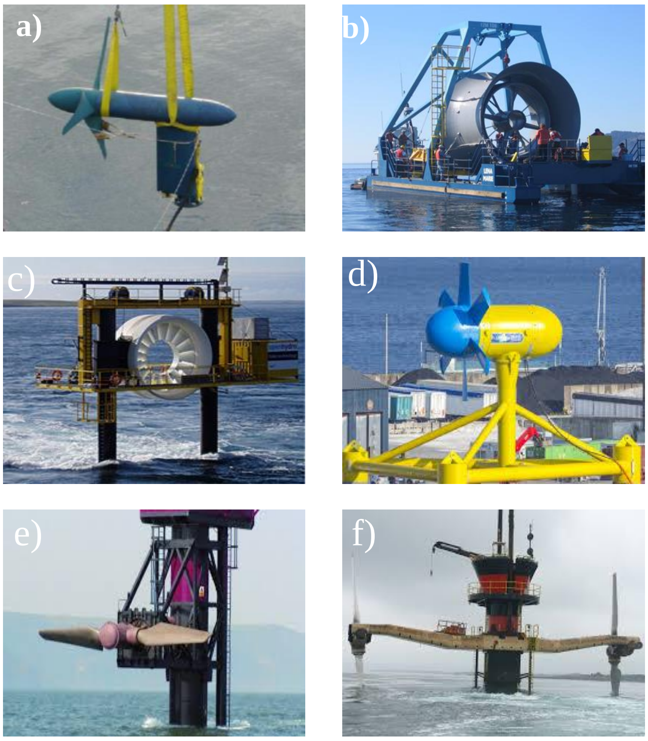

Figure 1: Turbine designs for tidal energy pilot projects. (a) Verdant Power, 35 kW, 5m in diameter, New York at Roosevelt Island (2006- 2008) (b) Clean Current, 65 kW, 14m, Race Rocks (Canada) 2006 - 2007. (c) Open Hydro, 1.5 MW, 15m, European Marine Energy Center (UK) 2006. (d) Sabella D10, 1 MW, 10m, Island of Ouessant, Brittany coast 2015. (e) SeaFlow Marine Current Turbine, 300 kW, 11m off Lynmouth, Devon Coast (2003 -2009). (f) SeaGen Marine Current Turbine, 1.2 MW, 16 m, Strangford Lough, (2008 -2013) [13].

Despite the analogy with wind turbines, there are major differences in the engineering of a tidal turbine. The tidal turbines have shorter, thicker blades than wind turbines. This is to withstand the larger stresses due to the density of the water that is approximately 800 times higher. This huge difference in density results in a smaller blade size for equivalent performance and the much slower speed of rotation [14]. There are also some challenges associated with higher density e.g. turbulence which gives high strain on the turbine. Even a moderate increase in flow velocity can add substantially to the load on the blades. The tidal turbine blades must be able to withstand much greater forces. Blade failures or fractures have been reported for some prototype devices such as:

1) The two Verdant Power tidal turbines installed in the East River of New York City in 2006 [15];
2) The OpenHydro turbine (16m in diameter) installed in the Bay of Fundy, Canada 2010 [16];
3) The Atlantis AR1000 turbine soon after its installation and connection to the grid of the European Marine Energy Centre (EMEC) in 2010 [17].

However, the blade failures have a significant impact on the tidal current turbine industry and its viability. Indeed, blade failures are a major barrier to full-scale commercialization of tidal energy. Today, precise information about the cause of damages occurring in operating tidal turbine are not generally available.

Figure 2: Failed blade of a Verdant Power tidal turbines [15]

III. Factor affecting tidal turbine blades

In addition to the various structural loading effects, tidal turbine blades can also be subjected to cavitation, bio-fouling, erosion and corrosion whilst in operation. These factors will affect the durability and the performance of tidal turbine blades and must be considered in the development of tidal current energy conversion systems.

A. Hydrodynamic Cavitation

Cavitation phenomena, does not affect wind turbines, and it is a limiting design parameter for tidal current turbines as it could lead to surface damage of the turbine blades and a subsequent decrease in efficiency. Cavitation occurs when the local water pressure drops below the vapour pressure. This local pressure drop, due to the high velocity of the turbine blades relative to the water, will result in small vapour cavities on the turbine blades. When these cavities collapse they give rise to shock pressures which can damage the turbine blades.

To avoid cavitation, a limited rotor tip-speed of around 7 m/s relative to the incoming water is recommended for first generation devices. A recent study shows that only rotor tip speeds greater than 12 m/s contribute to cavitation effects

[19]. However, this needs to be complemented by experiments and more study.

B. Biofouling

Monitoring and maintenance work for marine current turbines is a big challenge as the device is submerged in the ocean. One of the challenges is the accumulation of microorganisms, bacteria, fungi, plants, algae, or animals on the body of marine current turbines. This phenomenon is known as the biofouling. Fouling on the surface of the blade can cause deterioration on the blade and leads to blade failure. In addition, the presence of marine microorganisms' colonies, on the blade surface will also alter the hydrodynamic design of the blade and will increase the drag load due to an increase in surface roughness and effective area. This leads to a reduction in blades efficiency about 20%~70% depending on the size of biofouling and therefore decreasing the overall power generation [20]. Figure 3 shows the growth of plants and other marine life on the supporting structure of a tidal turbine.

Figure 3: Biofouling on TidGen turbine deployed in Eastport, Maine in North America (2007) [3].

To avoid (reduce) the effect of biofouling, antifouling paint could be used effectively for most of the deployed large scale marine current turbines, but may be toxic even in small concentrations [21]. In fact, there is antifouling paint available in the market which can perform well for 3–5 years. After the paint reaches the service life, a manual cleaning and reapplying of paint, which are both labor and cost intensive, is required to maintain the performance of marine current turbines. If an array of marine current turbines was to be constructed with a design life up to 20-30 years (ideally for good return) [22], such antifouling paint should be more durable to minimize the maintenance frequency and cost required. The lifespan of antifouling paint depends on the intensity of fouling attack and the erosion due to collision of sediments [23]. These two issues are different in the mechanism. For fouling attack, the effectiveness of durable antifouling paint depends on the chemical properties and surface topography of applied paint that react with seawater [24, 25]. For collision of sediments, it is a problem of physical erosion between free suspended solid with the coating of paint. Currently some researchers have proposed the application of carbon nanotubes to improve the mechanical strength of antifouling paint towards erosion [26, 27]. Other researchers focus on the development of environmentally friendly antifouling paints using biodegradable polymer and lower toxic substances [28]. This is an issue undertaking that requires further research and development.

C. Corrosion

Corrosion can be defined as the damage to metal caused by reaction with its environment. Tidal current turbines exposed to the seawater environment are at higher risk of corrosion, even more so after many years [29]. They are susceptible to different types of corrosion attacks such as: corrosion general, pitting corrosion, crevice corrosion, galvanic corrosion, intergranular corrosion and stress corrosion cracking. Corrosion can cause structural deterioration, facilitate fatigue cracks, brittle fracture and unstable failure leading to reduce the service life of tidal current turbine [30]. To avoid problems with corrosion each metal has to be protected by different methods either painted, galvanized or corrosion cathodic protection. The cathodic protection technique works by placing the metal to be protected in contact with a material that oxidises more readily, such as zinc, aluminium or magnesium [3]. The process uses the principles of galvanic corrosion; causing the iron to act as a cathode instead of anode resulting in the sacrificed material such as zinc corroding instead of the iron. The sacrificial anode, which are attached directly to the turbine, will need to be replaced regularly when general corrosion occurs. For example, the steel support structure of OpenHydro and SeaGen turbine was cathode protected. The use of cathodic protection on the OpenHydro turbine can be seen highlighted in Figure 3. When the steel is protected by using corrosion cathodic protection in conjunction with coating, the corrosion rates is about 0.1 to 0.2 mm/year (10 times less than when compared to non-protected steel [31]).

Figure 3: OpenHydro support structure with sacrificial anodes, weigh of each foundation ~400 tons (turbine fixed to the seabed via gravity only) [18].

IV. Material selection

Nowadays available information and documented data on the characteristics of tidal turbine blade materials, necessary to allow a reliable design and selection and to reduce the overall cost of installation and maintenance of a tidal turbine, is not sufficient. When selecting a material for a given application the material properties must satisfy the function and the operating conditions of the component or the structure being designed. A number of factors affects the selection of tidal current turbine material and can be summarized as following:

1) Component shape;
2) Dimensional tolerances required;
3) Mechanical properties (e.g., strength, stiffness, hardness, fatigue strength ..etc.);
4) Chemical Properties (e.g. Corrosion properties);
5) Physical Properties (e.g. density);
6) Life cycle cost (e.g. cost of material, cost of manufacture, cost of maintenance and cost of installation and removal).

These factors can not be viewed in isolation as there is a complex interaction between them. Factors such as corrosion resistance, weight, stiffness and strength all contribute to improved turbine performance.

However, the mechanical properties are the most important factor affecting the selection of materials for engineering design. Knowing the mechanical properties of a given material will provide a fundamental understanding of the structural performance of the blade. Tidal turbine blades require a material with the best possible combination of stiffness, strength, toughness, corrosion resistance, fatigue life. There are different candidate materials which can be used for different parts of current tidal turbines. In the following, we will present the characteristics of some of the most important candidate materials suitable for use in marine environments.

A. Carbone Steel

Steel is an alloy of iron and carbon. Because of its high density (7.2 g/cm3), low fatigue strength and low corrosion resistance steel is not the optimum choice for blade fabrication. At the beginning of tidal turbine blade development, some designers considered that it was necessary to produce marine rotors in steel, in order to ensure the stiffness of the structure. However, the production of compound-curved profiles in steel was very expensive. Moreover, steel is heavy and susceptible to corrosion induced by seawater [12].
However, steel is a dominant material that is used for the support structure, nacelle and hub of turbines in the manufacturing of tidal current turbines. For example, steel is used for most of the major components of the SeaGen turbine with nearly 89 per cent of the 465 tons total mass as see in figure 4 [32]. Steel is also used for the gravity base structure of Open Hydro prototype [3].

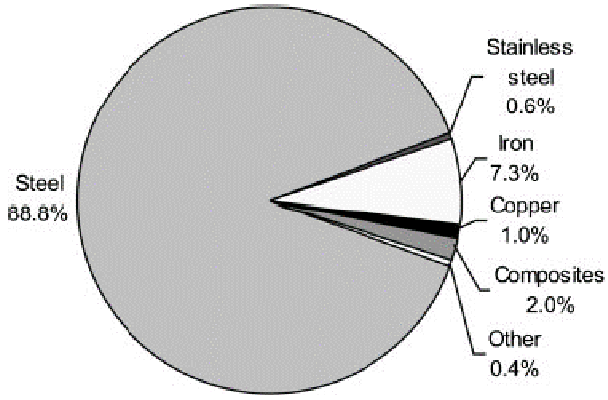

Figure 4: Materials used in the manufacture of the SeaGen turbine [32].

B. Stainless steel

Unlike carbon steel, stainless steel possesses good corrosion and oxidation resistance. Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required. Corrosion resistance may also be enhanced by nickel and molybdenum additions. Several types of stainless steel available meet the requirement for the turbine wheel and support structure. For marine application, the 316 stainless steel grade is recommended since it contains molybdenum which provides higher resistance to pitting corrosion in a chloride environment (such as seawater) [3]. Despite its corrosion resistance properties, stainless steel can cost up to 5 times more than carbon steel. The density of stainless steel varies depending on the alloy but is usually between 7.5 and 8 g/cm^3. If different metals are mixed in close proximity under water galvanic corrosion can occur. Stainless steel mixed with carbon steel could cause the carbon steel to corrode at a very high rate [33].

C. Aluminum alloy

Aluminum is lightweight metal with a density about a third that of steel but it has a low tensile strength and is less stiff than steel. It can be used only in testing situations because it was found to have a lower fatigue level than steel [34].

D. Titanium Alloys

Titanium Alloys represent an outstanding choice for seawater applications, having a unique combination of mechanical and physical properties. With a high structural efficiency and low density (half of the weight of steel), it can be interesting for marine application. It is generally resistant to stress corrosion cracking and corrosion fatigue

[35]. The use of titanium has so far been limited mainly due to high costs.

E. Composite

Composites are composed of two components, matrix and reinforcement. The matrix is the binding element of the material. The nature of the matrix is varied, it can be a thermoplastic or thermoset resin for instance polyester, vinylester and epoxy resin are widely used in the marine domain. The other main component of a composite material is the reinforcement, which is usually fibres for instance glass, carbon, polyester or aramid. The two materials work together to give the composite unique properties. The properties and performance of composites are far superior to those of the constituents. Generally, the fibres and their volume content determine the strength and stiffness of the composite material. Glass fibres and carbon fibres are widely used for marine composite application [12]. Composite materials have excellent strength-to-weight properties, good resistance to corrosion, high fatigue strength and the manufacturing process allows complex blade shapes to be produced. Therefore, composite have been used extensively in the manufacturing of turbine blades. Table 1 presents the properties of some alternative materials in comparison with Carbon-fibre.

Properties	Elastic modulus (GPA)	Tensile strength (Mpa)	Density (g/cm^3)
Carbone Steel	207	400-500	7.85
Stainless steel	193	750-850	7.75
Al alloys	70	300-550	2.7
Ti alloys	114	1170	4.5
Glass-fibre	45	1020	2.1
Carbon-fibre	145	1240	1.6

Table 1: Mechanical properties of various materials

Actually, the composite material is the dominant material used in the manufacturing of blades turbines. Generally, composites offer several advantages over metals such as superior fatigue characteristics, high stiffness to weight ratio, ease of manufacture of structures with complex curvature and a reduction in inertial loading [36]. The majority of tidal turbine developers (Marine Current Turbine, SeaGen, Alstom, open hydro, Atlantis, Sabella…) have preferred carbon fibre blades. The use of carbon fibre materials provides a high strength-weight and stiffness-weight ratio in comparison to glass fibers, thus, allowing the thinner, stiffer and lighter blades. High stiffness is vital when utilising hydrofoils in the design of a tidal stream turbine since the blade deformation will alter the hydrodynamic properties of the blade and ultimately affect the power output of the turbine. Furthermore, the carbon fibres are less affected by the biofouling. This was confirmed by the experimental results of Polagye and Thomson [37].

However, the use of composite materials did not prevent the failure of the blades. Nowadays there are no information and documented data available on the blade failure mechanism in the tidal current turbine. The blade failure mechanism seems to be an interesting track to explore.

The presence of carbon, having a very high electrolytic potential generates strong galvanic currents in the steel structure and thus can cause corrosion problems if not correctly protected [38]. This has occurred for Kobold prototype turbine after six years of experience in seawater, where its blade material use carbon fibre and epoxy resin [39]. This problem can be avoided by using antifouling paint on the blades and using different corrosion protection systems on the steel support structure (painting system plus impressed current and sacrificial anodes as corrosion protection).

Recently, the mechanical degradation behaviours have been observed for composite materials applied for marine environment [36,40]. This issue requires further research and experimental tests to study the impact of seawater absorption on the mechanical proprieties of composite.

V. CONCLUSION

Engineered materials used in tidal turbine blades influence longevity, durability and performance of the blade. This paper presented a review on the candidate material for current tidal turbine blades in the recent years. It should be noted that the most suitable material for the manufacture of blades is the composite, which is adopted by nearly all developers of turbines. Although carbon fibre can be an interesting material for blades turbine due to its corrosion resistance, their mechanical property under seawater should be further investigated. In this paper, much more attention is paid to the factors that contribute to improved blade performance such as stiffness, strength, cavitation, biofouling and corrosion. To promote the development of successful tidal turbine energy, further works should be done on the corrosion protection system to achieve the reliable conditions for facing aggressive and corrosive marine environment. More information affecting the performance of the corrosion protection systems should be collected in the future research. Although our paper deals particularly with the tidal turbine blades, much of the content will be applicable to a wide range of other applications where these materials are used in the marine environment.

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