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Review article

A critical review of technologies for harnessing the power from flowing water using a hydrokinetic turbine to fulfill the energy need

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ABSTRACT

The growing demand for clean, sustainable, and viable energy in the twenty-first century prompted researchers to focus their efforts on developing renewable-based technologies. In that context, hydropower energy can be one of the feasible alternatives to meet future energy demands. It has been observed that at reservoir dams, the breakdown of flooded biomass and organic matter produces a significant amount of Green House Gas (GHG), which contributes to global warming. Small-scale hydro-based technologies produces GHG emissions when compared to dam hydropower since they produce most of their emissions during the building and maintenance phases. Small-scale hydro-based technologies such as hydrokinetics can be considered one of the preferable options, which generate energy from flowing water. A complete review of harnessing the power from flowing water by hydrokinetic turbines (HKTs) has been carried out in this article. Information regarding the state of the art and current status of cutting-edge technology has been gathered with the working principles of hydrokinetic turbines, classifications of HKTs and their applications, the terminology used for HKTs, the dam's impact on the environment, and the selection of turbines, have been discussed thoroughly in this study. Furthermore, a detailed discussion of the design parameters of HKTs like solidity, power coefficient, Tip Speed Ratio (TSR), angle of attack, number of blades, type of blades, performance curve, Reynolds number, aspect ratio, blockage, augmentation and rotor mounting have been included. These parameters will aid in selecting HKT for a given environment condition. A comparison between the wind turbine and the hydrokinetic turbine has also been added. It has been observed that Micro Hydro River (MHR) technology is undergoing continuous R&D as compared to other rural electrification technologies. Various government policies, contemporary civilization, industrialization, and a standard way of life are also important factors that affect the use of HKTs as energy-harnessing devices.

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Nomenclature

SYMBOLS

A	Frontal area of turbine (m^2)
c	Chord length of blade (m)
CD	Drag Coefficient (–)
CL	Lift Coefficient (–)
Cp	Power Coefficient (–)
CT	Torque Coefficient (–)
d	Diameter of the rotor (m)
g	Gravitational acceleration (m/s^2)
h	Height of turbine rotor (m)
n	Number of blades (–)
N	Rotational speed of shaft (rpm)
Pin	Kinetic Power (W)
Pout	Rotor Power (W)
r	Radius of turbine (m)
T	Torque on the shaft (N-m)
V	Free stream velocity(m/s)
α	Angle of attack (degrees)
η	Efficiency (–)
λ	Tip speed ratio(TSR) (–)
P	Density of the water (kg/m^3)
σ	Solidity (–)
υ	Kinematic viscosity (m^2/s)
ω	Angular velocity of the turbine (rad/s)

ACRONYMS

AR	Aspect Ratio
GHG	Green House Gas
HAHT	Horizontal Axis Hydrokinetic Turbine
HEPS	Hydroelectric Power Stations
RCECS	River Current Energy Conversion System
RCT	River Current Turbine
RISEC	River In-Stream Energy Converter
MHR	Micro Hydro River
MNRE	Ministry of New and Renewable Energy
NACA	National Advisory Committee for Aeronautics
TSR	Tip Speed Ratio
VAHT	Vertical Axis Hydrokinetic Turbine

1. Introduction

Energy is essential for human well-being; it facilitates daily human activities such as far-seeing (television), far-going (transport), Health and far-listening (Telecommunication) (Liao et al., 2021; Percy et al., 2005; Rao et al., 2019). Depletion of fossil fuel reserves due to excessive consumption and its severe impact on the environment are the main reasons for searching new alternative and sustainable solutions to generate clean energy (Shahsavari and Akbari, 2018; Bose, 2010; Vermaak et al., 2014; Edenhofer et al., 2011; Panwar et al., 2011; Abbasi et al., 2022; Owusu and Asumadu-Sarkodie, 2016; Abas et al., 2015).

It is observed that the contribution of fossil fuels as primary energy consumption has decreased from 87% to 85% from the year 1995–2015, and it is predicted that consumption will further reduce up to 78% by 2035 (Welsby et al., 2021). However, fossil fuel consumption is decreasing significantly; still, it will remain the primary source of energy generation (Welsby et al., 2021). People are looking for sustainable and renewable energy alternatives to fulfill their growing energy demands and mitigate climate concerns (Owusu and Asumadu-Sarkodie, 2016; King, 2004; Sims, 2004). In this context, electrical energy generated from renewable sources like solar, wind, Biomass, geothermal, and tidal power has attracted significant attention. In the past, getting cost-effective electricity was a serious challenge for people; Now, researchers have developed several techniques in recent decades to achieve efficient energy (Bizon et al., 2017; Chong et al., 2019; Huang et al., 2020; Pan et al., 2021). In this approach, scientists explore a variety of energy-harvesting technologies, including massive hydropower plants (Zakaria and Loon, 2018; Cazzaniga et al., 2019; Kandi et al., 2022), thermal power plants (Machinda et al., 2011; Novosel et al., 2021; Qian et al., 2017; Abbas and Merzouk, 2012; Alobaid et al., 2017), nuclear power plants (Abbas and Merzouk, 2012; Banford and Fouracre, 1999; Li et al., 2014; Zheng et al., 2018), and internal combustion engines (Rahman et al., 2015; Hagos et al., 2014; Alagumalai, 2014; Srivastava et al., 2018; Reitz et al., 2020) that run the world. Initially, only efficient energy generation was a primary concern, but sustainability and environmental concerns have become crucial in today's world (Bianzino et al., 2012; Dyllick and Hockerts, 2002; Elkington, 1994; Omer, 2008; Schaltegger et al., 2017). As a result of this sustainability as well as ecological concerns, researchers have focused their efforts on developing clean and renewable energy technologies (Dasgupta et al., 2002; Dovì et al., 2009; Hart, 1997; Dincer, 2000). Recently, researchers have continued to explore renewable energy such as solar, wind, hydropower, geothermal, tidal, biofuel, and biomass to fulfill power requirements (Dincer, 2000; Khare et al., 2016; Olabi, 2016; Shi et al., 2013; Mohtasham, 2015; Amponsah et al., 2014; Sindhu et al., 2016; Hussain et al., 2017; Pacesila et al., 2016; Schenk et al., 2008). However, approximately 1.5 billion people worldwide do not have excess electricity, especially in communities residing in developing and undeveloped countries (Lata-García et al., 2018). Generally, the conventional energy produced from the hydropower plant is not economical and accessible to rural and remote area communities. To produce electrical energy from open water channels, known as hydrokinetic energy (HKT), can be the best alternative for electrical generation to meet the power requirements within a feasible cost for these areas. It is also a clean, renewable and viable option to provide electrical energy using the potential of rivers, canals, and oceans flowing water (Anyi et al., 2010).

Hydropower accounts for 16% of electricity generation and 80% of renewable electricity globally (Bilgili et al., 2018; Hussain et al., 2019). Technologies running on run-of-river systems offer better environmental performance than hydropower plants with dam systems (Hidrovo et al., 2017). There are several issues related to hydropower-generated electricity, such as

- Large dam caused flood and sediment in the river basement. After some time, the biodegradation process starts, leading to GHG emissions (Beck et al., 2012; Chen et al., 2016; Raadal et al., 2011).
- Large reservoirs in hydroelectric power plants cause many people to migrate directly or indirectly from their homes. As a result, individuals face problems with economic development, resettlement and livelihood (Beck et al., 2012; Schafer et al., 2018; Siciliano et al., 2015).
- The flora–fauna, rehabilitation of animals, and biodiversity of nature get affected due to large reservoirs (Santos et al., 2017; Chen et al., 2015).
- An elevated dam causes ecological concerns such as excessive rains, floods, earthquakes and other natural disasters (Chen et al., 2015; Elosegi and Sabater, 2012).
- Rivers are drying up due to large dams on rivers, changing the ecology around the rivers and affecting irrigation and clean water supply in the lowlands (Siciliano et al., 2015; Pandit and Grumbine, 2012).

Hydropower has a typical GHG emission factor of 15 g CO2 equivalent/kWh, which is 30–60 times less than the factors of usual fossil fuel generation (Gagnon and van de Vate, 1997). However, a significant variation of GHG has been observed in reservoir-based hydroelectric power plants. These changes in GHG emissions have been observed in the range of 1.5 g to 3747.8 g of CO2 eq per kWh (Wang et al., 2020; Gemechu and Kumar, 2022; Walling and Vaneeckhaute, 2020). Particularly in a hydroelectric reservoir in a tropical region, GHG emissions account for more than 90% of life cycle emissions (Gagnon and van de Vate, 1997; Gemechu and Kumar, 2022). Tropical regions receive more rainfall throughout the year, thus increasing flooding and sedimentation in the reservoir. Therefore, tropical regions have more GHG emissions than temperate regions (Hidrovo et al., 2017; Raadal et al., 2011).

Dionysius & Nilsson assessed more than 100 dams and concluded that, for the conservation of biodiversity and sustainable use of biological resources, there is a need to create a standard framework for free-flowing river systems and rehabilitation of the affected area (Dynesius and Nilsson, 1994). In the Indian context, according to the Central Water Commission (CWC) report 2020–21, which oversees dam restoration and upgradation, There are 5745 large dams in India as of June 2019; out of this, 5334 large dams have been completed, and 411 large dams are under construction (CWC, 2021). In the year 2013, the dam had an adverse effect on Uttarakhand. Many scientists believe that human interference with the natural flow of water is responsible for this distortion (Singh, 2018). HKTs can extract additional energy from the water current existing at tailraces and draft-tube outlets at the dam. Ladkum et al. have investigated the potential and feasibility of the installation of HKTs behind the dam at Nigeria's three main hydropower stations and estimated the power generation by using time series analysis of an array of 10, 25 and 50 hybrid HKTs with a swept area of 2.45 m^2 at Kainji Hydroelectric Power Stations (HEPS) having power generation of 263 MW, 268 MW and 305 MW respectively at Jebba HEPS having power generation of 252.2 MW, 286.2 MW and 342.4 MW respectively and at Shiroro HEPS having power generation of 228.7 MW, 229.8 MW and 231.7 MW respectively (Ladokun et al., 2018).

During the early stages of industrialization, people discovered some technologies to obtain energy from flowing water streams like Waterwheel, Gharat etc. (Güney and Kaygusuz, 2010; Khan et al., 2008). However, in the recent decade, many technologies have been developed for harvesting free-flow water energy (Güney and Kaygusuz, 2010; Khan et al., 2008; Kinsey et al., 2011; Kusakana and Vermaak, 2013; Lago et al., 2010; Saini and Saini, 2019). Among these technologies, Hydrokinetic Turbines (HKTs) came up with a simple design which works on the free flow of water, which is available throughout the times and seasons in tropical areas (Döll et al., 2009). Small-scale HKTs have minimal cost as it involves small constructions and it has no water logging (no dam) (Hidrovo et al., 2017; Raadal et al., 2011; Song et al., 2018).

Anuj and Saini have reported the advantages, disadvantages and conditions for the application of the HKTs used in the market. They concluded that this type of technology could fulfill the demand for electrical energy in rural and remote areas, mainly in developing and undeveloped countries, even without much environmental impact (Kumar and Saini, 2016).

A Ministry of New and Renewable Energy (MNRE) report of India studied that a potential of 21 133.65 MW is available for small hydropower (run-of-the-river) in India. In order to fulfill the theses energy goals, multiple HKTs can be the best option if installed in an array with a sufficient gap to produce energy and supply to the grid (EVG, 2022). Also, according to the Central Electricity Authority of India, the theoretical power available for HKTs in India is about 92 201 MW; however, detailed information about the total installed site is not mentioned (Government of India, 2021). In addition, different arrangements of HKTs turbines with different layouts (turbine arrangement) like tandem, fence, rectilinear, staggered and triangular have been studied experimentally and numerically, which can fulfill the present energy demands for remote and rural areas if installed in an array with the sufficient gap between consecutive rotors (Bachant and Wosnik, 2015; Sen and Bhattacharyya, 2014; Churchfield et al., 2013; Jo et al., 2012; Malki et al., 2014; Olczak et al., 2016). Each arrangement has different efficiency due to the front area of the rotor and the position of the rotor (Nag and Sarkar, 2021). Hence, multiple HKTs must be installed in an array to obtain the desired energy output. However, power output efficiency depends on various factors like array layouts of HKTs arrangements, turbine distance, the position of rotors, and the impact of the front and back rotors, etc. (Nag and Sarkar, 2021). Literature also shows that HKTs plants have been installed with different capacities, such as a 25-kW single unit installed at Yukon River near Eagle, Alaska USA (Products, 2022), 200 kW HKTs installed at Bathinda, Punjab, India (IMP, 2022), New Energy Corporation have developed a series of different turbines like 5 kW, 200 kW and 250 kW for tidal application (Products, 2022) etc.

There are some operational issues related to HKTs, e.g., it generally requires a minimum 2–3 m/s water flow speed based on the turbine type and its orientation. The depth and width of the site should be greater than 2 m and 3 m, respectively (Government of India, 2021). Debris in the flowing stream, Low efficiency, low energy capacity, indigenous technology is yet to be available, and existing technology is complex, imported and cannot be customized as per site specification. Hence, due to these issues, the

Table 1.1
Some of the current projects of HKTs power installed in India and the world (EVG, 2022).

S. No.	Project name	Turbine type	Company	Location
1	Chilla Power Channel	Axial flow (25 kW)	DLZ Corp., US	Chilla canal, Dehradun Uttarakhand, India
2	Neyveli Lignite Corporation Ltd.	Axial flow (4 × 5 kW)	M/s Smart Hydropower (German) in collaboration with M/s Imp Powers (Indian)	Neyveli Lignite Corporation India, Chennai, Tamil Nadu, India
3	Not yet installed	Axial flow	Elemental Energy Technologies (EET), Australia + Kirloskar, India	Not available
4	Kakkad HEP	Axial flow 5 × 5 kW (25 kW)	M/s Imp Powers (an Indian firm in technological collaboration with M/s Smart Hydropower, Germany)	Kerala, India
5	Duncan Dam	Cross flow	M/s Instream Energy Systems	Kaslo, British Columbia
6	Roza Canal			Yakima, Washington
7	Tiger Project	Cross flow	M/s Hydroquest SAS	France and UK
8	Sluice of Dutch icon Afsluitdijk, Wadden Sea	Axial flow	M/s Torcado	UK
9	Pointe du Bois	Cross flow	M/s New Energy Corporation	Manitoba, Canada
10	Canadian Hydrokinetic Turbine Test Centre			Lac Du Bonnet, Manitoba
11	Canoe Pass			British Columbia, Canada
12	RITE	Axial flow	M/s Verdant USA	Canada and USA
13	Hy Tide 1000	Axial flow	M/S Voith Hydro	Jino, Corea
14	Seeneoh	Cross low 25 kW	M/s GKinetic Ireland	River Garonne in Bordeaux, France

adaptability/application of these technologies is slow and in the embryonic stage (Puertas-Frías et al., 2022). The development of HKT's technology is still in the pre-commercial stage. Even though the HKTs are in the early stage of development. Currently, some projects are running in India and worldwide at a commercial scale are given in Table 1.1.

In the available literature, several synonyms of the hydrokinetic turbine have been used based on the location and position of the turbine (Khan et al., 2009). Since ancient times, people have used various terminologies such as watermill, water-wheel, and water turbine, which seem ambiguous to represent the particular turbine application (Khan et al., 2009). However, at present, many terms are being used for Hydrokinetic turbines based on the application area of the turbine. Ocean currents (tidal and marine) and river streams are the primary regions where hydrokinetic devices are employed (Kumar and Saini, 2014). Other application area includes artificial channels, irrigation canals, industrial outflow, and many others (Khan et al., 2008; Kumar and Saini, 2014; Behrouzi et al., 2016).

For river applications, the term Water Current Turbine (WCT) (Garman, 1986; Raulraoulro, 2006), Ultra Low Head Hydro Turbine, Free Flow/Steam turbine (van Els and Junior, 2015), Zero Head Hydro Turbine or In-stream Hydro Turbine (Raulraoulro, 2006; Jayaram and Bavanish, 2021) are used as synonyms for HKTs. For tidal application, the term Tidal In-Stream Energy Converter (TISEC) (Degraaf and Mather, 2010; Ruopp et al., 2015; Jahromi et al., 2013), In-Stream Technology, or Simply Tidal Current Turbine (Ruopp et al., 2015) are used as synonyms. According to reports, the number of technologies developed for river applications is less than for tidal energy (Behrouzi et al., 2016; van Els and Junior, 2015; Holanda et al., 2017; Yuce and Muratoglu, 2015). For artificial bays, River Current Turbine (RCT), River Current Energy Conversion System (RCECS), River In-Stream Energy Converter (RISEC), or River Turbine (Khan et al., 2008) are used as synonyms for HKTs.

In this article, a full review of the use of running water power by hydrokinetic turbines has been investigated thoroughly. The present state-of-the-art technology in the field of HKTs, the working principle, classification and applications of hydrokinetic turbines, terminology used for HKTs, the environmental impact of dams and the design and selection of turbines have been discussed in detail. Furthermore, a detailed discussion of the various design parameters of HKTs like solidity, power coefficient, Tip Speed Ratio (TSR), angle of attack, number of blades, type of blade, performance curve, Reynold number, aspect ratio, blockage, augmentation and rotor mounting has been included. These parameters will aid in selecting HKT for a given environment condition. A comparison between the wind turbine and the hydrokinetic turbine has also been made. It has been observed that there is a lack of R&D in Micro Hydro River (MHR) technology compared to other rural electrification techniques. Government policies, contemporary civilization, industrialization, and a standard way of life are important factors that affect the use of HKTs as energy-harnessing devices.

2. Hydrokinetic turbine

The hydrokinetic turbine is a class of Zero Head turbines through which available kinetic energy in the free-flowing water is extracted. Its working principle is similar to a wind turbine; only the fluid medium is changed from wind to water. It uses the free flow energy of water rather than the potential energy available in the water by using a dam. The basic schematic diagram for harnessing energy from flowing water is shown in Fig. 2.1.

The following steps are involved in the energy conversion process (Killingtveit, 2019):

Step 1: - A hydrokinetic turbine transforms the kinetic energy present in the flowing water into mechanical energy. This mechanical energy is available at the rotating shaft.

Step 2: - In this step, a set of gear box is used to optimize the speed and torque of the rotating shaft, which drives the alternator. The alternator must run at a fixed speed because every device is made to operate at a fixed frequency.

Step 3: - Alternator converts the mechanical energy into electrical energy. It works on the flaming right-hand rules.

Step 4: - In the final stage, either the electrical energy is directly connected to the grid, or a commutator and battery are used to store the electrical energy for future use.

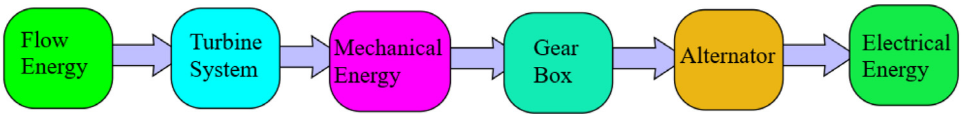

Fig. 2.1. Energy conversion processes/steps.

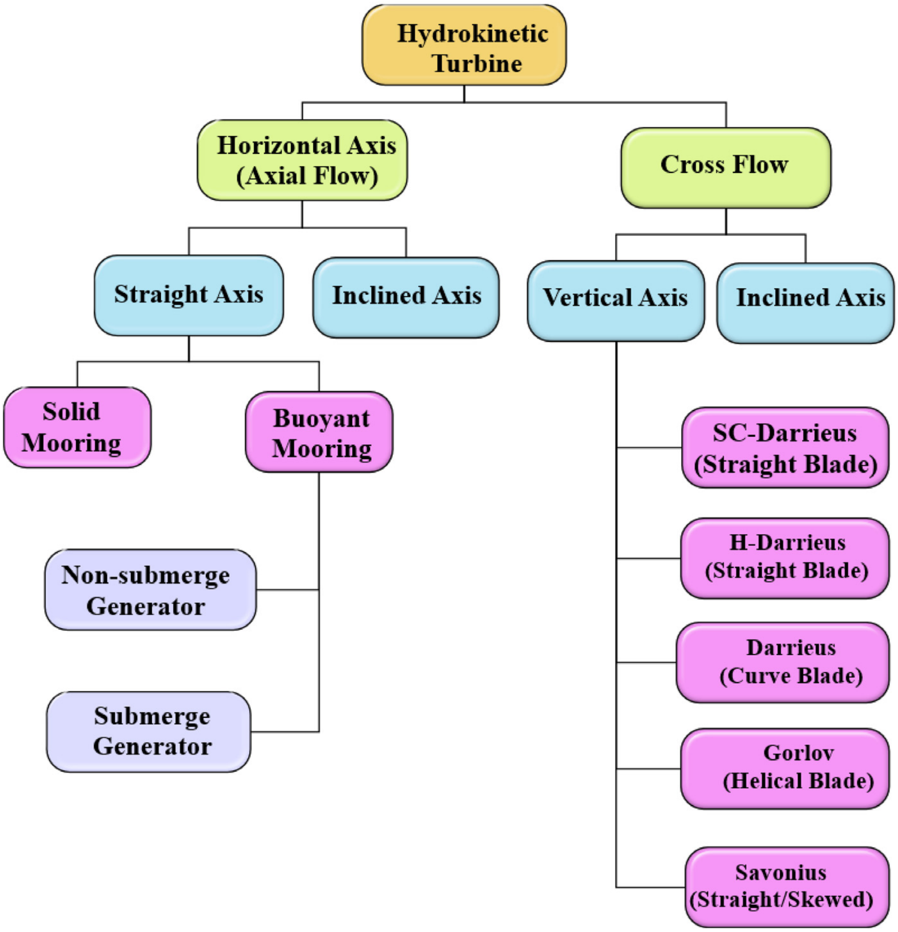

Fig. 2.2. Classification of hydro kinetic turbine.

2.1. Operating principle

Regardless of the application, all hydrokinetic turbines operate on the same conversion principle. HKTs are used to power the grid, operate household appliances, operate flour machines, lift water, irrigate the field and power the sensors used on the ocean floor for research.

The operating concept of an HKTs is identical to that of a wind turbine; the only variation is the fluid medium (instead of air, water is the fluid medium). At a given position, energy extraction is a function of mass flow rate (Khare et al., 2019). This turbine uses airfoil or hydrofoil blades that experience drag, lift, or a mixture of both forces on the blades, causing the turbine to spin on its axis (Aguilar et al., 2021; Muratoglu et al., 2021; Tamimi et al., 2022). When a turbine is placed in a flowing stream, the hydrofoil experiences drag and lift forces, leading to the rotor revolving. This mechanical energy is then converted to electrical power using a gearbox and alternator (Killingtveit, 2019). The power of a hydrokinetic turbine is governed by the equation below.

$$P = \frac{1}{2} C_p \rho A V^3$$

where,

P = Power (watt)
ρ = Water density (kg/m^3)
A = Turbine area (m^2)
V = Velocity of water (m/s)
Cp = Power coefficient

The amount of energy in the water depends on the density of the water, the blade's cross-section area, and the flowing water velocity. Velocity and area are the important factors which influence energy extraction.

Regarding the design and operation of wind turbines or hydrokinetic turbines, German physicist Albert Betz proposed a theoretical maximum efficiency. He concluded that only 59.3% of the kinetic energy could be extracted from the fluid. This theoretical maximum value is expressed as the maximum power coefficient Cp of 16/27 (Khan et al., 2006).

2.2. Classifications

A classification of the hydrokinetic turbine is shown in Fig. 2.2. The hydrokinetic turbine can be classified based on the rotor's orientation with the flowing water and the water's surface (Khan

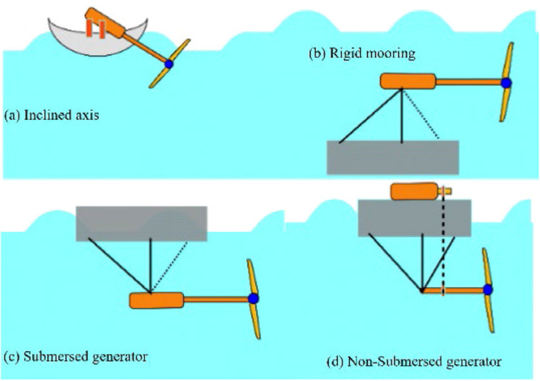

Fig. 2.3. Axial flow turbine.

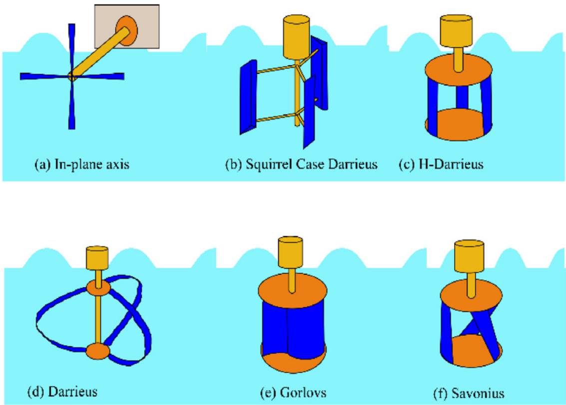

Fig. 2.4. Cross-flow turbine.

Fig. 2.5. Cross-flow (Courtesy of Kepler Energy Ltd).

et al., 2009). The rotor of the horizontal axis/axial flow turbine is parallel to the water flow and surface. These are the organizations which produce these types of turbines (Tocardo, 2022; Verdant Power, 2022; TidEl, 2022; SeaGen, 2022; The Heavyweight, 2022; REIF, 2022; Open Hydro, 2022; What we do, 2022; SIMEC, 2022). A simple representation of the axial flow turbine is shown in Fig. 2.3.

The rotor of a cross-flow turbine is vertical to the water flow (vertical axis) and parallel to the water surface (in-plane axis). These are the organizations which produce these types of turbines (Hydro, 2022; Blue, 2022; Micro, 2022; Hydrolienne, 2022; New, 2022; Low, 2022; The Technology, 2022; GCK, 2022; Water, 2022; Technology, 2022; Instream, 2022). A typical representation of a cross-flow hydrokinetic turbine is shown in Figs. 2.4 and 2.5.

3. Performance parameters for designing of HKTs

3.1. Solidity

The ratio of chord length to rotor pitch is used to describe solidity. If the rotor has a diameter of d, number of blades n, and a chord length of c, the solidity ratio is:

The water passing through the turbine is affected by solidity, which affects the performance of the turbine. The effect of solidity on ripple torque or power has been investigated by Winchester and Quayle (2009). They observed that the ideal operating condition for maximizing output power is a low solidity turbine running at a high tip speed ratio. However, they revealed that increasing the solidity of a turbine at a low tip speed ratio increases its output power. At the same time, it reduces the output power at a higher tip speed.

3.2. Power coefficient

The power coefficient is the ratio of theoretical power available in the fluid to the mechanical power developed at the shaft. The power coefficient shows how many fractions of theoretical water power are converted to useful power (shaft power). It is a dimensionless quantity. Mathematically, it is expressed as:

$$C_p = \frac{P}{1/2 \cdot \rho \cdot A \cdot V^3}$$

where

P = Power (watt)
ρ = Water density (kg/m^3)
A = Turbine area (m^2)
V = velocity of water (m/s)

3.3. Tip Speed Ratio (TSR)

The Tip Speed Ratio (TSR) is the ratio of the blade's linear velocity to the velocity of the flowing water. Tip Speed Ratio is an index of the rotor's rotational speed ω (rad/s) to the fluid velocity V (m/s). It is considered one of the vital parameters while designing an HKTs. It is a dimensionless quantity indicated by the symbol (λ). It may be expressed as follows:

$$\lambda = \frac{\omega \cdot r}{v}$$

where,

ω = is the angular velocity of the rotor
r = is the radius of the rotor
V = is the velocity of flowing fluid

Power and torque coefficients are also related to tip speed ratio (Khan et al., 2006), as shown below:

$$C_T = \frac{C_p}{\lambda}$$

It shows that if TSR (λ) decreases, the torque coefficient increases. Alternatively, the Power coefficients and Torque coefficients might be interpreted as direct proposals to one another. Several tests have been undertaken to see how ducting affects TSR and power coefficient (Kirke, 2011). Ducting is referred to the placement of a turbine within a confinement structure, as shown in Fig. 3.4. According to Kyozuka (2008), the torque coefficient is

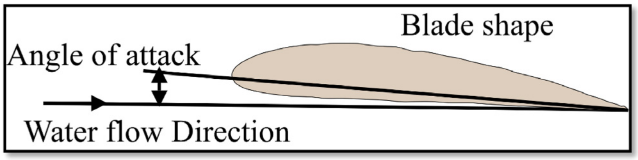

Fig. 3.1. Angle of attack in Airfoil blade.

Table 3.1
Effect of number of blades and solidity on the performance of the turbine.

Number of blade increment	Solidity	TSR	Parameter	Effects
From 2 to 3	Constant	All	Torque Thrust Lateral force ripples	Reduced Reduced Reduced
From 3 to 4	Constant	All	Torque Thrust Lateral force ripple	Reduced Reduced Reduced
		At low TSR	Torque ripple	Present

significantly higher at a tip speed ratio of 2.2, where the turbine is intended to generate energy.

The performance of the hydrokinetic turbine is influenced by ventilation and cavitation at high speeds (TSR). Cavitation is created by the evaporation of water, whereas ventilation is caused by drawing in air from a free water surface. Cavitation and ventilation are caused by reduced pressure resulting in high water velocities in the local area. Cavitation and ventilation can harm the operation of hydrokinetic turbines (Kirke and Lazauskas, 2008). Many experts advise not to operate turbines near the surface to prevent ventilation; however, the tip speed ratio regulates the cavity impact on the rotor. According to Kirke and Lazauskas, the Darrieus turbine should operate at high TSR to avoid a stall condition. The relationship between power coefficient and TSR with different fixed rotor solidity has been presented by Kirke and Lazauskas (2011). It shows that the increasing number of blades leads to increased solidity, which reduces TSR to operate the turbine and consequently reduces the peak power coefficient. At low solidity (0.3), Darrieus turbine achieves a 40% pick power coefficient at a TSR of about 3.3; however, at high solidity (0.84), the turbine achieves a 0.25% pick power coefficient at a TSR of about 2 (Kirke and Lazauskas, 2011).

3.4. Angle of attack

The angle of attack is formed by the airfoil's chord line and the fluid flow direction, as shown in Fig. 3.1. It is also a necessary parameter which affects the performance of HKTs and is denoted by 'α'. The angle of attack should be kept small to avoid the stall condition, and its value should keep below 9° for proper operation of HKTs (Kumar and Sarkar, 2016). According to Yavuz et al. HKTs have a maximum lift coefficient at a 12° angle of attack with minimum flow velocity (2 m/s) to generate electricity (Yavuz et al., 2015).

3.5. Number of blades

There is no formula for determining the number of blades for a given rotor configuration. According to researchers, a trade-off between the parameters for a particular application is required (Delafin et al., 2016). The rotor must have minimal blade interference, low fluid flow resistance (reduced obstruction), low fluctuation, high torque, optimal solidity, and optimal Tip Speed Ratio for electricity production.

Turbines with many blades can overcome torque variations and reduce vibration/shaking. Still, they cannot avoid stalling since increased solidity results in lower tip speed ratios, resulting in worse efficiency. It is clear from the trials that lowering the solidity raises the tip speed ratio (Healy, 1978; Parra-Santos et al., 2015). Delafin et al. investigated the impact of the number of blades and solidity on the performance of a vertical-axis wind turbine (Delafin et al., 2016). They observed that increasing the number of blades while maintaining the same solidity results in the same power outputs. To find out the optimum number of blades, solidity and rotor dimensions at low speed, Kiho et al. tested successfully on a three-bladed rotor with a diameter and height of 1.6 m × 1.6 m at a current speed of 1.1 m/s (Kiho et al., 1996). The observation of the number of blades and the solidity of the performance is listed in Table 3.1. The literature shows that for a 1 m^2 rotor area, mostly 3 or 4 blades have been used.

3.6. Type of blade

The choice of an airfoil is critical for controlling the Tip Speed Ratio, Solidity Ratio, Power Coefficient, and Torque both at rest and in motion. The ripple torque increases with the higher camber blade (Winchester and Quayle, 2009). As a result, more extraordinary precautions should be taken while choosing a blade type.

An experimental-based airfoil data bank was developed by Abbott et al. and found many commonalities between the most effective airfoils in drag and lift force (Abbott et al., 1945). Also, based on their experiments, they created an airfoil data repository. The slope of the airfoil (camber line) and the thickness distribution above and below the camber line are the two key variables that influence the forms of the airfoil blade. Based on these variables, a unique name is used to identify the blade type. People have built a family of similar airfoil shapes based on these two variables and given them formal expressions, such as the NACA four-digit series, NACA five-digit series, Modified NACA Four- and Five-Digit Series, NACA 1-Series or 16-Series, NACA 6-Series, NACA 7-Series, and NACA 8-Series. The NACA families are composed of a mean line and a thickness distribution over the chord, as shown in Fig. 3.2. Each blade has a unique purpose in different situations. A brief synopsis of these series is provided in Table 3.2.

The utilization of NACA blades for hydrokinetic turbines is described in-depth (Khan et al., 2006; Matsushita et al., 2008). In a Darrieus or Gorlov turbine, the blade design (camber, thickness) affects the torque or force variation (Winchester and Quayle, 2009). The blade design information for a tidal current turbine may be found in Sleiti (2017). NACA 0012, NACA 0015, NACA 0016, and NACA 0018, NACA 63018 are the most common hydrofoil blades used in hydrokinetic turbines.

NACA0018 airfoil is suggested for hydrokinetic applications as it has high efficiency with low torque in one revolution (Matsushita et al., 2008). According to Khan et al. (2006), The most frequent airfoil blades used in Darrieus turbines are NACA0012, NACA0015, NACA0018, and NACA63-018. However, with a solidity value of roughly 0.3, the blade shape (NACA63-018) is more suited for hydro applications. Although NACA63-018 is a non-symmetrical airfoil, it performs better than symmetrical airfoils (Parra et al., 2016). Kiho et al. conducted a 5-year trial in the Kurushima Strait, Japan, and they found that the Darrieus turbine has 56% efficient with a Tip Speed Ratio of 2.1 at flow speeds of 1.1 m/s (Kiho et al., 1996). According to a literature review, the blade profile utilized in hydrokinetic turbine applications is the same as in wind turbine applications. A brief description of the blade that researchers have used is described above.

Table 3.2
A summary of blades.

NACA series	Advantage	Disadvantage
4-Digit	• Good stall characteristics • Roughness has little effect	• Low maximum lift coefficient • Relatively high drag
5-Digit	• **Higher maximum lift coefficient** • Roughness has little effect	• **Relatively high drag**
16-Series	• Low drag at high speed	• Relatively low lift
6-Series	• High maximum lift coefficient • Optimized for high speed	• High drag outside of the optimum range of operating conditions
7-Series	• Very low drag over a small range of operating conditions	• Reduced maximum lift Coefficient • High drag outside of the optimum range of operating conditions

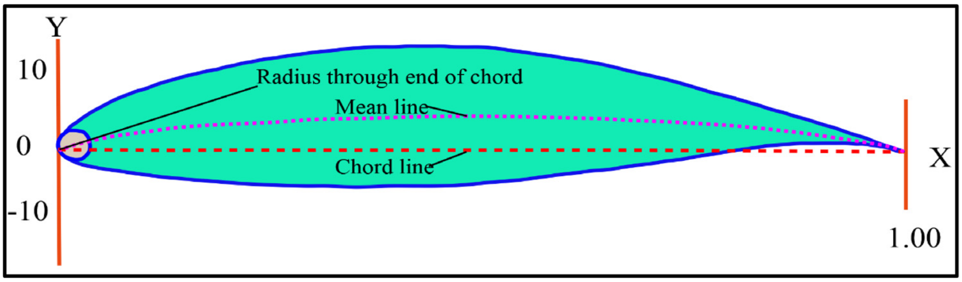

Fig. 3.2. NACA airfoil geometrical construction (Abbott et al., 1945).

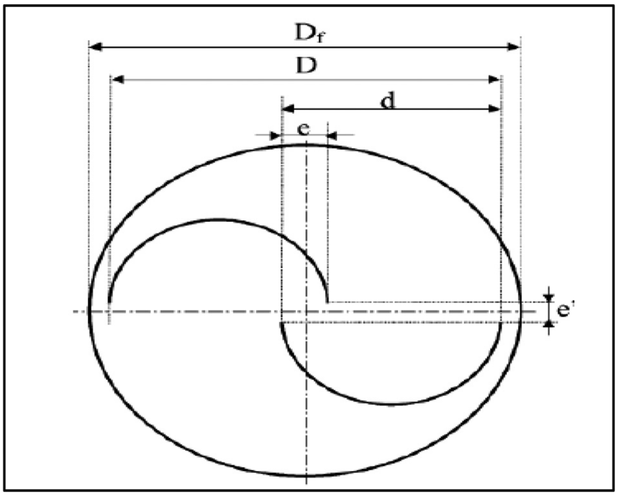

Fig. 3.3. Top views of Savonius rotor.

3.7. Reynolds number

It is a crucial parameter in fluid dynamics for predicting fluid flow behavior. The ratio of inertial force to viscous force is known as the Reynolds number.

$$R_e = \frac{\text{Inertial force}}{\text{Viscous force}} = \frac{(\text{Mass})\ (\text{Acceleration})}{(\text{Dynamic viscosity})\left(\frac{\text{velocity}}{\text{distance}}\right)(\text{area})} = \frac{\rho \cdot v \cdot d}{\mu}$$

where,
ρ = is the density of the fluid (kg/m^3)
v = is the velocity of fluid flow (m/s)
d = is the length of fluid flow (m)
μ = is the dynamic viscosity (kg/m-s)

Stringer et al. have documented the parameter affecting the performance scaling uncertainty. They observed the increasing effect of low chord and Reynolds number on the lifting surface performance like lift and drag force. Also, they revealed that the flow behavior around many standard foils below a Reynolds number of ∼105 becomes rapidly unstable due to a transitional boundary layer (Stringer et al., 2016).

3.8. Aspect ratio

The aspect ratio is the rotor height (H) ratio to rotor diameter (D). This is a critical design criterion for HKTs. Matsushita et al. found in their research that when the distance between the endplates and the diameter of the rotor is 1.08, the rotor's performance is excellent (Matsushita et al., 2008). It affects the solidity, blockage, TSR, torque etc. It is depicted in Fig. 3.3.

3.9. Blockage

The ratio of the turbine's frontal swept area to the channel's frontal swept area is called blockage. It can be written as

$$B = \frac{\text{Swept area of turbine}}{\textit{Swept}\ \text{area of channel}} = \frac{H * D}{H_w * W}$$

where,
H = is the Height of the turbine
D = Diameter of turbine
Hw = Height of water
W = Width of turbine

The end plates used on both sides of the turbine affect its performance as they apply an axial force to the endplate, reducing the resulting pressure.

3.10. Augmentation and rotor mounting

Argumentation refers to the placement of a turbine within a confined structure, also known as ducting. The augmentation is used to improve the performance of the turbine. This arrangement is made to increase the velocity of water near the turbine. Argumentation can be categorized based on the orientation of the wall to water flow. It can be termed as the vertical axis and

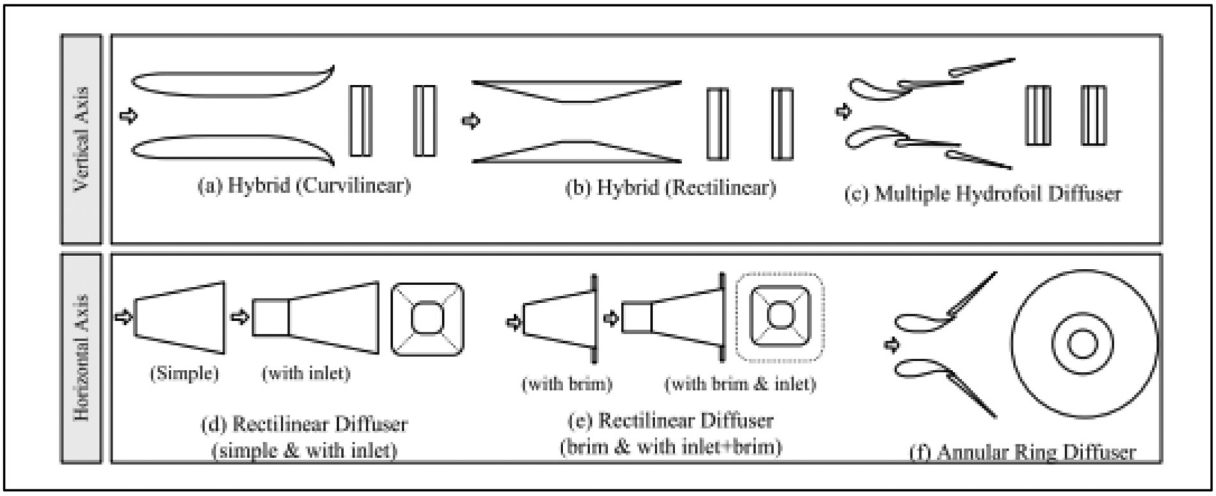

Fig. 3.4. Different augmentation techniques for horizontal and Vertical axis turbines (Khan et al., 2009).

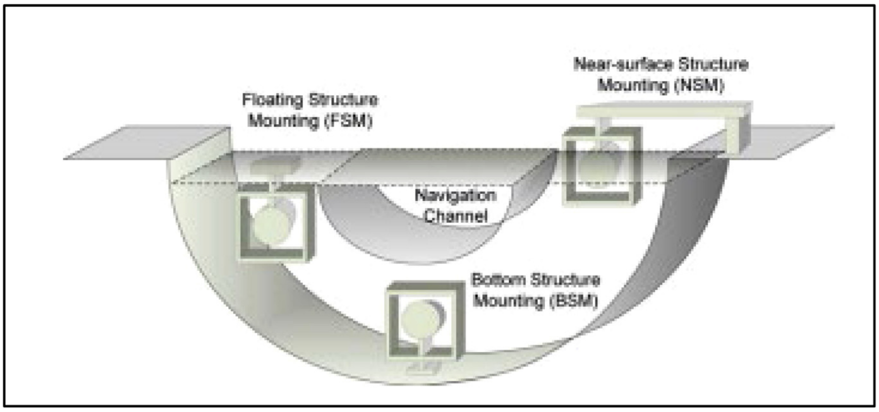

Fig. 3.5. Possible mounting positions of hydrokinetic turbines (Khan et al., 2009).

horizontal axis. Among the ducts, as shown in Fig. 3.4, the narrow duct is superior to the straight duct. Kirke investigated the performance of rotors with and without diffusers and changing pitch under various situations. The performance of the Savonius rotor is affected by the augmentation approach at higher water flow velocity (Kirke, 2011). Also, according to Vennell, by applying the argumentation technique in the hydrokinetic turbine, the coefficient of power can be increased beyond the Betz theory (Vennell, 2013). A typical mounting position is depicted in Fig. 3.5.

4. Current status of hydrokinetic turbines (HKTs)

Various types of HKTs are being used for special applications. Micro Hydro River technologies are in the early stage of development. The inclination towards research and development of Micro Hydro River (MHR) technology is less than other power generation technologies. This is due to the mindset of an energy-driven economy, the centralization of electricity generation and the lifestyle of people around the world. Khan et al. Outlined a set of fundamental definitions for current and future technologies for harnessing the power of flowing water (Khan et al., 2009). The authors also discussed the overall trend in system design, duct augmentation, and rotor placement techniques. They also thoroughly analyzed several turbines, including categorization and qualitative comparison (Khan et al., 2009). The majority of the technology for low water speed is proof of concept or in the R&D stage. A study on hydrokinetic power generation discussed the global trend of hydrokinetic turbines, project capacity, installation location, turbine type and selection of a suitable turbine for a specific area (Kumar and Saini, 2014).

Nevertheless, there are several areas where MHRs technology needs to be improved, such as

- Basic design of turbines and the corresponding design of generators.
- Reliability, long-term viability and cost-effectiveness are all important factors.
- Size optimization and operation research
- A techno-economic, techno-commercial, and environmental analysis are needed for rural applications.
- Supportive policies of governments for the development and deployment of MHR technology.

4.1. Darrieus turbine

G.J.M. Darrieus first proposed the Darrieus turbine design in 1926. The Darrieus turbine in-plane axis has generated much attention in both business and academia since it does not need a yawing mechanism. It is simple to attach with a generator set, inexpensive, and uses a minimal amount of material (Jin et al., 2015). The Darrieus turbine has two main drawbacks: low starting torque and vibration due to periodic changes in the angle of attack (Kirke and Lazauskas, 2011). Numerous experiments have been conducted on the Darrieus turbine to increase the effectiveness of rotors. A real-time test was conducted by Kiho et al.

in a tidal current, from 1983 to 1988, at Kurushima straits. He asserted that the maximum efficiency (56%) was found at a 2.1 tip speed ratio over 1.1 m/s flow speed (Kiho et al., 1996). However, most of the literature indicates that the Darrieus turbine has an efficiency of around 30%.

Variable pitch blade rotors have also been tested to overcome fixed pitch blade rotors. The variable pitch can produce strong initial torque with excellent efficiency by choosing the right pitch angle; however, shaking is still present. Researchers utilized helical blades to resist shaking in the same operation but could not provide high beginning torque. Kirke experimented and found that the helical fixed pitch blade was not self-starting (Kirke, 2011). For self-start, it is advised to retain high solidity and varied pitch. However, no information is available regarding a reliable, cost-effective variable pitch technique. Dai et al. worked on a Kobold turbine with a power output of 20 kW, which operated at a 23% efficiency. They started with a variable pitch to attain a certain speed before switching to a fixed pitch (Dai et al., 2011).

4.2. Savonius turbine

The Savonius rotor design was first proposed in 1920 by French engineer S.J. Savonius. Various experiments on various parameters have been presented in this section. The working of the cross-flow hydrokinetic turbine is independent of the direction of water flow. These turbines can also be installed in places where the water direction changes yearly, such as tidal waves or river muhana, Kayal (Kiho et al., 1996).

In addition to listing the power coefficient of different blade profiles of the Savonius turbine, Kumar and Saini (2017) analyzed the specification of Savonius rotor design parameters numerically and experimentally. The inference was made that there was no information regarding a higher Reynolds number with a modified blade profile. The authors also provide the performance parameter that will be used to boost the rotor's efficiency in the Savonius turbine studies' later stages. This study examines the effects of the Savonius rotor's end plates, aspect ratio, gap ratio, overlap ratio, number of blades multi-staging, blade profile rotor angle, Reynolds number, TSR, and rotor installation parameter on its performance (Kumar and Saini, 2016).

They concentrated on the blade arc angle, blade form factor, various stages, and operational variables, such as flow velocity and blockage ratio, in order to further analyze the twisted Savonius hydrokinetic turbine. The distance between the rotating axis and the bucket may lower the rotor's torque performance; however, in an overlapped bucket, the power coefficient is higher (Kumar and Saini, 2016). The velocity profile of a river's flowing water is highest at the surface and lowest at the bottom. Some study has been done on several phases of rotors with various rotor diameters (Kusakana and Vermaak, 2013; Saini and Saini, 2019; Khan et al., 2006; Möllerström et al., 2019).

Kailash et al. conducted research to determine the ideal position of the deflector plate (on the advancing side) to improve the performance of the Savonius rotor with two deflector plates (Kailash et al., 2012). The results show that using a deflector plate in the optimal location, at both the advancing and returning blade sides, increases the power coefficient by 0.35, but using a single deflector plate at the returning blade side results in Cp of 0.21 and TSR of 0.82. In the absence of a deflector plate, however, a power coefficient of 0.14 was measured (Kailash et al., 2012).

4.3. Gorlov turbine

Darrieus patented his novel innovation reaction turbine in 1931, which was superior to water wheel turbines. Scientists and engineers first coveted the Darrieus turbine due to its simplicity, capacity to operate at high speeds in low flow circumstances, and ability to maintain a large passage area without considerably increasing its diameter. Due to its pulsating nature, inability to self-start at low speeds, low efficiency, and blade wear failure due to its straight blade, which alters the angle of attack along a circular journey, it has not found widespread practical application. The helical turbine developed by Gorlov in 1994–1995 has rotor blades with a helical shape that lessen turbine pulsation while also increasing speed and efficiency (Gorlov, 1998).

Gorlov A. developed a helical turbine model for a small community or even a single home on a river or tidal coastline with a few kilowatts of power (Gorlov, 1998). The University of Michigan Hydrodynamics Laboratory tested a scaled-up model of a triple helix rotor in 1997. Three essential parameters – relative current velocity, the torque produced, and angular velocity – were monitored and recorded as the velocity varied from 1 to 10 f/s. The author claims the turbine was reasonably stable, had a tip speed ratio of 2.0–2.2 for maximum torque, and was 35% efficient (Gorlov, 1998).

Crouch presented a final research report (which covered the period from July 1996 to July 1998) to the US Department of Energy (DOE) (Crouch, 1998). This project investigated the applicability and advantages of a hydrofoil blade, a helical hydraulic turbine prototype. Additionally, the performance of helical and Darrieus rotors was compared. For this test, a rotor with the following specifications was founded: Three straight Darrieus blades and a helical rotor with three blades twisted at a 60° angle constitute the rotor. Both rotors have dimensions of 8.5 inches in height and 9 inches in diameter. Instead of optimizing the two turbines for maximum efficiency, this study attempted to compare them. Water heads from 1 to 8.5 inches and water velocity of 0.9 to 2.4 ft per second were used to test each turbine. Experiments using water head, water power, and peak turbine power were used to get the data. The water head and available water power both have an impact on a turbine's efficiency and power coefficient. The helical turbine outperformed the Darrieus rotor significantly in all crucial areas, such as turbine power, efficiency, and rotation speed. The rotor's solidity also contributes to the low water flow resistance of the helical rotor, which results in heads that are 30% to 50% greater than those of the Savonius turbine in all ranges of rotating velocity (Crouch, 1998).

A mathematical model was put forth by Gorban' et al. (2001) to forecast the hydrokinetic turbine's ideal efficiency in a free flow. This theoretical strength is required to build a rotor that can harness wind or water power. Due to the fact that it only considers a limited two-dimensional, partially penetrable plate in an incompressible fluid, this model works well for two-dimensional propellers but is less suitable for three-dimensional Darrieus and helical turbines. The authors claim that an aeroplane propeller can operate at a maximum efficiency of about 30% for free fluid, which is less than half of the Betz limit (60%). Betz's computations did not consider the fluid stream's curvature, which led to this overestimation. The researchers also showed that the three-dimensional helical turbine is 35% more effective than the two-dimensional propeller in water applications (Gorban' et al., 2001).

Sornes examined water current technology that produces an output of 0.5 to 5 kW in a free-flowing river (Sornes, 2010). The crass flow rotor is the Darrieus and Helical type rotor that can operate at a low-speed decrease (0.5 m/s). According to research by Gorlov and colleagues, the helical-bladed cross-flow turbine performs like a standard Darrieus cross-flow turbine.

Table 4.1
Comparison chart of horizontal axis turbine and cross-flow turbine.

SN.	Parameters	Horizontal axis turbine	Cross flow turbine
1	Operating range	Generally, 10 kW–2 MW	Generally, up to 10 kW
2	Area of operation	Tidal and marine application	River or marine application
3	Effect of direction of flow	Yawing mechanism need	No effect
4	Efficiency	40% (NAZMUL HUDA AL MAMUN, 2001); up to 71–76% (Müller et al. 2010), 65% (Zengin et al. 2016); 30% (Gorban' et al., 2001);	35% (Gorlov, 1998) or near about it.
5	Torque developed	Good torque develop	Not enough to self-start
6	Cut-in speed	Generally 2 m/s	Generally 0.6 m/s
7	Ducting	Difficult to duct	The cylindrical shape allows ducting
8	Self-starting	Self-start	Not self-start (Darrieus), Self-start (Savonius)
9	Design	Complicated	Simple
10	Noise	No noise as it is submerged in water	Less noise
11	Torque ripple	Not present	Present and affect the performance
12	Cavitation	Not issue	Major issue
13	Mounting of rotor	Bottom Mounted	Either floating or near-surface mounting
14	Performance	Better at high speed of the rotor (>3 m/s)	Better between moderate speed

Table 4.2
List of company which is currently working on low-speed hydrokinetic turbine.

S. N.	Manufacturer	Device name	Type of turbine	Min/max speed	Output power	Diameter (m)	Height (m)
1	Alternate Hydro solution Ltd. Canada	Free stream Darrieus Water Turbine	Cross axis	(0.8 m/s)/it depends on the diameter	1 to 3 kW	2.5	2.5
2	Seabell int. co. ltd (japan)	Stream	Dual cross axis	(0.6 m/s)/no limit	0.5 to 10 kW	Data not available	Data not available
3	Lucid Energy (USA)	Gorlov helical turbine	Helical Darrieus turbine	(0.6 m/s)/no limit	Up to 50 kW depending on the size	1	1
4	Thropton energy service (UK)	Water current turbine	Axial flow propeller	(0.5 m/s)/it depends on the diameter	2 kW	1.8	–
5	Electric Energy Ltd. (UK)	DuoGen	Axial flow propeller	(0.9 m/s)/(4.6 m/s)	100 W	0.31	Data not available
6	Electric Energy Ltd. (UK)	SailGen	Axial/Horizontal	3–4.1 m/s	125–280 W	Data not available	Data not available
7	Tidal Energy Pty. Ltd. (Australia)	Davidson Hill Venturi (DHV) Turbine	Cross Flow Turbine	1–2 m/s	0.77–6.16 kW	1.5	Data not available
8	New Energy Corporation	Current 025 Series	Cross axis	2.4–3.0 m/s	25 kW	4.8	2.4
9	New Energy Corporation	EnviroGen 005 Series	Cross axis	3 m/s	5 kW	1.5	0.75

4.4. Hybrid hydro kinetic turbines

Researchers have created a hybrid turbine design to overcome the beginning problem of the Darrieus turbine. In this design, two turbines with different initial torque characteristics are employed. A test revealed that the power coefficient of the Darrieus–Savonius hybrid turbine was lower than that of a single Darrieus rotor (between 0.16 and 0.24, or 70% of solo Darrieus). Additionally, because the two rotors operate with different characteristics in terms of fluid force, it was suggested that they not be used on the same axis of rotation (Kumar and Saini, 2015). However, according to Puspitasari and Sahim (2019) investigation, hybrid turbines have higher power than solo Darrieus (an increment of 18% power coefficient and 16% torque coefficient). The main difference is that the Savonius bucket uses a single deflector plate in front of the returning side. In most circumstances, performance improves by switching from a single Savonius rotor to a Savonius–Darrieus rotor or a Savonius–Darrieus rotor with a deflector (Saini and Saini, 2019).

4.5. Comparison table

There is a report on a 0.5–5 kW small-scale water current turbine that operates in free-flowing water (Sornes, 2010). An extensive list of tidal current turbine types, producers, and installation locations is provided in the article (Sleiti, 2017). In Tables 4.1 and 4.2, a comparison chart is made based on research articles and hydrokinetic manufacturing firms.

5. Design aspects of HKTs

While developing a hydrokinetic turbine the following factors need to be considered into account when designing a hydrokinetic turbine. Easy access to the location, choosing the proper equipment/devices and performing the necessary civil and electrical work are the essential aspect of harnessing the plentiful energy in nature. Determine the breakeven point in each aspect, then select the technology that best meets the requirements. A typical flow diagram of a design of a hydrokinetic turbine is shown in Fig. 5.1.

Environmental parameter: -

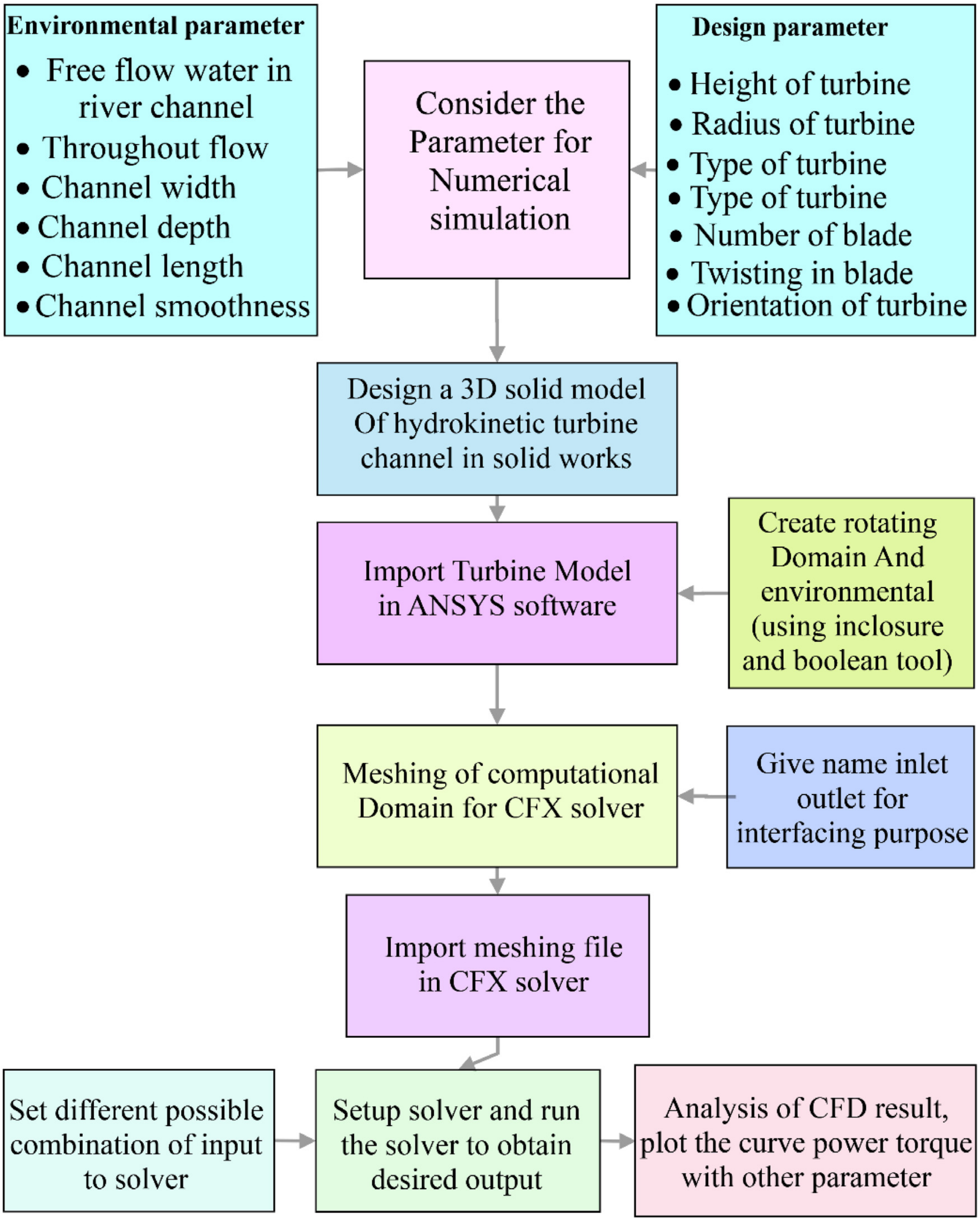

Fig. 5.1. Flow diagram of turbine design.

- Identifying a better turbine installation site (ocean current, tidal wave, or in-land river) (Zaidi and Khan, 2018).
- Water mean flow (speed fluctuation throughout the year) is necessary for the environmental impact analysis (Petrie et al., 2014).
- Availability of water flow throughout the year.

Civil work: -

- The rotor design is affected by a fixed structure or floating foundation (Khan et al., 2006).
- Impact of material used in civil work on nature (water, aquatic plants, animals, humans)
- The life cycle of civil work which contributes to GHG emissions.

Mechanical work: -

- Material for the turbine's rotor or other components
- Material's life expectancy (strength, erosion)
- Environmental impact (water, aquatic plants, animal, human) of materials used in mechanical work

Electrical work: -

- Electrical equipment (Alternator, Generator, Motor, etc.)
- Environmental impact (water, aquatic plants, animal, human) materials used in electrical work.
- Design of signal conditioning
- Performance analysis and optimization

6. Conclusions

The current methods and technologies for free-flowing water have been thoroughly reviewed, emphasizing the relevant performance and design parameters. Relevant literature has been analyzed for hydrokinetic turbine definition, classification, application area, performance parameters and design parameters to harness free-flow water energy.

- In the literature, a horizontal axis (axial turbine) with a robust mooring mounting has been used for the underwater bottom-mounted position into sea floor location majorly. However, floating structure mounting and Near-Surface structure mounting have been observed frequently in the river or along the seashore.
- Stall condition occurs in the vertical axis turbine; to avoid the stall, the angle of attack should keep below 9°. Also, Solidity and the number of blades are important parameters which affect the stall condition. Researchers use hybrid HKTs and variable pitch to gain the initial torque and avoid the stall condition.
- High Tip Speed Ratio increases the ventilation and cavitation effect; however, high TSR requires avoiding the stall condition. It has been observed that for proper generation of electricity and to prevent the impact of ventilation and cavitation effect, TSR should be at least 2.2. Moreover, to reduce the ventilation and cavitation effect, use the end plate in the rotor, and the rotor should mount below the water surface.
- By employing hydrofoil blades, the performance of HKTs can be improved. It is found that the non-symmetrical airfoil blades have a better response than the symmetrical ones. Blades like NACA0012, NACA0015, NACA0018, and NACA63-018 are widely used in hydro applications. There is still a need to optimize the rotor configuration (dimensions, solidity, and blade shape).
- Augmentation technique improves the performance of the turbine. The vertical axis turbines have been given more preference for using augmentation techniques as compared to horizontal axis turbines.
- There is less information available on rotor diameter with respect to the top to bottom water flow profile in rivers.
- A hydrokinetic turbine needs flowing water for its operation. However, it does not require a dam to store water. The flow available in the river is affected by the water withdrawal and dam. Most rivers, including the Brahmaputra, Ganga, Nile, Amazon, Rine, and Wanghee, have the capacity to flow throughout the year.
- Compared to dam hydropower, solar electricity, WECS, and other RE, HKTs have a cheap initial cost and are simple to install. Therefore, for distant villages, both large-scale and small-scale manufacturing is best suited for it. Consequently, like wind turbines, these small-scale units can be grouped together to fulfill our energy needs. The vast majority of people reside beside the river. Hence, Decentralized energy production can be possible based on location and demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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