Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1522745

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 7 - Issue 5: 917-927 / September 2024

ENERGY CONVERSION BY HELICAL HYDROKINETIC TURBINE IN A PIPE

Mehmet Salih TÜRKER[1]*, Mehmet İshak YÜCE[2]

[1]*Ankara Yıldırım Beyazit University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, 6010, Ankara, Türkiye*
[2]*Gaziantep University, Faculty Engineering, Department of Civil Engineering, 27470, Gaziantep, Türkiye*

Abstract: Hydrokinetic turbines are mechanisms designed for the purpose of utilizing the kinetic energy present in the movement of water bodies like rivers, tidal currents, or ocean currents, and transforming it into electrical power. These turbines' function based on a principle akin to that of wind turbines; however, they are positioned underwater to harness the energy of the water flow. This study focuses on the fundamentals of hydrokinetic turbines and presents existing research. Additionally, simulations have been conducted to observe how the hydrokinetic turbine responds hydrodynamically inside a pipe. A three-bladed vertical-axis helical hydrokinetic turbine was installed within a circular conduit and subjected to analysis under varying flow conditions. The k-ω SST turbulence model was employed in the analyses. The results indicated that increasing the turbine's angular velocity initially raises the torque and the power coefficient until a peak is reached, after which the power coefficient decreases. The highest power coefficient was observed at a flow velocity of 2 m/s. Moreover, consistent with previous studies, the hydrokinetic turbine within the pipe surpassed the Betz limit.

Keywords: Hydrokinetic energy, Pipe hydropower, Helical turbine, Vertical axis turbine, Current energy devices

***Corresponding author:** Ankara Yıldırım Beyazit University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, 6010, Ankara, Türkiye
Mehmet Salih TÜRKER https://orcid.org/0000-0001-7294-9424
Mehmet İshak YÜCE https://orcid.org/0000-0002-6267-9528

Received: July 31, 2024
Accepted: August 26, 2024
Published: September 15, 2024

Cite as: Türker MS, Yüce Mİ 2024. Energy conversion by helical hydrokinetic turbine in a pipe. BSJ Eng Sci, 7(5): 917-927.

1. Introduction

Renewable energy is energy that is generated from natural and replenishable sources such as sunlight, geothermal heat, wind, water, and biomass. For the last decades, renewable and sustainable energy conversion systems have been under investigation by many researchers. Since the most prevalent energy source is fossil fuel, therefore increasing energy demand, environmentally hazardous effects, and high prices of fossil fuel have demanded to find new, healthy, renewable, and sustainable energy sources. Renewable energy sources generate more economical energy in comparison with fossil and nuclear energy sources (OECD/IEA, 2024). The management planning and prioritization of energy resources should be decided well (Kantoglu and Argun, 2022). This issue is important in terms of commissioning different energy sources from day to day (such as aquifer thermal energy), for future energy consumption and meeting demand (Ertuğrul et al., 2018). Hydropower energy sources are the most utilized one, with 53.6 %, among renewable energy sources (Cuming et al., 2015). The reasons for this are reliability, availability, cost, and payback period of hydroelectricity.

Water, which covers about 70% of the Earth's surface, contains significant potential energy in the form of flowing water, ocean currents, and waves. This energy can be harnessed for various applications, highlighting the vast potential of water as an energy source. Hydropower, or hydroelectric power, is primarily generated by constructing dams to store the flowing water of rivers or streams. However, dam projects are extensive and costly, with substantial environmental impacts, including local climatic variations, and inundation of agricultural land, historical sites, and residential areas.

On the other hand, scientists and experts have been investigating clean and environmentally friendly alternative energy sources that demand lower investment costs and shorter installation times. (Al-Dabbagh, 2017). Through examining the historical evolution of hydropower, research and development have attained unprecedented levels. These endeavors encompass a broad spectrum of technical concepts and diverse application areas, indicating that hydrokinetic technologies could emerge as a successful alternative energy source in the future (Khan et al., 2009).

Kinetic energy has the potential to be transformed into power through the utilization of hydrokinetic turbines, which are alternatively referred to as low-head turbines. These turbines require minimal civil work and minimal environmental impact (Muratoglu, 2014). Unlike dams, hydrokinetic systems do not require water storage, making them a cost-effective and environmentally acceptable energy solution (Rajaonary,2016).

Hydrokinetic turbines, categorized as small-scale turbines concerning energy generation, have the potential to be installed in numerous units to enhance power generation, akin to wind turbine arrays (Muratoglu, 2014). Recently, some turbines have been utilized for urban applications, generating power for domestic, agricultural, and industrial districts (Casini, 2015). Studies regarding hydrokinetic turbines frequently reference the principles of wind turbine technology due to the analogous operational characteristics shared between the two systems, with distinctions primarily arising from the nature of the fluid involved. Hydrokinetic systems are commonly composed of a propeller equipped with blades that undergo rotational motion along either a horizontal or vertical axis. Water movement produces drag and lift forces that drive the rotational motion of the blades (Al-Dabbagh, 2017).

Horizontal-axis turbines are defined by an axis parallel to the fluid flow and are equipped with propeller-type rotors, commonly referred to as axial flow turbines. These turbines are frequently used in tidal energy converters and operate similarly to wind turbines in terms of their fundamental principles and design configuration. Conversely, vertical-axis turbines have a rotating shaft perpendicular to the flow. Hydrokinetic turbines are employed in various water flows, including rivers, tidal flows, and ocean currents. Recently, tubular turbines placed within pipes have also been introduced, as depicted in Figure 1. These in-pipe hydro systems can generate electricity under diverse pressure and flow conditions. They can be installed in pipes made of materials such as steel, ductile iron, and concrete, and are not affected by weather conditions (Casini, 2015).

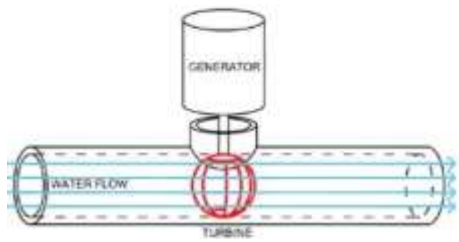


Figure 1. Placed hydrokinetic turbine in pipe.

Hydrokinetic turbines are important not just for generating energy, but also for managing water networks efficiently. By integrating these turbines into the system, the pressure within water networks can be optimized through a monitoring system powered by the turbine. This optimization helps prolong the service life of the pipes (Casini, 2015).

In this study, the hydrokinetic turbines were evaluated and reviewed. Furthermore, an example of a numerical study, which is related to a hydrokinetic turbine in a pipe, was investigated.

2. Background of Hydrokinetic Turbines

Mainly two types of hydrokinetic turbines exist in the application. They are horizontal and vertical axis turbines. Horizontal axis turbines have propeller-type rotors and an axis parallel to fluid flow. These turbines are known as axial flow turbines. These turbines, resembling wind turbines in concept and design, are commonly employed in tidal energy converters. A turbine's shaft is vertical when perpendicular to flow, called vertical axis turbine. Besides their application in river flows, tidal flows, and ocean currents, there is also a relatively new concept known as tubular turbines, which are installed within pipes.

Hydrokinetic power has come from the ancient Near East in the 3rd century BC with water mills, which are utilized for grain grinding. Because watermills drive mechanical operation with water motion. However, this technology is under development, especially in the last decades, and it is an emerging source of renewable energy.

Moreover, the Archimedean screw, which is an ancient invention (287-212 BC), can be categorized as hydrokinetic power because screw turbine uses the principle of the Archimedean screw. Schleicher et al. (2014) developed a unique Archimedean spiral rotor for a micro-hydro turbine. The maximum efficiency was obtained numerically at 72%, aligning well with experimental results, which ranged from 68.2% to 74.5% (Schleicher, 2014).

Furthermore, hydrokinetic systems can be economically competitive with fossil fuels and other energy sources. According to Güney and Kaygusuz (2010), the cost of generation ranges from $4.8 to $10.8 per kilowatt, but this amount can be reduced through further research and development (Güney and Kaygusuz, 2010).

The conversion system has a minimum environmental impact in comparison with other systems. Because there is no need for any huge construction work. Also, the system does not need to be set like a dam to create the head difference. Hydrokinetic turbines, unlike traditional dams, don't significantly alter water flow because they harness the kinetic energy of natural water currents rather than impeding or redirecting them. Therefore, the flow path of the water remains constant after placing the turbine in a river. Moreover, climate change is not observed due to the hydrokinetic conversion systems.

The blades of the hydrokinetic turbine can be helical or straight in shape. Al-Dabbagh and Yuce (2018) conducted a study indicating that the efficiency of a helical turbine outperforms that of a straight-blade turbine when both are of the same size and operate under identical conditions (Figure 2).

The tip speed ratio often denoted as TSR, represents the ratio between the rotational velocity of the rotor tips and the velocity of the free stream flow. Helical turbines have a promising future technology, if necessary, investigations are performed.

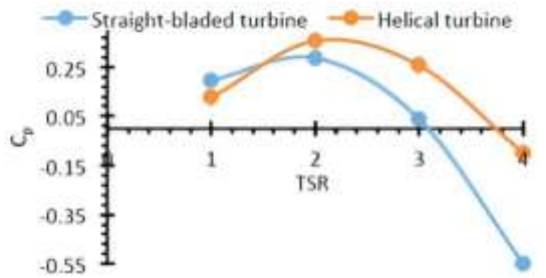


Figure 2. Power coefficient- tip sped ratio graph (Al-Dabbbagh and Yuce, 2018).

Two types of turbines are utilized for the hydrokinetic energy conversion systems. Horizontal and vertical axis turbines differentiate them according to their rotating axis. Vertical axis turbines offer advantages such as simple design, minimal tool requirements, and reduced noise. Vertical axis turbines have certain advantages such as simpler design, reduced tool requirements, and lower noise levels. However, they are plagued by issues like low starting torque, torque ripple, and lower efficiency. In contrast, horizontal turbines offer benefits stemming from the extensive knowledge base established through wind turbine technology, along with enhanced performance and the potential for further improvement with the use of ducts and similar components. (Khan et al., 2009).

Vibration is a serious problem for the turbines. However, some studies indicated that, this problem can be solved by flexible blades. Zeiner-Gundersen, 2015 investigated a vertical-axis turbine with flexible blades as shown in Figure 3. The study was done on a river in Norway and the power coefficient was as 0.37 for the flow velocity is 0.79 m/s case (Zeiner-Gundersen, 2015).

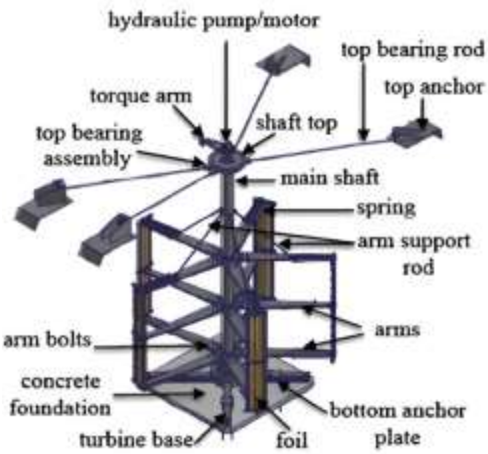


Figure 3. Components of turbine with flexible blades (Zeiner-Gundersen, 2015).

The hydrokinetic turbine provides a great opportunity for rural areas. Electricity can be generated as off-grid in rural areas by the turbines. Case studies were done in some regions of the world and they were edited by Anyi and Kirke (2010). In the study, they investigated case studies, which are done in Africa, Australia, South America, and the UK. The best efficiency for each study was 0.12, 0.50, 0.25, and 0.27 respectively as shown in Table 1. Generally, the main problem was debris and sedimentation for the open channel domain, because, sand, silt and other waste materials in the river cause damage and low efficiency for the turbines. Otherwise, high efficiency was observed due to the placed duct around the turbine (Anyi and Kirke, 2010).

Table 1. Characteristics of case studies reviewed by Anyi and Kirke (2010)

Study Region	Rotor diameter (m)	Flow velocity (m/s)	Overall efficiency (%)
Africa	1.8	1.5	12
South America	0.8	—	50
Australia	2	1.1	25
UK	2.75	1.25	27

According to investigations, augmented turbines provide more energy due to the increasing flow velocity of the fluid. There exists Betz law, which limits the efficiency of the turbine for bare turbines. The law expresses that, the efficiency of traditional open turbines can't exceed the %59 efficient rate. However, this law does not apply to the ducted or augmented turbines. Therefore, more power efficiency can be obtained with ducted turbines, although it is more expensive (Khan et al., 2009).

Wind turbine technology experiences stated that an augmented wind turbine creates sub-atmospheric pressure, so more air passes through the blade plane (Phillips et al., 1999). Moreover, a wind turbine with augmentation produces approximately four times more power compared to a standard turbine of the same size. (Fletcher, 1980).

Usually, the hydrokinetic turbine studies are based on the wind turbine approach. Nunes et al. (2019) completed the development of a diffuser-enhanced propeller hydrokinetic turbine (Nunes et al., 2019). A wind turbine approach is implemented in the study. The study showed that different kinds of diffusers increase the efficiency of the turbines as shown in Table 2.

Table 2. Results of Shrouded Turbines (Nunes et al., 2019).

Configuration	Power Coefficient	Tip Speed Ratio
Free Runner	0.39	1.4
Diffuser S1223	0.58	2.0
Diffuser Lens CII	0.70	2.3

Shahsavarifard et al. (2015) investigated the impact of a shroud on a horizontal hydrokinetic turbine. An experiment conducted at the University of Manitoba involved testing a 19.8 cm diameter turbine in a water channel. The study evaluated two shroud designs, comparing power and thrust curves between shrouded and unshrouded turbines across their performance range. Results indicated that the power coefficient surpassed 91% without the use of a shroud (Shahsavarifard et al., 2015).

Pudur et al. (2022) revealed that a two-blade Savonius rotor stands out as the most efficient for harvesting hydrokinetic energy compared to three and four-blade variants. With the aid of a suitable gear system, power extraction from free-flowing rivers is feasible. In the study, observation indicated that the two-blade rotor experiences minimal balancing issues due to high water turbulence, whereas the four-blade rotor rotates smoother compared to the three-blade variant. Moreover, theoretical analysis also supports these findings, suggesting that an increase in the number of blades leads to a decrease in turbine revolution. However, practical experimentation revealed discrepancies between theoretical predictions and observed behavior, particularly attributed to the significant jerking effect in the two-blade system caused by the substantial distance between subsequent blades. They concluded that the experiment serves to validate the theoretical concepts (Pudur et al., 2022).

3. Hydrokinetic Turbine in Pipe

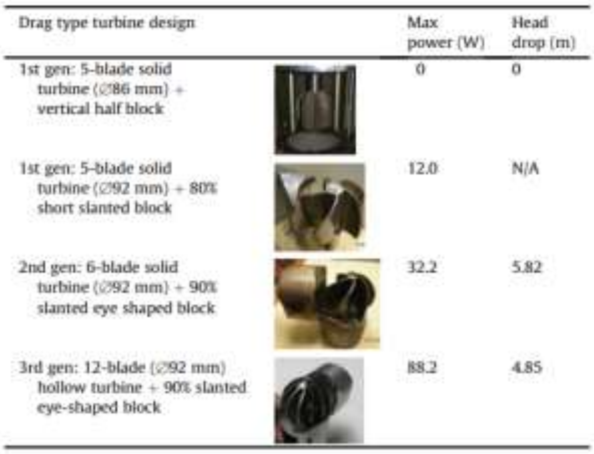
Recently, the adoption of hydrokinetic turbines installed within pipes has gained popularity due to their higher efficiency compared to bare turbines. Additionally, these systems can replace Pressure Reducing Valves (PRVs) to generate power instead of dissipating energy. The enclosed nature of the pipe system offers advantages such as predictability and protection from external factors like debris and fish.

Water loss in the water supply network is the main problem for the municipalities. To prevent water loss, some devices are needed such as a flow meter, data logger, pressure-reducing valve…etc. Therefore, energy supply is important for these systems. Hydro Spin Company installed a turbine into the pipe to supply energy for the measurement devices to observe the water losses in the water distribution network (Hydro Spin, 2017).

Pressure-reducing valves (PRV) are designed to decrease the water pressure to the desirable level for safety downstream. PRV breaks the pressure on the water distribution networks, which are utilized in residential, industrial … etc. As a summary, excessive energy in the systems is broken by PRV. However, excess pressure can be turned into energy by integrating a hydrokinetic turbine into the system. With present technology, at least the need of one hundred homes of electricity can be supplied in this way. Turbine can be placed in a pipe, especially a gravitational water network system. Onedia and Thorn Run reservoirs had PRV in the network. In 2012, the Rentricity Company installed an energy-producing turbine system onto the existing infrastructure, resulting in an annual generation of 131.4 MWh.

Hong Kong Polytechnic University, together with Sino Group and Arup, initiated a groundbreaking research endeavor focusing on in-building hydropower. The objective was to harness untapped water head in pipelines. The first installation was implemented at the Olympian City 2 shopping mall, powering the elevator lighting system. This initiative is projected to save approximately 700 kg of carbon dioxide emissions annually, equivalent to the environmental benefit of around 30 trees.

Chen et al. (2013) conducted a study on hydrokinetic turbines placed within pipes, focusing on a vertical axis turbine designed for monitoring water supply networks. The turbine, featuring a 100 mm pipeline, aimed to maximize energy generation with a water velocity of 1.5 m/s and an estimated water head drop of 5 m. Through 20 simulations and experiments, they achieved a power generation of 88.2 W using a hollow turbine with an eye-shaped block, as illustrated in Figure 4 (Chen et al., 2013).



Drag type turbine design	Max power (W)	Head drop (m)
1st gen: 5-blade solid turbine (∅86 mm) + vertical half block	0	0
1st gen: 5-blade solid turbine (∅92 mm) + 80% short slanted block	12.0	N/A
2nd gen: 6-blade solid turbine (∅92 mm) + 90% slanted eye shaped block	32.2	5.82
3rd gen: 12-blade (∅92 mm) hollow turbine + 90% slanted eye-shaped block	88.2	4.85

Figure 4. Testing results of turbine (Chen et al., 2013).

Turbine material has effects on the turbine performance. Oladosu and Koya (2018) studied how turbines in water pipes could generate electricity. The study conducted turbine models and simulations implemented in water distribution network pipes to generate electricity using lift-based turbines. They found that the available power depended on factors such as the density of the turbine material, discharge, and pipe diameter. In their study, a stainless-steel turbine achieved a power output of 1080 W in a 250 mm diameter pipe, while an aluminum turbine reached a peak power value of 1663 W (Oladosu and Koya, 2018).

A water supply and distribution system's inline tubular propeller was the subject of an experimental study by Samora et al. (2016). The 85 mm diameter type was tested and optimized for flows between 5 and 50 m^3/h, removing heads that were less than 7.5 mWc. The optimal efficiency points, approximately 63.75%, were attained with a head of 0.34 bar and a flow rate of 15.95 m^3/h. Furthermore, it was determined that the highest power output of 328 W could be obtained at a rotational speed of 1500 rpm. With an efficiency of 60%, the study indicates that the turbine has room for improvement given the positive and satisfactory results (Samora et al., 2016).

Bizhanpour et al. (2023) investigated the performance of vertical-axis in-pipe turbines equipped with different types of deflectors across various operational conditions to identify the optimal deflector geometry for harnessing energy from urban water supplies. The research combines numerical simulations, validated by experimental tests. The study primarily aims to enhance turbine performance under off-design conditions by utilizing deflectors, commonly employed to direct flow towards turbine blades effectively. Five different deflector geometries have been investigated and the study numerically assessed their impact on the efficiency of an in-pipe Savonius turbine across varying flow rates. Results indicated that a dynamic guide vane deflector, capable of adjusting its position dynamically at different flow rates, significantly enhanced performance outside the optimal design point. Furthermore, a novel systematic design procedure was proposed for such deflectors within the constraints of small-scale pipes. Numerical simulations were validated against experimental data from the provided test rig, ensuring accuracy (Bizhanpour et al., 2023).

Kumar and Sarkar (2023) employed a spherical-shaped Darrieus hydrokinetic turbine (SDHKT) within the pipeline. Six distinct SDHKT models were devised by altering diameters, solidity, and blade number. In the study, performance assessment was conducted through experimental and numerical analyses under varying pipe flow conditions. As a result, turbine performance exhibited enhancement with an increased blockage ratio. Also, pressure drop across the turbines escalated with a rising Tip Speed Ratio (TSR) and increased pipe flow (Kumar and Sarkar, 2023).

4. Material and Methods

Several non-dimensional parameters are essential for evaluating the performance of hydrokinetic turbines, as they significantly influence their overall efficiency. These parameters include aspect ratio, tip speed ratio, lift and drag forces, solidity, and overall efficiency.

4.1. Tip Speed Ratio

One important metric in hydrokinetic turbines is the tip speed ratio (TSR), which is represented by λ and is the ratio of the rotational velocity of the rotor tips to the flow's free stream velocity. It plays a key role in determining the optimal angular velocity range of the turbine for generating maximum power. The relationship between turbine performance and TSR is often depicted graphically using the Cp-TSR curve. The TSR value can be calculated using equation 1.

$$\lambda = \frac{\omega R}{v_\infty} \quad (1)$$

(ω) is the angular velocity, (R) is the radius, and (v) is the flow velocity in the equation. According to Gorlov (1998), in order to produce more torque and avoid cavitations for a three-bladed helical turbine, the TSR value should be between 2-2.2 (Zingman, 2007).

The power coefficient usually increases as the tip speed ratio (TSR) goes up, but only to a certain point. After reaching this point, if the TSR keeps rising, the power coefficient starts to drop. This increase begins at the cut-in speed, where the best TSR value is found. When the cut-off speed, or stall point, is reached, the fluid inside the turbine starts to separate, causing the performance to decrease.

4.2. Solidity

The solidity, expressed as the ratio of chord length to turbine circumference, is calculated using equation 2.

$$\Sigma = \frac{c\,x\,n}{2\pi R} \quad (2)$$

where (n) is the number of blades, (c) is the chord length, (R) is the turbine radius, and (σ) indicates the solidity of the turbine. Increasing solidity affects turbine performance and rotational speed by raising flow resistance. The turbine functions as a barrier, impeding water flow and preventing the production of electricity, when the angular velocity is greater than the flow velocity. Thus, the number of blades must be carefully selected to optimize turbine performance during the design process. Higher solidity values result in increased torque and reduced TSR, leading to poorer turbine performance. This relationship between torque coefficient and TSR is illustrated in Figure 5.

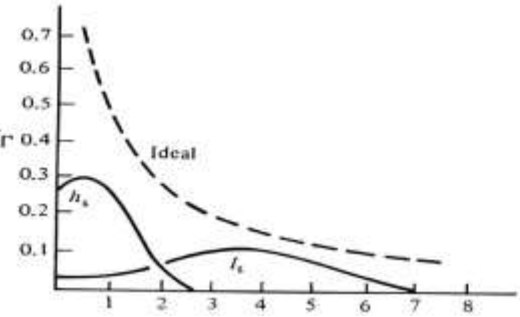


Figure 5. Torque coefficient – TSR relationship (Al-Dabbagh, 2017).

4.3 Lift and Drag Effects

Lift and drag forces are key factors in determining the performance of turbine blades. These forces result from changes in velocity and pressure, as well as variations in viscosity. Hydrodynamic loads are influenced by factors such as velocity, density, frontal areas, and the size and orientation of the body (Çengel, 2006). Figure 6 illustrates the forces acting on the hydrofoil section of the turbine.

The drag force, aligned with the flow direction, arises from factors such as viscous effects, friction, and pressure distribution disparities across the hydrofoil section. The drag force is influenced by both surface friction and pressure drag coefficients acting on the turbine.

Conversely, the lift force is generated by variations in pressure between the upper and lower surfaces of the hydrofoil. The camber induces higher fluid velocities on the upper surface, resulting in lower pressure compared to the lower surface. This pressure differential gives rise to lift forces, directed perpendicular to the chord line.

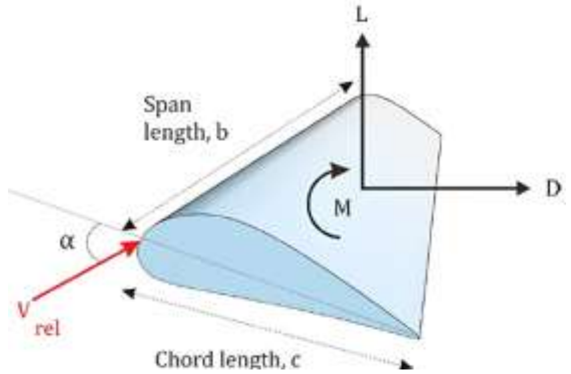


Figure 6. Forces on the hydrofoil (Muratoglu, 2014).

4.4. Aspect ratio

The aspect ratio, AR, reflects the overall dimensions of the turbine's axial length. It's computed by dividing the blade height by the rotor radius (D = 2R), as depicted in Figure 7 (equation 3), primarily relevant for vertical axis turbines. (D'Ambrosio and Medaglia, 2010; Brusca et al., 2014).

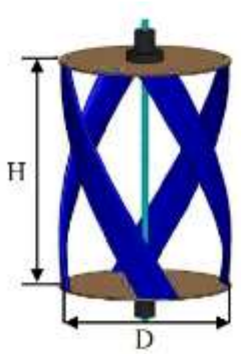


Figure 7. Aspect ratio of vertical turbine.

$$AR = \frac{H}{R} \quad (3)$$

It can also be defined as the ratio between the chord length of the hydrofoil to the blade length for Darrieus and Gorlov turbines, where the general design consists of blades with a hydrofoil cross-sectional shape (equation 4) (Al-Dabbagh, 2017).

$$AR_B = \frac{L}{c} \quad (4)$$

where (c) is the chord length of the hydrofoil (m), L is the blade length (m).

The aspect ratio is a critical factor in determining the torque and performance coefficient of the turbine. Typically, higher aspect ratios lead to increased power coefficients. However, exceeding a certain limit can lead to blade deflection and vibration issues. Moreover, limitations on the aspect ratio are imposed by installation constraints and the size of the domain where the turbine will be placed (Al-Dabbagh, 2017).

4.5. Power Coefficient (Cp)

The performance of the turbine is characterized by the efficiency or performance coefficient, a dimensionless parameter calculated using the following equations 5, 6 and 7.

$$P_t = T\,\omega \quad (5)$$

$$P_w = 0.5\rho A v^3 \quad (6)$$

$$C_p = \frac{P_t}{P_w} = \frac{T\omega}{0.5\rho A v^3} \quad (7)$$

where:

C_p: efficiency

P_t: output power.

P_w: available energy in water.

T: Torque (N-m).

ω: angular velocity of the turbine (rad/s).

ρ: density of water (kg/m3).

A: frontal cross-sectional area of turbine (m2).

v: fluid velocity (m/s)

4.6. The Betz Limit

The Betz limit represents the maximum theoretical power coefficient achievable by a hydrokinetic turbine. At the Betz limit, theoretical efficiency is roughly 59.3%. Figure 8 shows the tip speed ratio versus power coefficient for a variety of turbine designs and their respective Betz limitations.

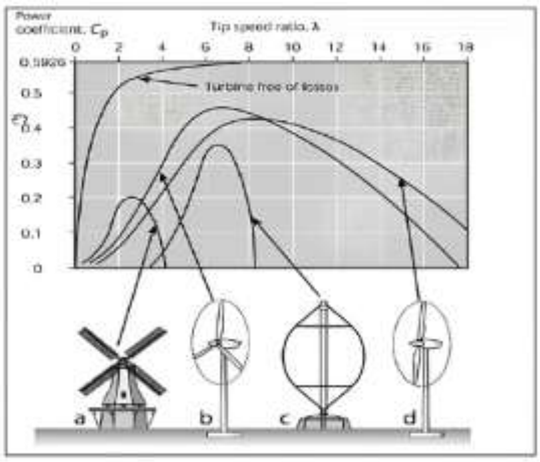


Figure 8. Power coefficient and betz limit of turbines (D'Ambrosio and Medaglia, 2010).

The Betz limit typically applies to free streams without constraints. However, studies have shown that the Betz limit can be surpassed when turbines are positioned within a pipe or duct. For instance, an inline tubular propeller for a water supply system was studied by Samora et al., and they were able to attain a maximum efficiency of 63.75% (Samora et al., 2016).

5. Case Study

This part presents a simulation of the flow field and uses ANSYS FLUENT 17.1 to evaluate a hydrokinetic turbine example, a Gorlov type 3-bladed hydrokinetic turbine. This chapter also provides an explanation of the simulation steps.

5.1. Turbine Geometry

The turbine blades exhibit quasi-rotation around their vertical axis, as depicted in Figure 9. This turbine is categorized as a vertical axis type, characterized by a rotating vertical shaft submerged in water. To reduce the complexity and duration of the analysis, the shaft and support components are omitted. These components are not expected to significantly impact the flow characteristics; thus, their exclusion does not alter the analysis results.

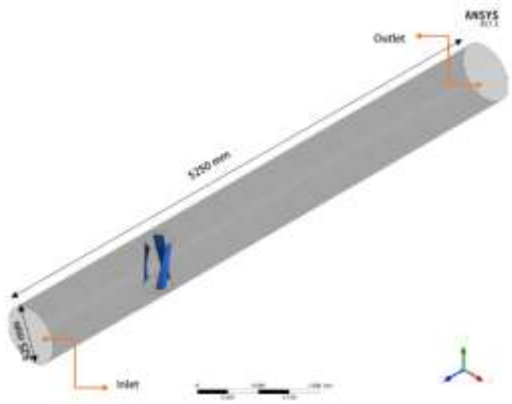


Figure 9. Isometric view of the pipe.

As indicated in Table 3, the turbine is mounted in a pipe that has a diameter of 525 mm and a length of 5250 mm. It has three blades that are designed by the NACA 4415 airfoil. It is placed close to the inlet to gauge its effect on the flow.

Table 3. Turbine properties

Dimension	Length (mm)
Height	450
Width	219
Diameter of Turbine	219
Diameter of Pipe	525
Length of Pipe	5250

5.2. Numerical simulation

The complete domain and geometry are assigned to the numerical simulation once it has been meshing. First, the physical and hydrodynamic parameters are provided as Table 4 illustrates. The density of the fluid is 998.2 kg/m^3 (water) at 20 °C temperature.

Table 4. Fluid Properties

Property	Value
Density	998.2 kg/m^3
Viscosity	0.001003Kg/m-s
Temperature	20 °C

The pressure-based absolute solver is utilized, appropriate for low-speed and incompressible flow conditions, in contrast to the density-based solver, which is applied to high-speed and compressible flows. The k-ω SST (Shear Stress Transport) model is selected as the turbulence model for this study. Throughout the various simulation scenarios, all these parameters (pressure-based and k-ω SST) were maintained as constants.

6. Results and Discussion

In the simulations, different flow velocities of 1 m/s, 1.5 m/s, and 2 m/s are analyzed. While selecting the flow velocities, studies in the literature and water velocities used in existing water distribution networks were taken into account. The results are consistent across these different flow velocities. Detailed visual outputs, including velocity contours, pressure contours, and velocity streamlines, are presented for each case at maximum efficiency and TSR values. Other parameters, such as pipe diameter and turbine location, are kept constant. The computational fluid dynamics (CFD) analysis demonstrates significant advantages in terms of time and cost over experimental studies.

6.1. Distribution of Velocity Contour

The depiction of velocity distribution within the pipe is presented via contour plots, illustrated in Figure 10. The direction of flow proceeds from right to left. Three different cases were analyzed for inlet velocities of 1 m/s, 1.5 m/s, and 2 m/s. The outlines delineate a notable enhancement in the flow velocity within the turbine section for each scenario. Upon the inlet flow velocity reaching 1 m/s, a surge to approximately 3.5 m/s was evident within the turbine section. This escalation remained uniform throughout all three scenarios. After traversing the turbine section, the flow velocity commenced reverting to its initial condition. The most elevated velocity outlines were identified surrounding the turbine blades, with no-slip conditions being observed at the pipe boundaries (Turker, 2019).

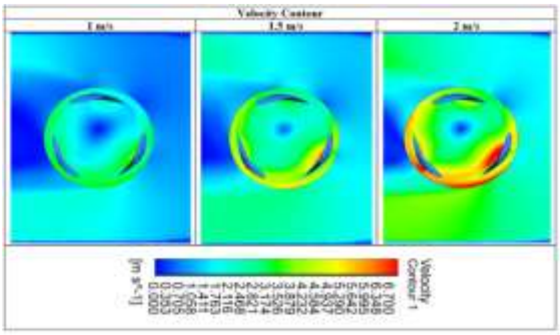


Figure 10. Velocity contours.

6.2. Pressure Contours Distribution

The pressure distribution is illustrated through contour plots in Figures 11 and 12. Figure 11 shows the pressure contours for the entire domain, while Figure 12 focuses on the pressure distribution around the blades. The flow direction is from right to left in both figures. The pressure at the tip of the blades increases with the flow velocity, indicating the impact of the flow dynamics on the turbine blades (Turker, 2019).

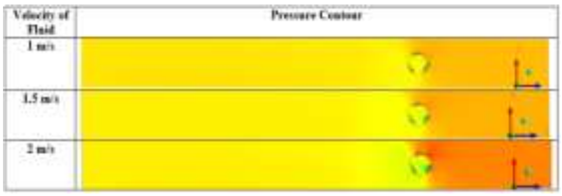


Figure 11. Pressure contours.

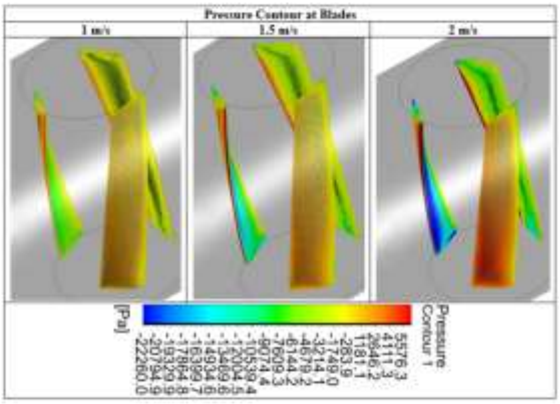


Figure 12. Pressure contours at blades.

6.3. Distribution of Velocity Vectors

The vector distribution for each case is depicted in Figure 13, clearly demonstrating the turbine's rotation on its vertical axis driven by the vector movements. Additionally, velocity streamlines are presented in Figures 14 through 16. As the flow velocity increases from 1 m/s to 2 m/s, the rotation speed of the turbine correspondingly increases, thereby enhancing the generated power. The streamlines indicate a significant velocity increase around the turbine with rising flow velocity (Turker, 2019).

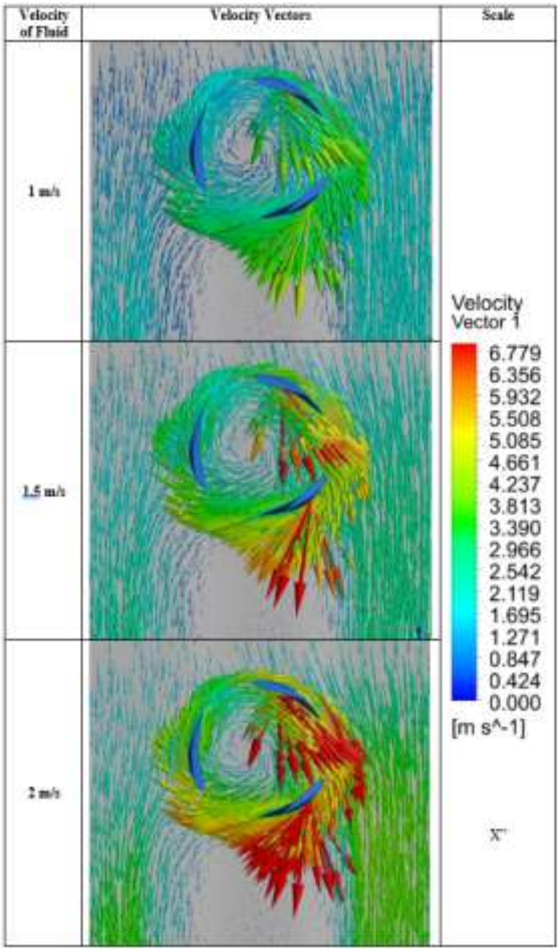


Figure 13. Velocity vectors for different flow velocity cases.

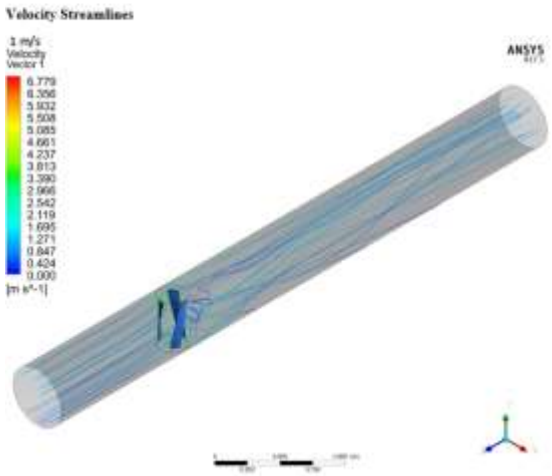


Figure 14. Streamlines for the case of 1 m/s.

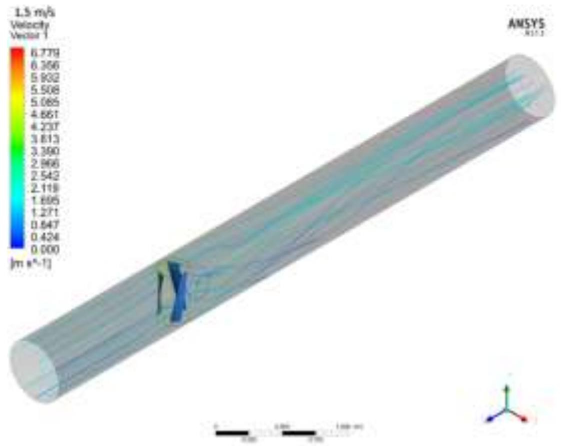


Figure 15. Streamlines for the case of 1.5 m/s.

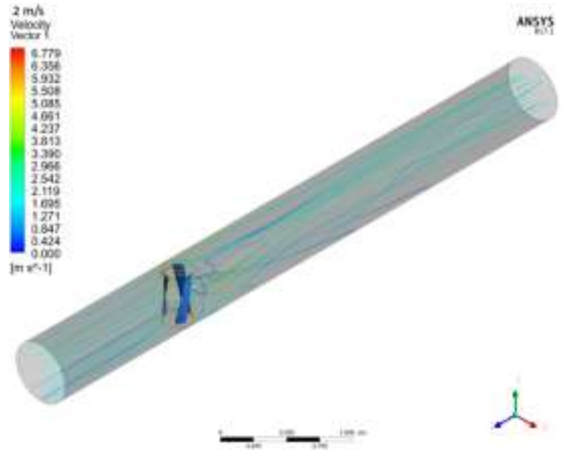


Figure 16. Streamlines for the case of 2 m/s.

6.4. Results of the simulations

The vertical hydrokinetic turbine of the helical (Gorlov) type was examined at various flow rates. Using a particular formula, the power coefficient (Cp) was determined as the turbine power to potential power ratio. The best power coefficients were 0.69 at 1 m/s, 0.71 at 1.5 m/s, and 0.75 at 2 m/s flow velocities, according to the results, which are shown in Table 5. It was found that up to a certain angular velocity, power coefficients and torques both rose; beyond that, they started to decline. This decrease happens because the rotating turbine begins to act like a thick wall at greater angular velocities, impeding flow and decreasing efficiency (Turker, 2019).

Table 5. Power coefficient for various flow velocities (Turker, 2019)

Flow Velocity (m/s)	TSR	W (rad/s)	T (N.m)	Potential Power	Turbine Power	Cp
1.00	0.50	4.57	0.40	49.19	1.80	0.04
1.00	1.00	9.13	1.54	49.19	14.03	0.29
1.00	1.50	13.70	2.47	49.19	33.78	0.687
1.00	2.00	18.26	1.87	49.19	34.13	0.694
1.00	2.50	22.83	0.69	49.19	15.78	0.32
1.00	3.00	27.40	-0.43	49.19	-11.80	-0.24
1.50	0.50	6.85	0.94	166.00	6.41	0.04
1.50	1.00	13.70	3.71	166.00	50.76	0.31
1.50	1.50	20.55	5.67	166.00	116.53	0.70
1.50	2.00	27.40	4.28	166.00	117.34	0.71
1.50	2.50	34.25	1.60	166.00	54.96	0.33
1.50	3.00	41.10	-0.93	166.00	-38.05	-0.23
2.00	0.50	8.73	1.65	393.49	14.38	0.04
2.00	1.00	17.47	5.51	393.49	96.16	0.24
2.00	1.50	26.20	10.25	393.49	268.64	0.68
2.00	2.00	34.93	8.47	393.49	295.77	0.75
2.00	2.50	43.67	3.99	393.49	174.18	0.44
2.00	3.00	52.40	-0.51	393.49	-26.57	-0.07

The graphs made the turbine's response to rising angular velocity easier to see. Figure 17 displays the graphs of the tip speed ratio (TSR) vs power coefficient (Cp). The graph indicates that the power coefficient started to decline when it reached its highest value. The maximum power coefficient recorded was 0.75 at a 2 m/s flow rate (Turker, 2019).

The best efficiencies are obtained at tip speed ratios (TSR) of 2, as shown in Figure 17. At a fluid velocity of 2 m/s, a maximum efficiency of roughly 0.75 is recorded. The power coefficient starts to decline at this point (TSR = 2), suggesting that the turbine behaves more like a solid barrier after a certain angular velocity (Turker, 2019).

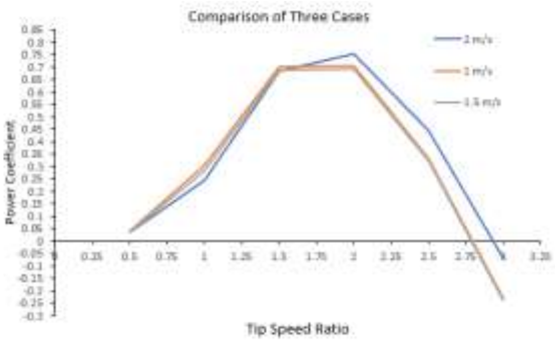


Figure 17. Comparison of the Cp - TSR graphs.

7. Conclusion

Hydrokinetic energy harnesses water's kinetic energy for electricity generation. It's sustainable and eco-friendly but less efficient than conventional hydropower, requiring further improvement.

In this study, hydrokinetic turbines were reviewed in different aspects. Various studies and case studies were presented. In addition, some parameters have an impact on the design of the turbines. Additionally, this study stands out from previous hydrokinetic turbine research by focusing on a helical (Gorlov) type vertical axis turbine installed within a pipe, simulated using ANSYS FLUENT CFD software. Vertical axis turbines offer advantages over horizontal axis counterparts, including independence from the current direction, easier generator placement, stacking capability, and self-starting without the need for pitching mechanisms. Moreover, turbines installed in pipes offer predictability advantages over those in open channels, as the flow can be controlled and unaffected by external factors such as debris, climate change, or flow regime variations.

Three distinct velocity scenarios were simulated involving a turbine within a fully developed circular pipe flow. The computational fluid dynamics (CFD) simulations employed the Reynold-Averaged Navier Stokes equations, with the k-ω SST turbulence model applied uniformly across all scenarios.

Visualizations including velocity and pressure contours, velocity vectors, and velocity streamlines were generated. Additionally, results were summarized in tables and graphs. The maximum efficiency of 0.75 was achieved at a flow speed of 2 m/s with a tip speed ratio of 2. This study sheds light on hydrokinetic turbine performance, particularly within pipes, and highlights the potential to surpass the Betz limit in pipe-based systems. It also provides insights into using CFD simulations to optimize hydrokinetic turbine efficiency.

Additionally, the hydrokinetic turbine system can serve dual purposes in water distribution systems by acting as a pressure reducing valve (PRV) while simultaneously generating electricity. Pressure management is a critical concern for municipalities, and turbines offer a solution by reducing pressure and preventing leakage. Moreover, the enclosed nature of the turbine within the pipe minimizes its impact on aquatic life, addressing environmental concerns.

As a result, hydrokinetic turbine technology holds promise for the future, offering potential benefits in renewable energy generation and water management. However, further advancements are necessary to enhance its efficiency and expand its applicability in various settings. Continued research and development efforts are crucial to unlock the full potential of this technology and address existing challenges.

Author Contributions

The percentage of the author(s) contributions is presented below. The author reviewed and approved the final version of the manuscript.

	M.S.T	M.İ.Y
C	35	65
D	60	40
S	40	60
DCP	60	40
DAI	50	50
L	60	40
W	70	30
CR	40	60
SR	60	40
PM	40	60
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

References

Al-Dabbagh MA, Yuce MI. 2018. Simulation and comparison of helical and straight-bladed hydrokinetic turbines. Int J Renew Ener Res, 8(1): 514-519.

Al-Dabbagh MA. 2017. Simulation of Helical hydrokinetic turbines in river flows. PhD Thesis, Gazinatep University, Institute of Science, Gaziantep, Türkiye, pp: 167.

Anyi M, Kirke B. 2010. Evaluation of small axial flow hydrokinetic turbines for remote communities. Ener Sustain Devel, 14: 110-116.

Bizhanpour A, Hasanzadeh N, Najafi AF, Magagnato F. 2023. Investigation of different deflector geometry and mechanism effect on the performance of an in-pipe hydro Savonius turbine. Appl Ener, 350: 121697.

Brusca S, Lanzafame R, Messina M. 2014. Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance. Int J Ener Environ Eng, 5: 333-340.

Casini M. 2015. Harvesting energy from in-pipe hydro systems at urban and building scale. Int J Smart Grid Clean Ener, 72: 00196. https://doi.org/10.12720/sgce.4.4.316-327

Çengel YA, Cimbala JM. 2006. Fluid mechanics fundamentals and applications, Ebook. McGraw Hill, New York, US, pp: 1005.

Chen J, Yang HX, Liu CP, Lau CH, Lo M. 2013. A novel vertical axis water turbine for power generation from water pipelines. Energy, 54: 184-193. https://doi.org/10.1016/j.energy.2013.01.064

Cuming V, Mills L, Strahan D, Boyle R, Stopforth K, Latimer S, Becker L. 2015. Global trends in renewable energy investment 2015. https://www.fs-unep-centre.org/wp-content/uploads/2019/11/Global_Trends_Report_2015.pdf (accessed date: May 11, 2023).

D'Ambrosio M, Medaglia M. 2010. Vertical axis wind turbines: History, technology and applications. Polytechnic International Press, Montreal, Quebec, Canada, pp: 152.

Ertuğrul NA, BağcI ZH, Ertuğrul ÖL. 2018. Aquifer thermal energy storage systems: Basic concepts and general design methods. Turkish J Eng, 2(2): 38-48.

Fletcher CAJ. 1980. Diffuser-augmented wind turbine analysis. Institution of Engineers, Vienna, Australia, pp: 435-438.

Gorlov A. 1998. Development of the helical reaction hydraulic turbine. Final technical report, July 1, 1996--June 30, 1998 (No. DOE/EE/15669-T1). Northeastern University, Boston, MA, USA, pp: 124.

Güney MS, Kaygusuz K. 2010. Hydrokinetic energy conversion systems: A technology status review. Renew Sustain Energy Rev, 14(9): 2996-3004.

Hydro Spin. 2017. https://www.h-spin.com/ (accessed date: May 10 2024)

Kantoglu B, Argun ID. 2022. Evaulation of renewable energy source alternatives prioritization. Turkish J Eng, 7(1): 1-8.

Khan MJ, Bhuyan G, Iqbal MT, Quaicoe JE. 2009. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. Appl Ener, 86: 1823–1835. https://doi.org/10.1016/j.apenergy.2009.02.017

Kumar R, Sarkar S. 2023. Performance analysis of spherical-shaped Darrieus hydrokinetic turbine for an in-pipe hydropower system. Ener Conver Manag, 294: 117600.

Muratoglu A. 2014. Design and simulation of a riverine hydrokinetic turbine. PhD Thesis, Gazinatep University, Institute of Science, Gaziantep, Türkiye, pp: 238.

Nunes MM, Mendes RCF, Oliveira TF, Brasil Junior ACP. 2019. An experimental study on the diffuser-enhanced propeller hydrokinetic turbines. Renew Ener, 133: 840-848. https://doi.org/10.1016/j.renene.2018.10.056

OECD/IEA. 2024. https://www.iea.org/ (accessed date: May 10, 2024).

Oladosu TL, Koya OA. 2018. Numerical analysis of lift-based in-pipe turbine for predicting hydropower harnessing potential in selected water distribution networks for waterlines optimization. Eng Sci Technol Int J, 21: 672-678.

Phillips DG, Richards PJ, Mallinson GD. 1999. Computaional modelling of diffuser design for a diffuser augmented wind turbine. Phoenics J Comput Fluid Dynam Appl, 12: 158-172.

Pudur R, Rajak MK, Zafar S. 2022. Analysis of savonius rotor with multiple blades for hydrokinetic application. Springer, Singapore, pp: 623-634.

Rajaonary TT. 2016. Design and optimization of a hydrokineic turbine with CFD. MSc Thesis, Gazinatep University, Institute of Science, Gaziantep,Türkiye, pp: 99.

Samora I, Hasmatuchi V, Minch-Alligni C, Franca MJ, Schleiss AJ, Ramos HM. 2016. Experimental characterization of a five blade tubular propeller turbine for pipe inline installation. Renew Ener, 95: 356-366.

Schleicher W, Ma H, Riglin J, Kraybill Z, Wei W, Klein R, Oztekin A. 2014. Characteristics of a micro-hydro turbine. J Renew Sustain Ener, 6: 013119. https://doi.org/10.1063/1.4862986

Shahsavarifard M, Bibeau EL, Chatoorgoon V. 2015. Effect of shroud on the performance of horizontal axis hydrokinetic turbines. Ocean Eng, 96: 215-225.

Turker MS. 2019. Design of a hydrokinetic turbine in a pipe. MSc Thesis, Gaziantep University, Institute of Science, Gaziantep, Türkiye, pp: 80.

Zeiner-Gundersen DH. 2015. A novel flexible foil vertical axis turbine for river, ocean, and tidal applications. Appl Ener, 151: 60-66. https://doi.org/10.1016/j.apenergy.2015.04.005

Zingman AAO. 2007. Optimization of a Savonius rotor vertical-axis wind turbine for use in water pumping systems in rural honduras. PhD Theis, Massachusetts Institute of Technology, Massachusetts, USA, pp: 163.