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Research Article

Concept design and simulation analysis of floating water turbine

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ABSTRACT

Researchers in Malaysia are attempting to advance and develop the renewable energy sector in response to increased emissions, fossil fuel exhaustion, and the need for electricity in remote areas. Water turbines are known to have a high potential for generating electricity. This paper aims to propose a new floating turbine concept and analyse it using Computational Fluid Dynamics. In the study, finding the idea started with infaring the market needs in Malaysia and transforming them into design requirements by utilising tools like the requirement table and the objective tree. After that, the requirements were changed to a function box to understand the functionality of the turbine. A task specification table was implemented to assign the specifications and create four concepts. One of the four concepts was chosen using the evaluation chart to undergo CFD analysis. The selected concept was validated using the dynamic mesh technique in ANSYS Fluent. A grid independence study and boundary sensitivity study were conducted to ensure the accuracy of the solution. The sliding mesh technique measured the performance of the turbine. It was found that the proposed turbine has higher performance than typical Savonius turbines, from 0.1 to 0.42 and 0.8 to 1.3 C_p (Turbine Performance) and TSR (Tip Speed Ratio), respectively.

1. INTRODUCTION

The dependency and interest in clean energy are increasing due to the exhaustion of fossil fuels, pollution, and climate change. Therefore, clean energies need to be more reliable and predictable to meet the demands. One of the most reliable and predictable sources is tidal and river energy [1]. Tidal energy alone is projected to have a global capacity of 120 GW [2, 3]. Water turbines have been recognised as offering more valuable and predictable energy compared to solar and wind technologies [4]. These turbines can be implemented in tidal estuaries, oceans, rivers, and water channels [5-7]. Turbines can be divided into horizontal (HAT) and vertical (VAT) [8]. HAT turbines consist of a parallel radial axis rotor to the inlet stream, whereas VAT turbines are perpendicular to the inlet velocity. Vertical turbines have been widely and successfully used in small and medium-scale power generation [9]. Unlike horizontal turbines, these turbines have a simple structure and are independent of stream paths [10]. Therefore, this study focuses on developing small-scale vertical turbines.

In addition, Malaysia's dependency on fossil fuels is increasing more and more. For example, Malaysia's energy demands were 82,000 GWh in 2005, whereas the energy demands in 2020 were 190,000 GWh [11]. That has led to an increase in CO_2 in Malaysia by around five times [12]. Therefore, developing tidal turbines is vital to meet the energy demands, and developing these turbines can also help indigenous people in Malaysia dwell near water resources. It will also help provide stable electricity to remote and off-grid areas [3]. Malaysia has set a goal to increase clean energy production. Now, the electricity produced by the renewable sector is 2%, and the government aims to reach 20% by 2030. The percentage is not bonded to water turbines but to all the clean energy sectors, including solar, wind, and tidal [13]. Therefore, developing small-scale water turbines can help to meet the Malaysian goal for clean energy.

Many types of research have been conducted to develop tidal and river turbines worldwide using Computational Fluid Dynamic (CFD) analysis. For example, using CFD simulations, some researchers explored the effect of the number of paddles and profile changing on a Savonius turbine in Malaysia. They increased the torque by setting two paddles rather than three, maintaining the overlap ratio [14]. Others worked on enhancing the deflector around the turbine to develop the performance, and they constructed a 3D model to analyse it, using a CFD method to improve the performance [15]. Other researchers in Japan proposed combining wind and water floating turbines, which can cancel the electric generator's reaction torque and produce additional energy from the water [16]. Implementing a floating turbine can reduce the maintenance cost; therefore, the Operation and Maintenance (O&M) will be reduced.

Another water floating wheel turbine is designed to harness the river's energy, and a CFD analysis is implemented to understand the dynamics of the fluid [17]. Although there are many significant studies to improve and analyse large-scale hydro-kinetic turbines, the number of designs of small-scale water turbines is limited [18]. In addition, large-scale hydropower plants with more than 1MW are not considered renewable [19] because building massive dams or reservoirs causes environmental damage to natural habitats, and establishing large reservoirs can also emit greenhouse gases like methane [20].

Therefore, this study aims to conceptualise and simulate a new floating small-scale water turbine using CFD techniques because it can improve the efficiency of harnessing power from small-scale turbines, which are cost-effective, easy to maintain and environmentally friendly.

2. DESIGN AND SIMULATION

2.1. Turbine selection

A new concept for floating turbines was developed to analyse floating turbines, and a design methodology created the idea. Each step of the design process consists of specific tools to achieve the required tasks to develop the final concept that would be simulated. The first step was to infer customer and market needs and identify the requirements [21]. Then, the function and task specifications were determined. After that, a conceptualisation process occurred, and the alternatives were evaluated [21]. Finally, embodiment and details design were established to conduct CFD analysis [21].

2.2. Computational fluid dynamic

For the CFD analysis, Ansys Fluent was used to analyse the flow movement and assess the performance. The first step was to make a grid independence study to ensure the mesh was suitable for this turbine [22]. Unstructured 2D (Two Dimensional) mesh was used to mesh the rotating and outer domains. All the meshes were evaluated in Tip Speed Ratio (*TSR*), that is, the ratio of the tip velocity to the freestream velocity = 0.8, water inlet speed = 0.56 m/s and the time = 10 sec. The suitable number of elements was found to be around 310,000. In addition, a boundary size study was conducted. The boundary and mesh can be seen in Figure 1. The suitable size for the boundary was A = 2 *m*, B = 2 *m*, C = 2 *m,* and D = 4 *m* after conducting a boundary-independent study. To prove the concept, a dynamic mesh technique was applied. The turbulence model was *k-ω* SST since it provides a high accuracy rate for transient cases [23]. To assess the performance, C_p would be found for different *TRS*s. The sliding mesh technique was used to draw the performance curve. The simulation was repeated 10 times with different *TSR*s.

2.3. Requirement determination

To arrange the requirements, the requirements should be ranked from 1-10, where 10 was the most important and 1 was the least important. In addition, if the requirements were considered essential, a letter 'D'

(Demand) shall be notated, whereas a letter 'W' (Wishes) should be assigned if the requirements were not essential.

Table 1 shows the requirements for the floating turbine, D&W, and the ranking for each requirement. Each condition is inferred from the need for Malaysian to live near water resources and lack enough electricity supply [3]. For example, electricity generation and cost are demands, meaning it must be achieved, but low noise is a wish that the customer hopes to exist. The next essential step at this design stage is to organise the customer requirements to clarify the objectives [24].

One way to do this is to use The Objective Tree Method, which helps concisely clarify the existing project requirements. This method uses a diagrammatic form to illustrate the objectives, which can help reduce the confusion between the customers and the design team [24]. As Figure. 1 displays, the main objectives are cost-effectiveness, safety, efficiency, and convenience, which drive and progress the design in the next steps. This is to say that the required outcome should contain these criteria and their branches.

Table 1. The ranked requirements for the turbine

D&W	Requirements	Ranking
D	Electricity Generation	10
D	Reasonable cost	10
D	Safe for humans	10
D	Utilise water to Generate electricity	10
D	No Need for Fuel	10
D	Portable	10
D	Works in the sea and the river	10
W	Environmentally Friendly	9
W	Easy to maintain	9
W	Weatherproof	8
W	Easy to Install	8
W	Low Noise	2
W	Safe for the Marine and River Species	7
W	Easy to stop	4
W	Debris Resistance	4

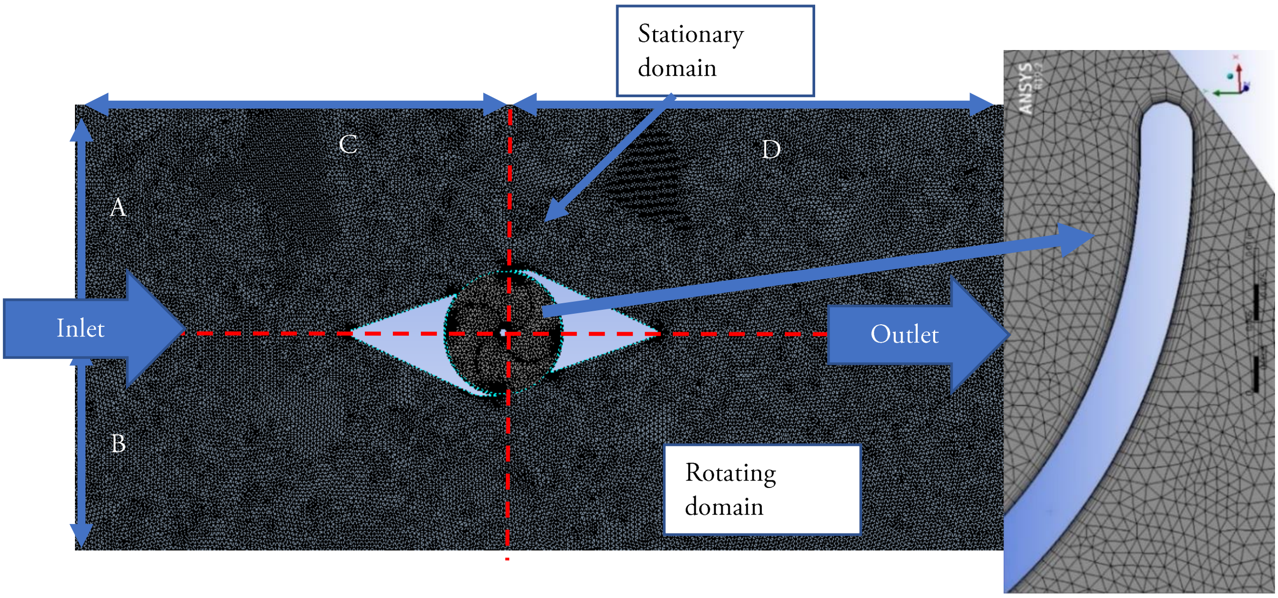


Figure 1. Boundary conditions and mesh for the floating turbine, with 310,000 elements.

2.4. Function analysis

A product's overall function (also called 'black box') represents the relationship between the inputs and output, and this function could be divided into subfunctions by which the product could operate, as seen in Figure 2. This function was to create a solution-neutral engineering action, showing how the turbine would operate, and, in this stage, the requirements would be signified into engineering terminology that was more relevant to the designers [21, 24]. The water was the source of energy that would be guided to the blades to rotate and then transfer power to the gearbox to rotate the generator. In addition, other sub-inputs were assigned, such as turbine stability while floating and movement to stop the turbine.

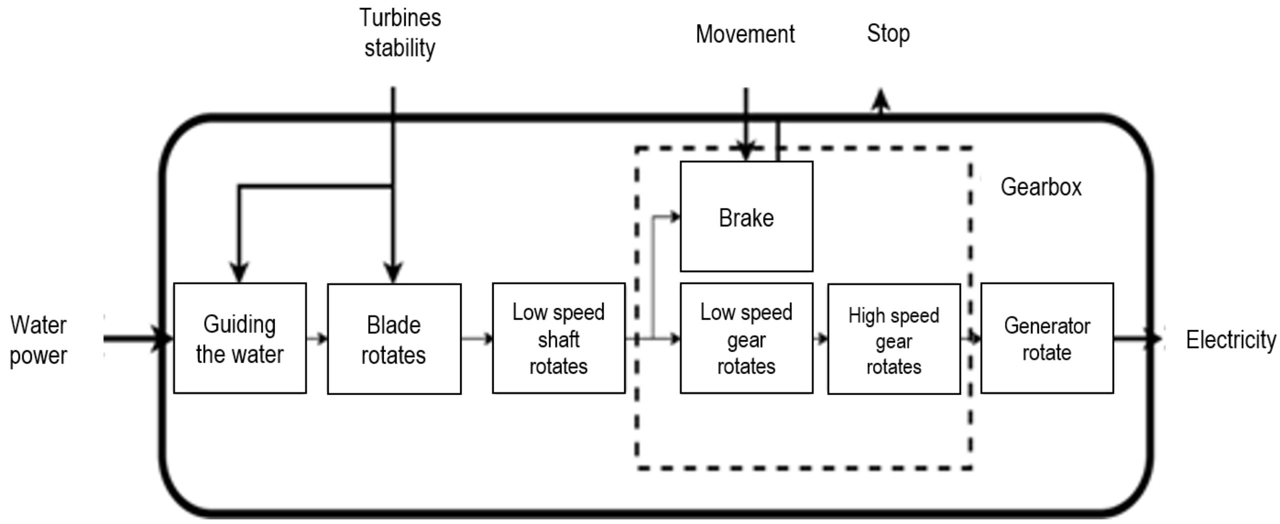


Figure 2. Function box for the floating turbine.

2.5. Task specification

The performance specification method was used for this part. The specification would define the required performance instead of the required product, showing the performance the concept should be achieved. In this stage, this method should not discuss or suggest any physical component that could achieve that performance, but it would only translate attributes of the required performance into engineering characteristics.

Table 2 displays the required engineering tasks and the specifications. The table was to assign specifications for each requirement. The portability, for example, was transformed into the specification of geometry, with 2x2x1 *m* dimensional space, and safety was changed into standards like ISO and ISE.

2.6. Conceptualisation

After knowing the functions, it was necessary to identify each function's and subfunction's work principles. The principles should depend on the physical effects required to achieve the given function, depending on the flow of materials, information, data, and energy. For the conceptualisation part, the morphological Chart would be used to show each function and how it can achieve it. A morphological chart provided an organised approach to generate concepts to enlarge the area of research and get all the possible options that could be used [25], as Table 3. This way was a visual way to represent functionality, navigate the alternatives and visualise the combinations.

Table 2. Task specification table.

Matric	Specification
Geometry	2×2×1
Kinematic motion	Rotational
Energy	1000 Watt
Materials	Light materials like plastic or reinforced fiberglass
Safety	No electricity leakage and safe for human use
Quality	Should follow ISO and IEC standard
Assembly	One assembly step
Maintenance	< 30RM annually
Cost	< 1000RM
Weight	< 14 kg
Stop	< 5 sec
Vibration magnitudes	< 5 mm
Lifecycle	> 5 years
Colors	two vivid colors
Stars	<5 sec
Runs	24 hours for the entire lifecycle
Steps to operate	2

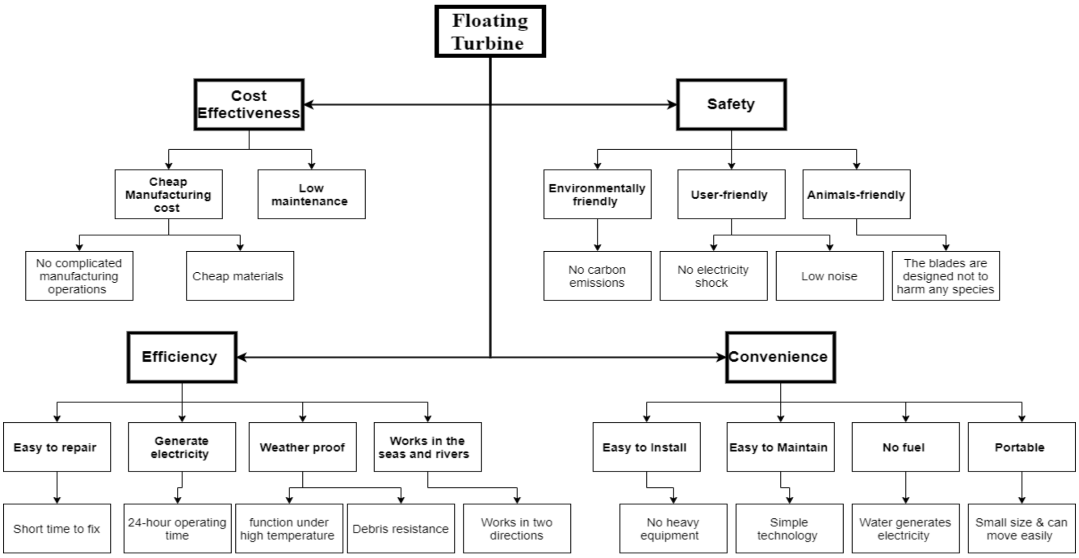


Figure 3. The Objective Tree for the floating turbine.

2.7. Concept evaluation and embodiment design

Different functional alternatives should be created based on the morphological chart at this stage. Then, alternatives should be chosen and sketched as a whole, with around 4 to 8 alternatives. The sketches should not be detailed, but it was only for presentation purposes. This step will help to visualise the concepts and the functional mechanisms for the designers and the customers. SolidWorks designs were used for this stage to understand each concept, as Tables 4 and 5. After considering the possible concepts, the design team should choose an idea to become the datum that is against all other concepts. The datum was chosen as an industry standard that could be commercially available in the market, and it was the floating water wheel. To compare, the selected concepts would be compared to the datum. If the concept was better, the same, or worse than the datum, the values would be set as (+), (S), or (-), respectively. Then, a weighted score was calculated, as in Table 6, depending on the negative and positive signs, and the higher the score was, the better concept it would be. Therefore, Concept 2 was chosen to undergo the CFD analysis because it acquires the highest points.

Table 3. The outer shape concepts for the floating turbine.

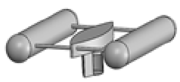
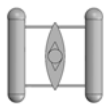
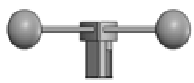
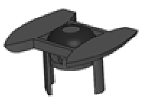
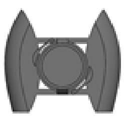
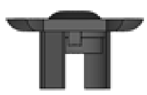
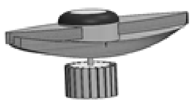
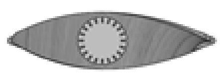
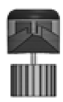
Concepts	Front view	Bottom view	Side view
1			
2			
3			
4			

Table 4. Morphological chart for the floating turbine.

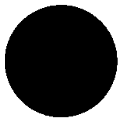
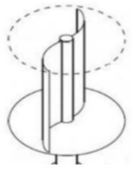
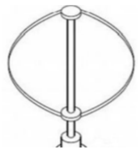
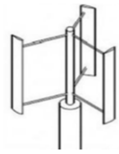
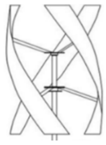
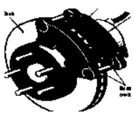
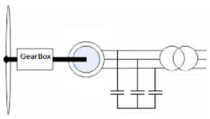
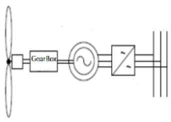
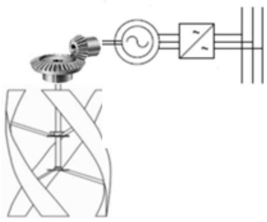
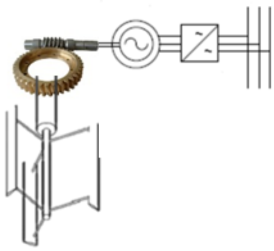
Function	Option 1	Option 2	Option 3	Option 4	Option 5
Deflecting the water	Double-straight deflectors 	Guided deflector close side 	Long-guided opened side  deflector	No deflector 	
Harnessing water energy	 Savonius	 Darrieus	 H-Darrieus	Helix 	 Cross-Flow
Floating Boat	 Double-edge hull	Inflatables 	 Single-edge double hull		
Converting energy	Bevel 	Worm 	Spur 	Chain 	 Planetary
Brake	Disk Brake 	Drum Brake 	ABS 	Calliper brake 	
Generator	Fixed speed 	Variable 			

Table 5. The internal-detailed concepts for the floating turbine.

Concepts	The inside combination	Details
1		- Guided deflector close ended - Savonius blade shape - Double-edge hull - Planetary - Fixed speed generator - Drum brake
2		- Guided deflector close ended - Savonius blade shape - Chain Gear - Inflatables floating boat - Fixed speed generator - Calliper brakes
3		- Bevel gear - Single-edge double hull - Helix blades - Variable generator - Double-straight deflectors - Desk brake
4		- Double-edge hull - Variable generator - ABS brake - Worm gear - Without deflector - H-Darrieus blade

2.8. Design Details

The first detailed step in designing the turbines was to start with designing the rotor. Savonius turbine was used because it was in the concept that was chosen by the evaluation chart. The primary geometric parameters for this type of turbine can be seen in Figure 4. The diameter and the turbine's height were chosen to be 0.4 and 0.3 *m*, respectively, for the prototype.

These were chosen according to the customer's demands versus datum. The aspect ratio was another important factor in designing the Savonius turbine because it directly impacts the rotor's aerodynamic behaviour [26]. The aspect ratio could be found by dividing the height over the diameter, so, in this case, it was 0.8, while the end plate ratio was 1.26.

For this prototype, the number of blades is 4 blades, with a 0.15 m radius, to maintain the continuous rotation in a guided, close-ended deflector. Another critical parameter is the overlap ratio, which is the distance to the blade's diameter, and the value for this ratio is 0.126. The freestream velocity is 0.56 *m/s*, the lowest water velocity in Malaysia [27]. The maximum power contained in a freestream is given by [28-30]:

$$P_{max} = \frac{1}{2}\rho A v^3 \tag{1}$$

where $\boldsymbol{P_{max}}$ is the maximum available power in Watt, $\boldsymbol{\rho}$ is the fluid density in kg/m^3, and the fluid velocity is defined by v in *m/s*. The cross-sectional area in this equation is defined by $\boldsymbol{A}$ in meter, which is the diameter (*D*) x height (*H*).

On the other hand, the power extracted from the rotor is given by:

$$P_{rotor} = T\omega \tag{2}$$

where P_{rotor} is the power extracted from the turbine in *Watt*, T is the torque extracted by the turbine in *N.m*, and ω is the angular velocity of the turbine in *rad/s*.

From these equations, the performance of the turbine, which is dimensionless, can be expressed as:

$$C_p = \frac{P_{rotor}}{P_{max}} \tag{3}$$

Another measure of the turbine performance is the coefficient of torque, which is given by:

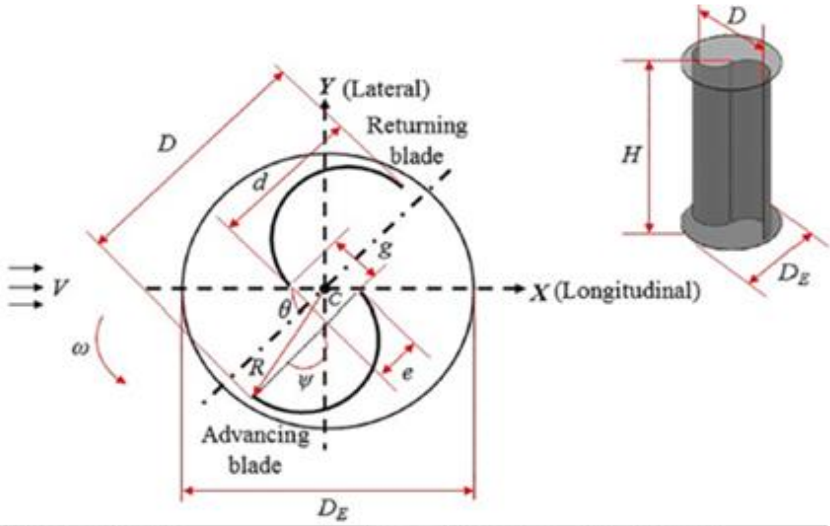
$$C_t = \frac{T}{\frac{1}{4}\rho D^2 H v^2} \tag{4}$$

The performance coefficient of the turbine depends on TSR, which can be expressed as:

$$TSR(\gamma) = \frac{\omega D}{2v} \tag{5}$$

The performance can also be calculated by applying the equation below:

$$C_p = \gamma C_t \tag{6}$$



C	Center of turbine	V	Freestream velocity (m/s)
D	Diameter of turbine (m)	θ	Turbine rotor angle (°)
D_E	End plate diameter (m)	ω	Angular velocity of turbine (rad/s)
d	Diameter of blade (m)	ψ	Blade arc angle (°)
e	Overlap distance (m)	AR	Aspect ratio [H/D]
g	Gap distance (m)	ER	End plate ratio [D_E/D]
H	Height of turbine (m)	GR	Gap ratio [g/d]
R	Radius of turbine (m)	OR	Overlap ratio [e/d]

Figure 4. Main geometric parameters of the Savonius turbine [31].

3. RESULTS AND DISCUSSION

According to the evaluation chart (Table 6), design two acquires the highest total marks, meaning that design two is the selected design to undergo CFD analysis. Therefore, the remaining designs are neglected because they do not pass the criteria selection.

A dynamic mesh technique is used for the CFD simulation to evaluate the working principle of the selected design. It is found that the CFD model is valid and rotates properly, as shown in Figure. 5. The selected turbine speed is between 3.1 and 4.9 rad/s in the water inlet measured for the last 700 timesteps.

A grid independence study is conducted to ensure the accuracy of simulation results, as shown in Table 7. The number of elements is increased for each test to check the stability of the mesh. It is found that after mesh number three, the mesh is stable, and a further increase in the number of elements does not affect the result. Hence, mesh number 3 is chosen to undergo further simulation.

The torque acquired from the test at 0.8 *TSR* can be seen in Figure. 6. The test is taken for 1500 timesteps for ten tests after conducting a time step sensitivity study. The first 200 timesteps are not taken in calculating the performance because they are when the turbine is initiated [22, 26]. Instead, the last 500 timesteps are taken to access the performance. The positive and negative signs indicate the positive and negative torque accompanied by the rotation of the turbine.

Table 6. The evaluation chart of the floating turbine

Evaluation Table **Specification**		**Concepts**				
Requirements	Weight	1	2	3	4	**D**
Safety						**A**
Safe for the environment	8	S	S	S	S	**U**
Safe for humans use	10	+	+	+	S	**T**
Safe to animals	5	S	S	-	-	**M**
Cost-effectiveness						
Affordable to produce	7	-	+	-	+	
Affordable to customers	10	-	+	-	-	
Low maintenance cost	9	+	-	-	S	
Efficiency						
Easy to repair	6	-	-	S	+	
High electricity generation capacity	10	-	+	+	-	
Weatherproof	7	S	-	S	S	
Work in the sea and river environment	9	+	+	+	+	
Convenience						
Easy to install	5	+	S	-	+	
Easy to maintain	4	+	-	-	+	
Fuel is not needed	8	S	S	S	S	
Portable	6	+	+	S	-	
+		6	6	3	5	
-		4	3	7	4	
Total		10	26	-11	0	

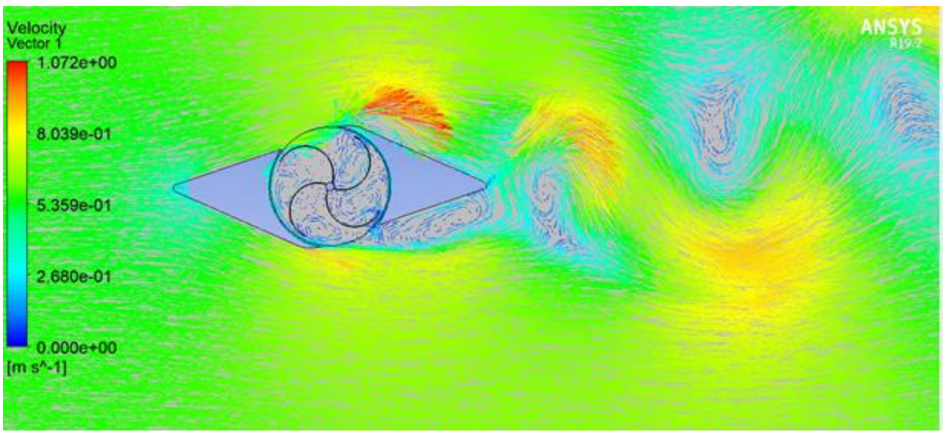


Figure 5. Dynamic mesh technique in freestream of 0.56 m/s, with turbine speed of 3.3 rad/s.

Table 7. Grid independence study.

Mesh number	The number of elements	Coefficient of performance	Hours (9 cores computer)	Average Local velocity (rad/s)
1	75,000	0.005	32 mins	7.1
2	150,353	0.04	55 mins	4.97
3	217,600	0.095	2.5 hours	3.01
4	310,000	0.1	3 hours	2.999
5	615,303	0.12	7.2 hours	3.02
6	1100,120	0.099	10.2 hours	3.14
7	2500,000	0.09	14.9 hours	2.994

The velocity contour in different time steps at 0.8 *TSR* is shown in Figure. 7. It can be seen that the turbine deflects the water and creates a vortex inside the deflector. The velocity in the deflector is approximately 1.1 *m/s*, which is higher than the inlet velocity. Therefore, the turbine increases the velocity around the rotor, increasing the rotational speed of the rotor. The turbine's performance can be seen in Figure 8 in different *TSR*s compared to experimental studies done on typical Savonius turbines, without the proposed concept. The overall trend shows that the power coefficient increases as the *TSR* increases. In 0.2 *TSR*, the performance is insignificant, while after 0.8 *TSR*, the performance rises rapidly. This result shows that the new turbine design has higher performance compared to typical vertical Savonius turbines, like research done by Hayashi and Li in and Kamoji [26, 32-34].

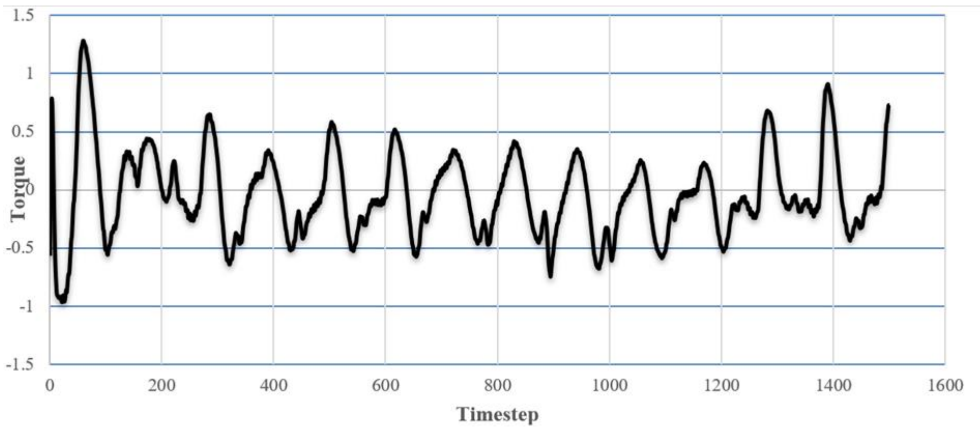


Figure 6. Torque-timestep diagram at 0.8 *TSR*.

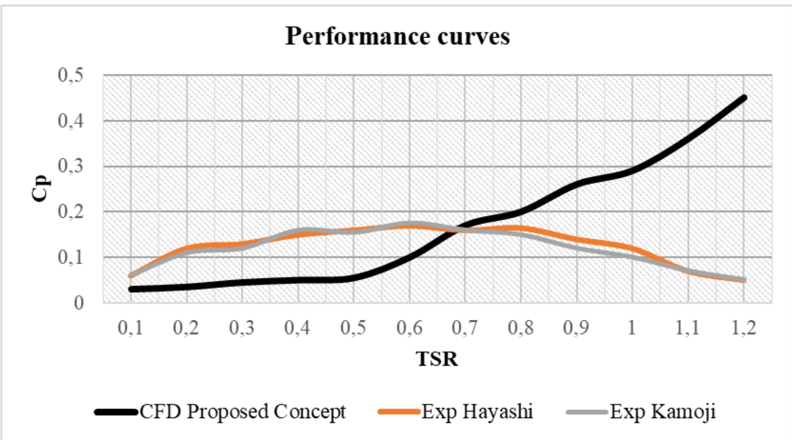


Figure 7. Performance curve by sliding mesh technique from 0.1 to 1.4 TSR for different turbines.

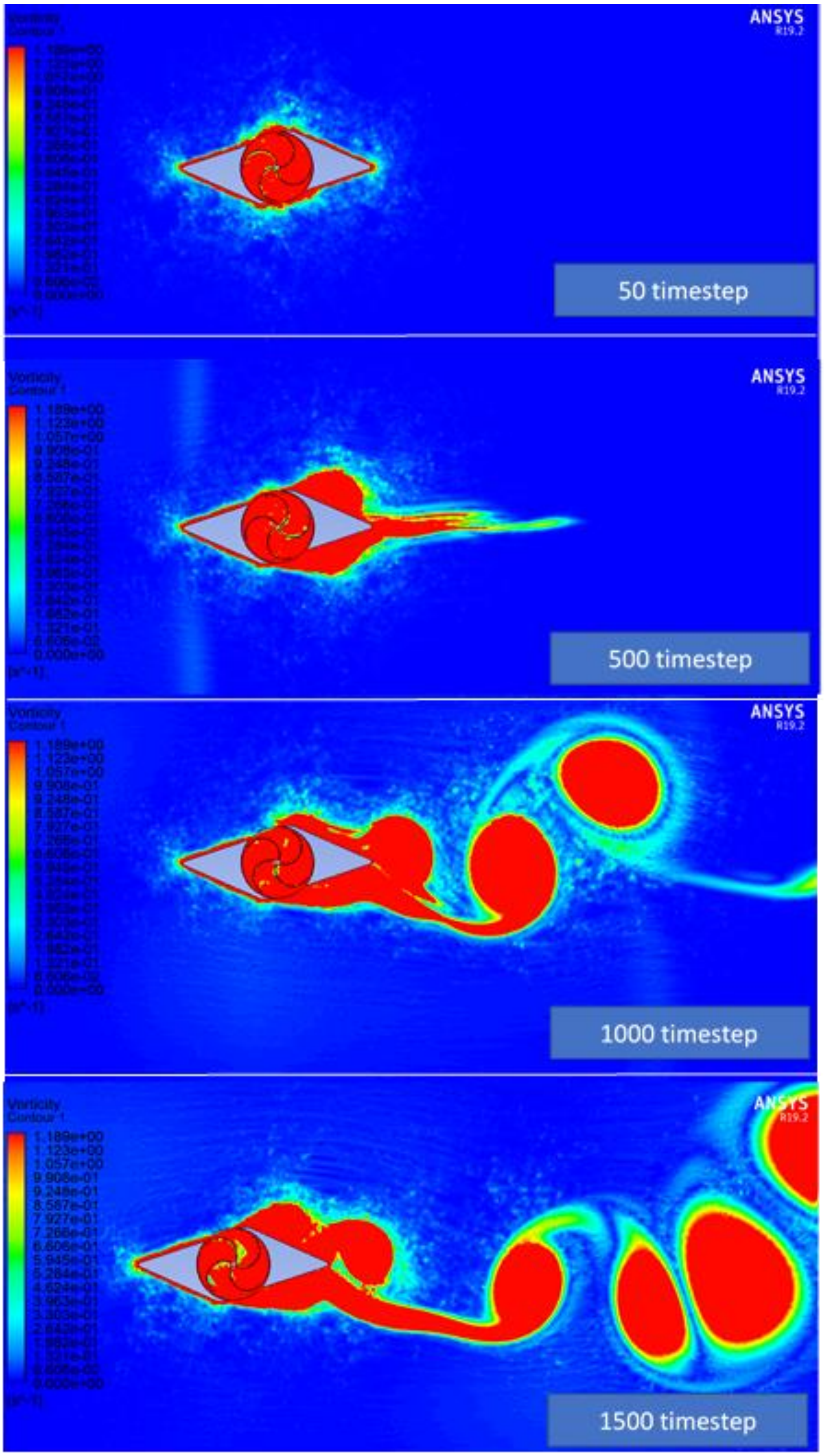


Figure 8. Velocity contour at 0.8 TSR at various timesteps and turbine speed from 0 rad/s to max 3.1 rad/s.

4. CONCLUSION

This paper presents a new concept of floating water turbines and analyses it using the CFD technique. The created turbine is a nondirectional floating turbine, making maintenance cheaper. In addition, the turbine is environmentally friendly and has no negative impact on natural habitats, unlike large-scale turbines. The performance achieved by the turbine is comparatively higher than the traditional small-scale turbines, especially compared to the conventional Savonius turbines that are widely known for their poor performance. Certain tools are used to achieve the goal of each concept-creating step. The designing stages start with infaring the market needs and changing them into requirements. The tools used at this stage are the requirement table and the objective tree. After that, this paper changes these requirements into a function box. Then, a task specification table is used to assign the specifications, and the possible concepts are created to be evaluated in the next stage, which creates four turbines. The evaluation chart is used to find the suitable concept by comparing the concepts to a datum. It is found that concept two, with guided deflector close-side, Savonius blade shape, chain gear, inflatables floating boat, fixed speed generator, and Caliper brakes, is the most suitable concept for this application. Finally, the chosen turbine undergoes CFD analysis. After conducting a grid independence study and boundary sensitivity study, the dynamic mesh technique validates the concept. The highest performance can be obtained at 1.3 *TSR* with C_p equal to 0.45 in the given dimensions after checking the feasibility of the concept by the dynamic mesh technique. For future work, this study recommends conducting an experiment to assess the new concept's performance, studying the proposed concept's feasibility on a larger scale, and exploring higher ranges of *TSR*s to check the performance at higher speeds in freestreams.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest affecting this publication.

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