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Augmented Diffuser for Horizontal Axis Marine Current Turbine

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ABSTRACT

The potential of renewable energy sources is enormous as they can make a major contribution to the future of energy needs. The ocean has a great potential to become a practicaland predictable energy source compared to other energy resources such as solar, wind, and nuclear. It offers different sources of energy which can be utilized namely wave, tidal, offshore wind, thermal, and tidalcurrent. Among these sources, marine tidal current has major advantages such as higher power availability and predictability. The main objective of this research work is to design and develop a horizontal axis marine current turbine (HAMCT) that suitable for operating within Malaysian ocean, which has low speed current (0.5 – 1 m/s average). A prototype of augmented diffuser 4-bladed HAMCT applying NACA 0014 was proposed in the current study. The turbine model has 0.666 m diameter, and it was designed to produce as much as power from flowing water current. Model was constructed and tested at Marine Technology Center (MTC) in three conditions, namely, free tow testing, ducted tow testing, and ducted diffuser tow testing in order to predict the power and efficiency of the turbine system. The results showed that the application of duct was significant to concentrate the flow and diffuser arrangement was effective when it was placed behind of the rotor in this condition of low water current speed. The maximum efficiency Cp obtained in the current system was 0.58.

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1. INTRODUCTION

Tidal current power is one of the most important clean power resource in the world especially micro applications. Major advantages of this energy are the nature of the current flow, which can be predicted and the great density of water fluid [1]. Moreover, the density of energy produced by water flow is approximately a thousand times more than that by wind energy. Therefore, tidal current energy is considered to be a highly available energy source and as yet not fully utilized. Water turbines used for tidal current generations were originally developed for wind force generations [2]. The types of employed tidal current power can be characterized by their rotational axis orientation with respect to the water flow direction. Hence, there are two main technologies for the energy extraction from marine currents. They are horizontal flow turbines (HAT) and cross flow turbines. Horizontal flow turbines have axes parallel to the fluid.Based on the comparison between the three methods, it was noticed that HAMCT offered the highest potential in generated power from water current [3, 4].

Malaysia is a country that is surrounded by ocean, thus it needs to develop the tidal current technology for developing the energy sector [5, 6]. Malaysia has main problems which are low velocity of current and low water depthappears. The optimum current speed for ideal marine turbine operation is at least 2 m/s [7]. However, the averagely current velocity in many location in Malaysia is only 1 m/s [8]. Moreover, open turbines extract energy from the fluid by reducing the flow velocity with little or no pressure reduction as the fluid passes through the turbine rotor. The streamlines must therefore expand to maintain continuity and they cannot expand indefinitely [9]. Hence there is a theoretical limit to the percentage of kinetic energy that can be extracted from the fluid. This limit has been shown by Betz to be 59.3% [10] for a single actuator disk. A number of compromises and modifications are required for turbine design in order to exceed Betz limit [11]. Hence, Kirke [9] increased the power coefficient more than Betz limit by utilizing double actuator disk which proved that the corresponding limit is 64% for this case. FurthermoreVennell [11], Vennell [12] and Vennell [13] exceeded the Betz limit by utilizing farms of turbines in channel

The simplest method to enhancethe HAMCT efficiency is to enclose it into a ductor nozzle. Using duct or shroud around turbine enhances the flow velocity around the runner. In this case, the velocity is higher compared to a free rotor. This enhancement increases the total harnessed power from tidal Current River or open sea. Furthermore, this idea has been proposed for decades in the wind turbine technologies but it is not successful commercially [4], [14]. Scherillo *et al.*, [15] achieved 7.5% increase in the HAT efficiency based on diffuser exit area. Their study was carried out by numerical and experimental investigations. Luquet et al. [16] optimized the design of the duct and the rotor of current turbine to enhance the flow rate through the turbine by using the RANS numerical method; they achieved a higher power coefficient of 0.75 with optimum design of the duct and the rotor.

The pressure drop available to a ducted turbine depends on the shape of the duct and the flow through and around it. If the duct is designed as a diffuser it will draw more fluid through it and will also increase the available pressure drop across the turbine by recovering some of the velocity head downstream as pressure head, the turbine then becomes “diffuser- augmented”[17]. Considerable work has been done on diffuser-augmented wind turbine design, but the concept has not so far been systematically applied to water turbines. However the diffuser concept has lesser much published in the literature for current water turbine. Kirke [9] showed that the theoretical maximum power coefficient for a diffuser-augmented turbine based on turbine area is 1.96 times higher than the Betz limit. This is possible because flow is drawn in from a greater area upstream than that intercepted by the same sized turbine in open flow. On the other hand, David et al. [18] proved numerically that the diffuser configuration produced 3.1 times more power than the turbine with no diffuser. Furthermore, Buyung et al. [19] and Chen et al. [17] conducted experimentally a test on horizontal-axis wind turbine with and without a flanged diffuser, their results showed that the flanged diffuser can significantly increase the power output, torque output, and rotor rotational speed of the wind turbine. Ponta [20] represented diffuser-augmented floating hydro-turbines to improve the technical and economic performance. Shahsavarifard *et al.*, [14] designed and tested experimentally in the water tunnel facility at the University of Manitoba a 19.8 cm diameter HAT with two shrouds. The peak power enhancement of 91% over the unshrouded turbine was obtained with the straight wall diffuser. Elbatran et al. [21] deployed diffuser augmented channel around cross flow / Banki turbines.

This low current characteristic is the main consideration of the current study. Hence, modifications of the existing marine current turbines are needed to overcome low current speed in Malaysian ocean [6]. Thus, this study is mainly focusing on developing ocean energy device for harnessing and utilization of Malaysian ocean current characteristic. A duct diffuser has been proposedexperimentally to enhance the flow velocity through turbine runner, which is suitable for utilizing at Malaysian Ocean of low speed current.

2. RESEARCH METHOD

2.1. Design Concepts of Diffuser-Augmented HAMCT

The design concept of diffuser augmented HAMCT has been developed and considered to be more suitable for Malaysian Ocean characteristics. HAMCT design principle is almost the same basis as the wind turbine technology. This can lead to many advantages because wind turbine is a well-developed technology. Nevertheless, in order to design a ‘wind turbine’ as marine current turbine, several considerations must be taken to make sure the development is suitable for marine charctristics. Modificationsshould be carried out to make sure the technology applied can withstand the marine environment. The concept design of HAMCT in this study (Figures 1 and 2) has been developed to capture as much as energy for Malaysian Ocean. The design mostly applied previous HAMCT design concept can be used for harnessing Malaysian current energy.

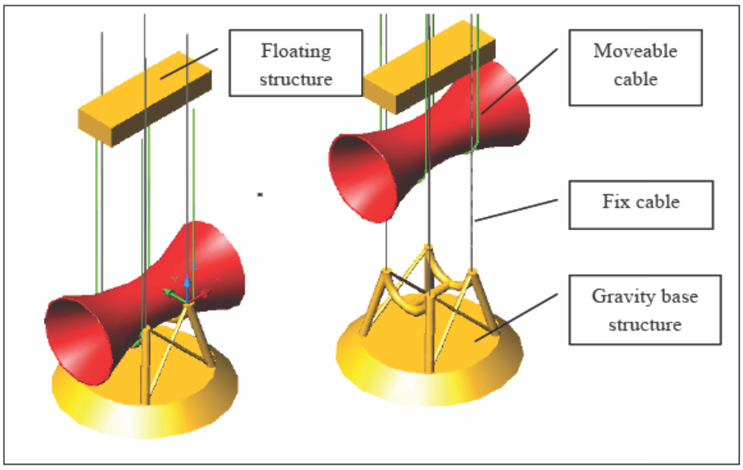


Figure 1. Diffuser-Augmented concept for Malaysian ocean HAMCT

This design is attached at the seabed with gravity base structure. During the operation, the fixed gravity base structure and the fixed cable will support the turbine for harnessing energy from the water current. The fix cable will also act as a mooring system for the floating structure. The design also allows the cylindrical duct to become removable. The turbine rotor consists of ducted diffuser, rotor holder, rotor, and con-alike hub. The holder is used to include the rotor,in additionthe electric cable can be placed inside the holder.

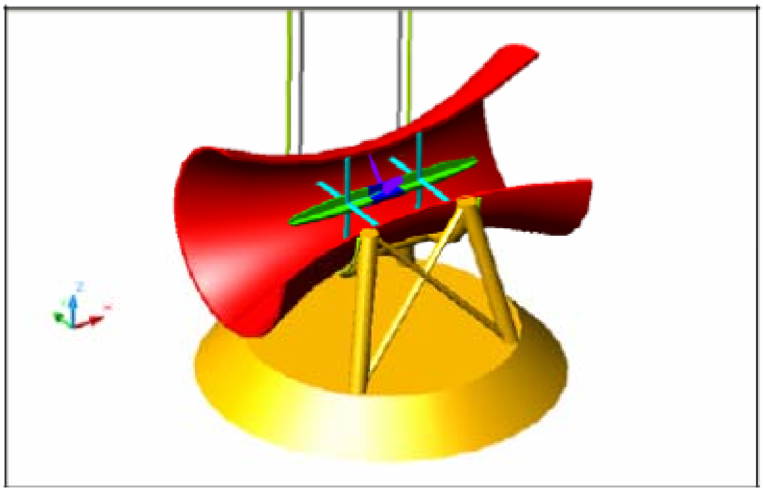


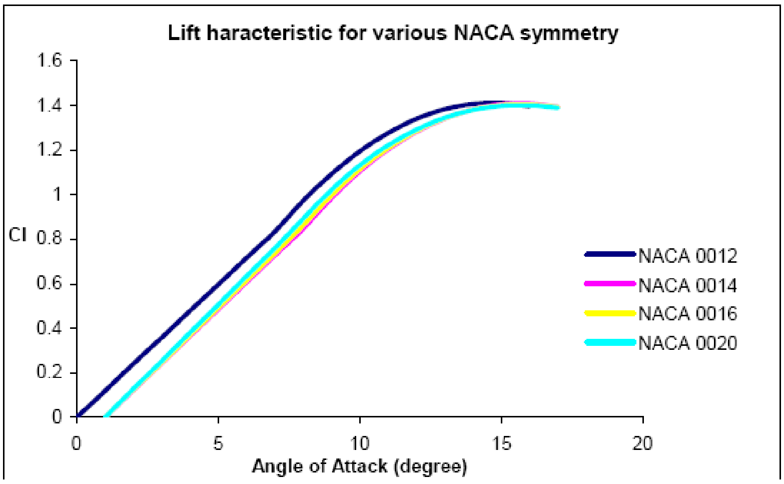
Figure 2. Turbine design concept

The rotor design is the mostimportant part in this HAMCT for low speed water current. There is a need of special intention for the rotor design because it is worked in fluctuation of current speed and the current appears in multi directions. The rotor design should also able to withstand the ocean current loading on the blades. The designs feature applied are fixed pitch 4 symmetric blades rotor, which are easier for the construct process. Number of blades applied is related to the torque characteristic, tip-speed ratio, weight, and power. Four blades were chosen based on wind turbine technology which studied in reference [22].

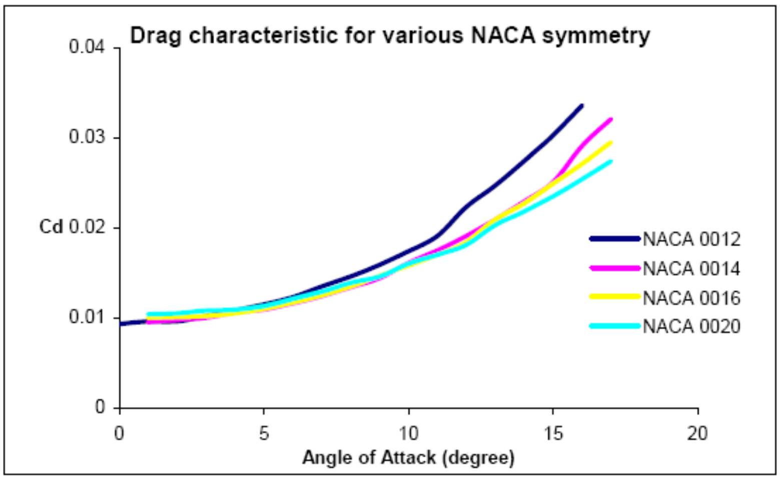
2.2. Design Procedures

Based on the concept design developed, the details design was made. The details designed of the current system consists of blades design, duct design and diffuser design. The main concern in the blades design is the lift and drag characteristics, since it is strongly related to the torque that will be produced by the turbine. The most effective parameter for HAMCT is the lift force whilst drag force can be considered as waste force that should be kept as low as possible. Based on the literature study, it was found that, the most ideal blades sections for turbine blades in the development stage is the symmetric NACA airfoil sections. Thus, the lift (Cl) and drag coefficient (Cd) for series of NACA symmetric sections have been studied using DESIGNFOIL software [23], as shown in Figure (3).

It was noticed that the selected different NACA airfoil sections have nearly the same maximum Cl, but NACA 0012 recordededthe highest value of lift coefficient. It alsohas maximum drag coefficient. Hence, NACA 0012 is the most preferable section that can be utilized for the turbine blades according to the lift force results, especially it also has a lighter wight. However, the highest value of the drag force can diminish this advandage.Based on the expected loads from seawater, NACA 0014 airfoil section was the most suitable optionbecause it is thicker than NACA 0012. Although, the 0016 and 0020 has thicker blades and lowerCd at higher angles of attack than 0014, but the Malaysian ocean with low speed current needs a turbine with less weight, thus, choosing thicker blades (0016 or 0020) can increase weight of the overall design. For these reason NACA 0014 was chosen for the blades design.



(a)



(b)

Figure 3. C_l and C_D for various NACA symmetric airfoil sections

Figure 4 shows the details of the HAMCT augmented diffusersystem, which consists of four parts: inlet diffuser or funnel to 'capture' the flow into designed turbine, the duct cylinder to uniform and consentrate the water flow through the turbine and the outlet diffuser to reduce wake of the moving fluid passing the turbine and the turbine configuration which contains 4 blades, static hub, moving hub, and rotor holder. The overall dimensions of the diffuser augmented HAMCT and its model can be seen in Table 1.

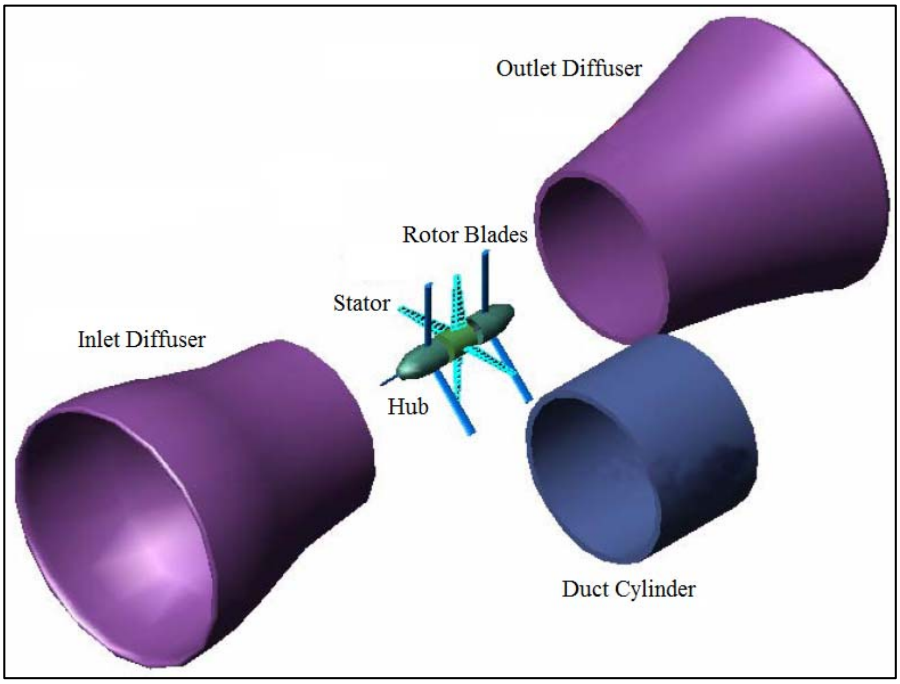


Figure 4. Concept Duct system for the proposed HAMCT

Table 1. Detail design parameters

Parts	Details	Model Scale
Inlet Diffuser	Length	1.433 m
	Outer Diameter	1.400 m
Outlet Diffuser	Length	1.490 m
	Outer Diameter	1.360 m
Duct Cylinder	Length	0.700 m
	Diameter	0.917 m
Blades	Diameter	0.833 m
	Actual Radius	0.333 m
	Moving Hub Diameter	0.087 m
Hub	Moving Hub length	0.087 m
	Static Hub Legth	0.120

2.3. HAMCT Model Construction

The model construction process for the augmented diffuser HAMCT in the current research work was divided into the building of the turbine rotor, cylinder duct, and the diffusers ducts. All the construction process was done at Marine technology center (MTC), Universiti Teknologi Malaysia (UTM).The turbine consists of 4 blades runner, static hub, moving hub, and rotor holder. Blades and static hub were made of wood, PVC for the moving hub, two bearing and stainless steel shaftas shown in Figure 5. Cylinder duct was constructed using fiber-glass and the mould was constructed using thick plywood with wood for the mould structure. The same approaching was done for the diffusers duct.

Figure 5. The construction procedures

2.4. Experimental Apparatus

There are three types of model testing proposed in order to determine the HAMCT performances which are Free Tow Model Test, Ducted Tow Model Test and Ducted Diffuser Tow Model Test as shown in Figure 6. The equipment for this model testing are towing Tank, underwater camera, laptop, non-contact Tachometer, angle ruler, G - clamp and ruler to get an accurate data for RPM, torque and power, these equipments installation are shown in Figure 7. The results of power, torque and efficiency were determined at different current speed and varying yawing angles. Hence, the speeds of the water currents for the HAMCT model can be found in Table 2.

Based on the detailed design and construction procedures of the augmented diffuser HAMCT device, it is essential to test it in term of performance. The constructed model was then tested for performance and further power prediction assessment. Figure 8 illustrates the current system during measurement and observation.

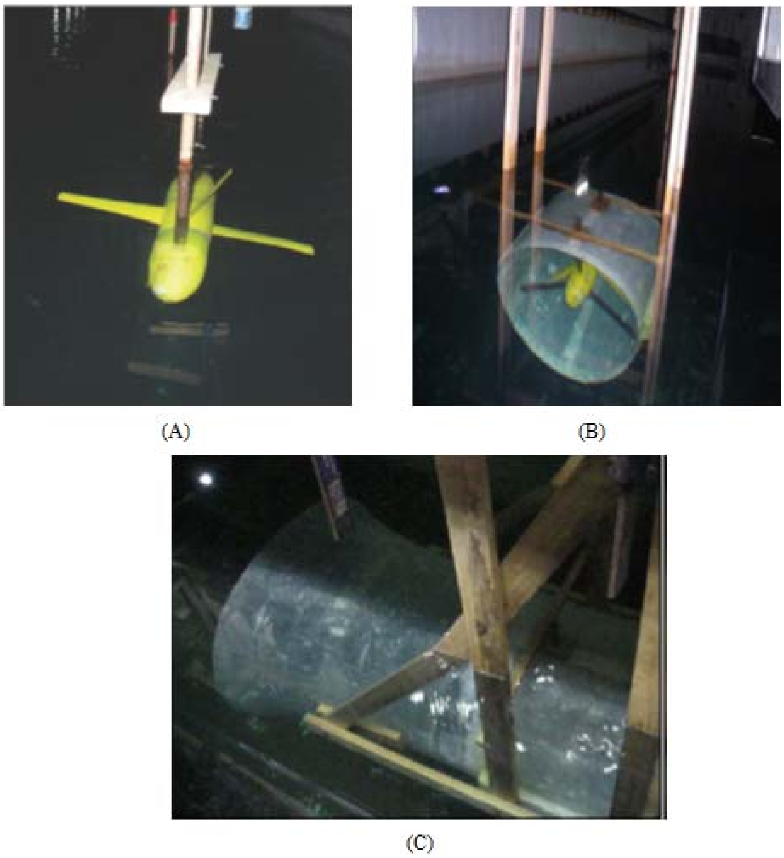


Figure 6. (A) Free tow model test, (B) Ducted tow model test (C) Ducted diffuser tow model test

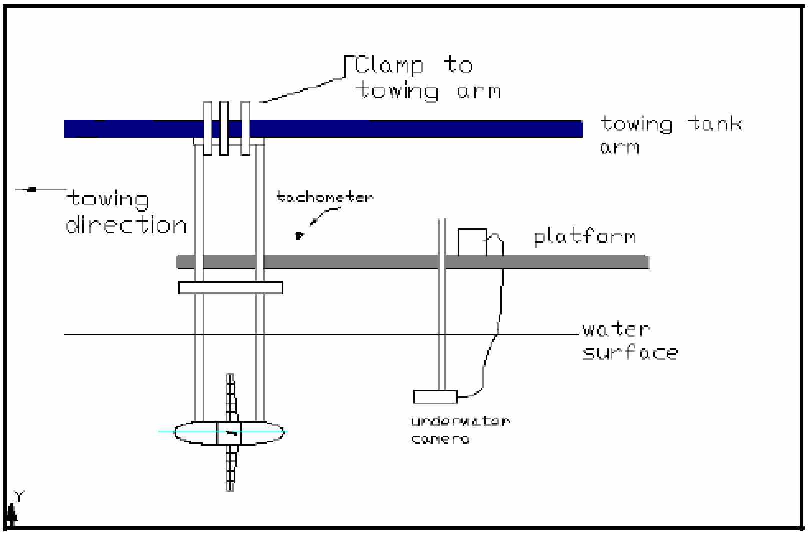


Figure 7. Model setting at the towing carriage

Table 2. Correspondence velocity for system model

Test Case	Current Velocity (m/s)
1	0.42
2	0.63
3	0.84
4	1.05

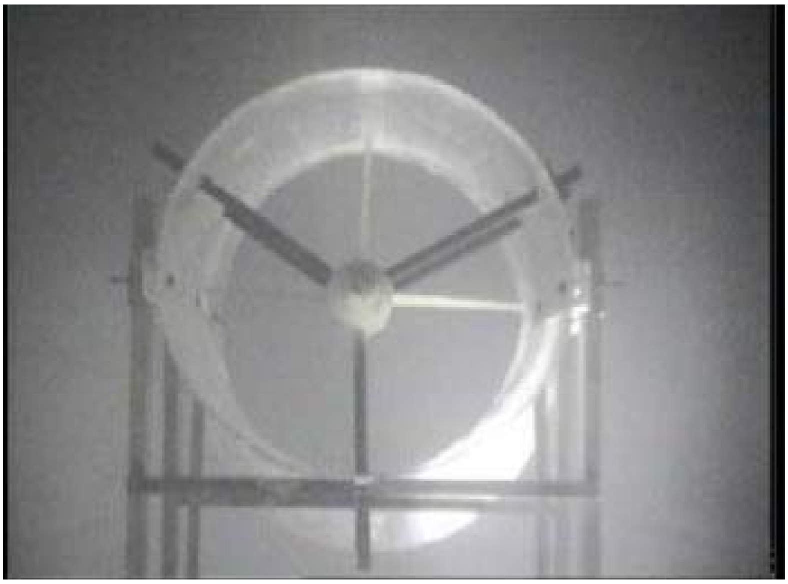


Figure 8. Augmented Diffuser HAMCT device through observations

3. RESULTS AND DISSCUSSION

The main goal of the present work was investigating the performance characteristics of augmented diffuser system to increase the effectiveness of the tidal current horizontal turbine efficiency which used in low velocity regions. This was done through measuring the performance properties of turbine performance. This is described through the Equation below:

$$P = T * \omega \qquad [1]$$

Where P is the output power, T represents the output torque, ω is the angular velocity. Moreover torque is given by:

$$T = F_L * r \qquad [2]$$

Where r is blade radius and F_L is lifting forcewhich represents in Equation [3]:

$$F_L = 0.5\, \rho U^2 A_B\, C_l \qquad [3]$$

Where ρ is water density, U is a free flow velocitity, A_B is turbine blades areaand C_l is lift coefficient.

Enhancing the flow speed can increase the lifting forces as well as power generated, which is the main interest of the Malaysia sites.

The power coefficient (Cp) of turbines was used to reflect the turbine performance, as presented in Equation (4):

$$C_{p=\frac{T*\omega}{P}} \qquad [4]$$

From the model testing conducted, there are two major characteristics needed to be observed which are the increasing flow characteristics and flow concentration due to yawing angle. Increasing the speed is a crucial factor in designing for Malaysian Ocean low speed current appearance. Ducted diffuser can increase the flow of the current and can redirect the flow perpendicular to the rotor blade and can increase the flow at the duct intake. Increasing flow characteristic theoretically can be achieved using ducted diffuser while concentrating flow by applying ducted cylinder surrounded the blade turbine.

Figures 9 shows the the variations of output power at different y awing angle in case of free tow and ducted tow. It can be seen clearly that the application of ducted turbine are really significant to increase the produced power from the current system because the duct able to increase flowing speed of the fluid and concentrate the flow towards the blades of the turbine.

Multi-directional current approaching the turbine can be predicted from the experiments and the results is shown in Figure (9). The power increased with the increment of yawing angle until reached to the maximum value at 20°, after that the power was suddenly dropped. In the other words, the presence of duct were not effecting the flow speed at 0° yawing angle, however, at about 20° degree of yawing, there wasthe optimum angle which recorded the maximum power, and it was lesser when it reached at 30° degree yawing angle. Moreover, the maximum power output of 90 W in case of ducted tow at 20° yawing angle but the significant power can be harnessed in case of free tow is 78 w at 10° current approach .Consequently, it was believed that duct was an effective speed-augmentation device

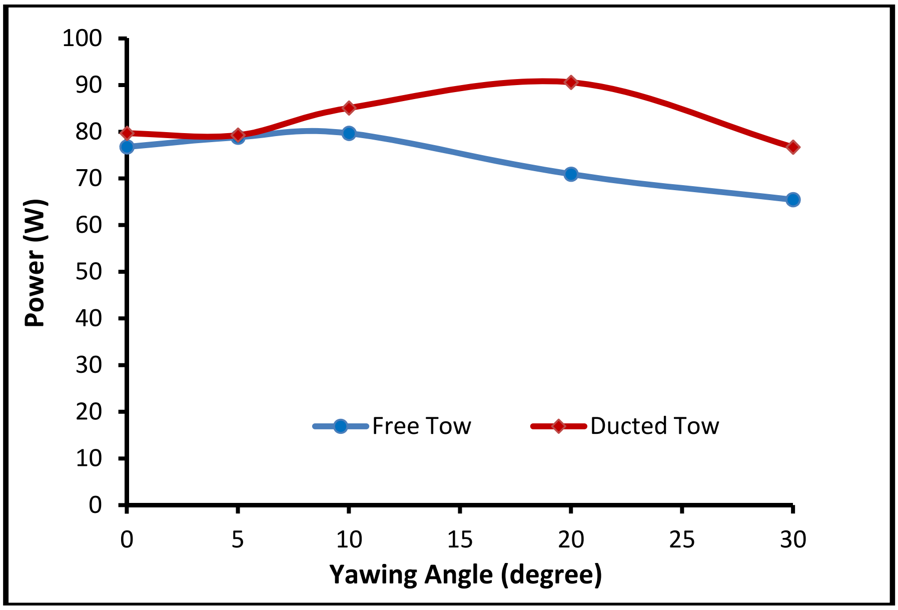


Figure 9. Potential of harnessing energy in multi-directional current approaches

The free tow, ducted tow, forward diffuser and aft diffuser configuration cases were tested at different various current speed. The performance characteristics curves of tested cases are shown in Figures 10 and 11. It was observed that the output power leads to increase with the increase of flow current speed for all tested cases as shown in Figure 10. Moreover, the maximum power output recorded for the aft diffuser case which was slightly around 250 W at a current speed 1.05 m/s. On the other hand, the power curve indicated that forward diffuser case was the second perfect configuration which recorded maximum power of almost 190 W. This is while the cases free tow and ducted have shown poor characteristics compared with the other two caseswhich the maximum output power was nearly166 W in the cases of free tow and ducted tow.

An early assumption was that the forward arrangement can gives a large effect for the speed increment. However, it turns out to be the aft arrangement was more effective rather than the forward arrangement. This should be due to the effect of the current backflow that affect the whole system, whilst aft arrangement reducing wakes of the flow and directing the outflow smoothly.

The power Coefficient “efficiency”, Cp, was considerably higher for aft diffuser case for all current speed studied in this work, as shown in Figure 11. It is interesting that the minimum Cp for aft diffuser test was higher than the maximum Cp for the other cases, this proved that the importance of using the diffuser after the duct to get significant power extraction. Furthermore, the maximum Cp obtained for aft diffuser case was 0.58 at 0.84 m/s current speed, which were more than 1.3, 1.6 and 1.7 times the maximum Cp for forward diffuser, ducted tow and free tow respectively.

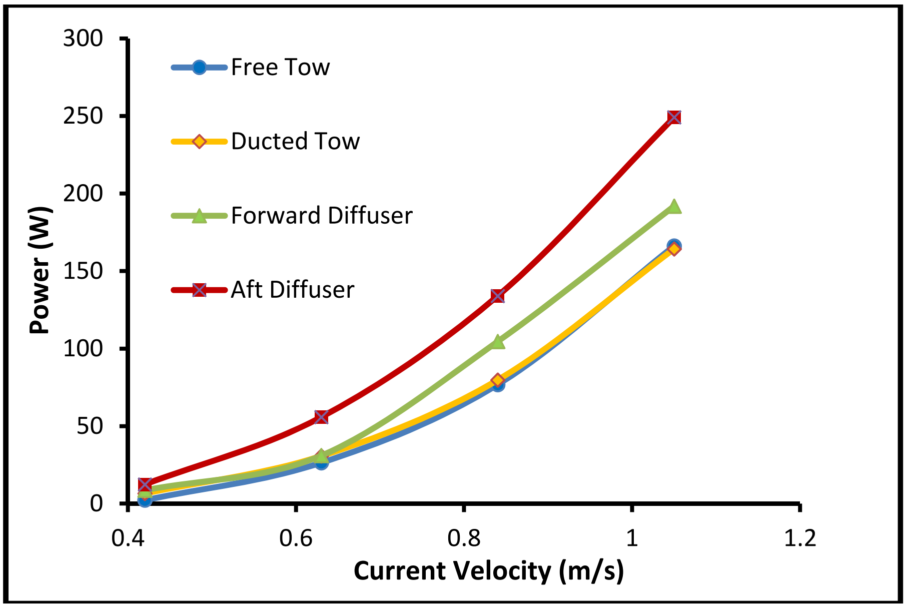


Figure 10. The potential of harnessing the power at different speed current approaching

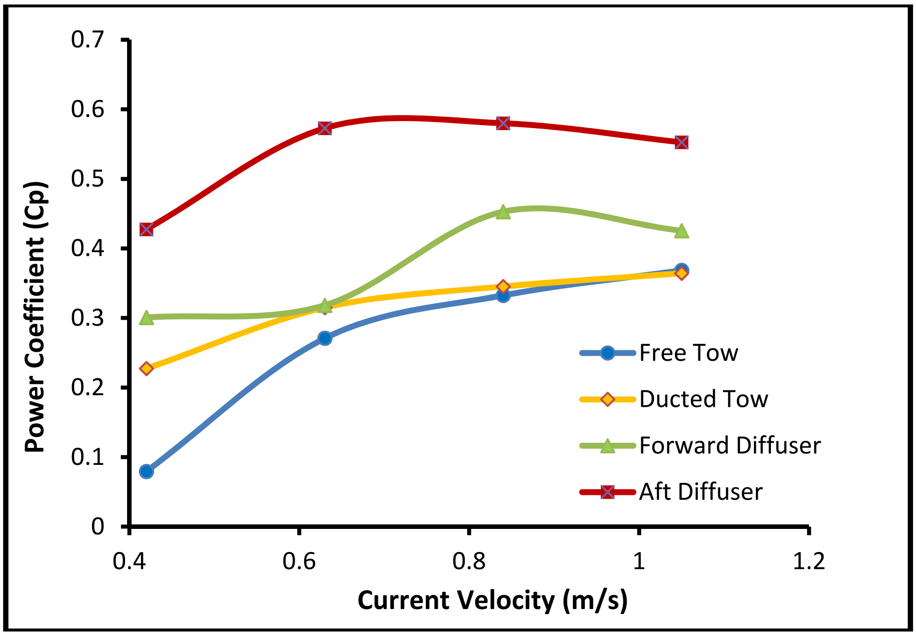


Figure 11. the power coefficient at different current speed for all cases

4. CONCLUSION

The objective of this work which was to design a horizontal axis marine current turbine was pursued. it was studied the previous developed HAMCT device, the flow concentrating devices as well as speed increasing devices, and to study from wind turbine technology. The design of HAMCT has been developed based on the literature studied. It consists of 4 blades rotor using NACA 0014 design profile surrounded by a cylinder diffuser with an attachment of diffuser to increase the speed flow. A model was built to predict the performance of the designed turbine and to study the effectiveness of the ducted when applied to current turbine. It was found that when utilizing augmented- diffuser around horizontal current turbine, the velocity through the turbine and augmentation diffuser and the rotor was increased. The maximum power output increased from nearly 166 W in case of free flow to slightly above 249 W for augmented- diffuser, also the Coefficient of power also increased by 1.7 times for this case. Diffuser arrangement were stated more effectively when it is attached behind the rotor rather than front of the wind turbine rotor.

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