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Experimental Studies on Savonius-type Vertical Axis Turbine for Low Marine Current Velocity

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A B S T R A C T

Renewable energy resources need to be explored to maintain and meet energy demand and replace the slowly depleting fossil fuels. Malaysia, surrounded by sea with long coastlines, is poised to exploit the potential of this energy. This research work aims at designing a suitable device to extract energy from Malaysian sea current. Malaysia's ocean has a low current velocity, averaging 0.56 m/s, which is below the working velocity of presently available current energy devices. To overcome this velocity limitation, a Savonius-type Vertical Axis Marine Current Turbine (VAMCT) design was proposed. The experiment to measure the torque of a Savonius-type turbine, which hitherto has been used for wind energy application, is presented in this paper. The laboratory experiment was carried out in the towing tank facility in Marine Technology Laboratory at Universiti Teknologi Malaysia. The Savonius model was attached to the towing carriage and current flow was simulated by moving the carriage in still water. The results show that turbine with double stacking rotors, each with two paddles and overlap ratio of 0.21 gives the best performance.

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NOMENCLATURE

C_p	Coefficient of power
C_t	Coefficient of torque
d	Diameter of the cylinder (paddle) in the rotor / distance for torque calculation [m]
d_m	Diameter of model paddles [m]
D	Diameter of rotor [m]
D_m	Diameter of model rotor [m]
e	Gap between paddles : main overlap [m]
e'	Gap between paddles : second overlap [m]
F	Force of model/turbine [N]
H	Height of rotor [m]
r	Radius of paddle [m]
T	Torque of turbine [Nm]
T_m	Average torque of model [Nm]
P	Power [W]
P_p	Power of prototype [W]
V_m	Current velocity for model [m/s]

Greek Symbols

α	Aspect ratio
β	Overlap ratio
ω	Angular velocity [rad/s]
ρ	Density [kg/m^3]
λ	Tip speed ratio

Subscripts

p	Prototype; Power
m	Model
t	Torque

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1. INTRODUCTION

Recent increase in the price of crude oil and environmental issues are forcing governments and researchers to consider the incentives for development of alternative clean sources of energy. One of the potential sources of clean energy is the ocean. In this respect, a number of initiatives are being pursued by various governments, such as New Zealand [1], United Kingdom [2], Australia [3], European Union [4], the United States [5] and Japan [6].

There are various forms of ocean energy viz. thermal difference, tides, waves, ocean current and salinity gradient. One of the potential ocean energy sources is in the form of marine current energy. Although capital cost is expected to be high, marine current energy devices have merits in low running cost, minimal environmental impact, minimal visual impact and predictability.

Currently, marine current energy is being harnessed using two types of turbines; vertical axis marine current turbines (VAMCTs) and horizontal axis marine current turbines (HAMCTs). Yaakob et al. [7] also briefly described and classified some of the most common VAMCTs being currently developed.

A summary of various concepts and their present design current speeds are given in Table 1. The table indicates that most of the existing VAMCT are for current speeds above 1.1 m/s (2.45 knots). Since most areas of the ocean have low marine current speed, there is thus a need to review and modify current designs or completely introduce a new design.

Malaysia's ocean has a low current velocity and shallow water depth. The annual average velocity current of ocean in Malaysia is shown to be 0.56 m/s with depth water about 15-30 meter [12]. Because of the low speeds associated with Malaysian tidal currents, the Savonius-type turbine (usually used to extract wind energy) was proposed by Yaakob et al. [13]. Being a drag-based rotor, it has the potentials to capitalize on the higher density and viscosity of seawater to obtain better torque characteristics even at low current speeds. CFD numerical studies were carried out and reported in Yaakob et al. [14]. Figure 1 shows the model used during the simulation studies.

TABLE 1. Various VAMCTs and their specifications

No	Type of vertical axis turbine	Current speed [m/s]	Efficiency (η)	Power (P)	Dimension H [m]	D [m]
1	Darrieus [8]	1.1	20%	15W	1.6	1.6
2	Helical [9]	1.5	35%	0.5 kW	0.85	1
3	Kobold [10]	1.8	23%	20kW	5	6
4	Davis [11]	2.5	30%	4 kW	1.2	1.2

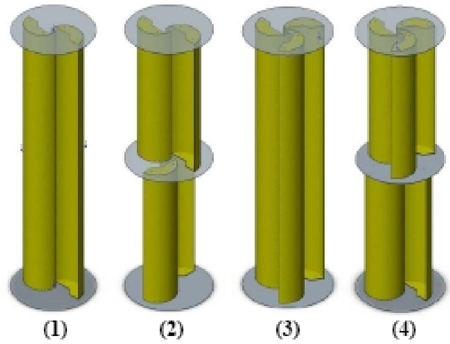

Figure 1. Savonius models for simulation

Some recent works on Savonius rotor for tidal current application has also been reported by Nakajima et al. [16] and Kyozuka [17]. Nakajima et al. [16] conducted experiments on the Savonius rotor in a horizontal orientation, hence essentially not a vertical axis rotor. However, their findings confirmed results reported by Yaakob et al. [14] that a double step rotor with a 90 degrees phase angle is more efficient that a single step rotor. To improve the starting torque of a Darrieus turbine, Kyozuka [17] tested a combined Darrieus-Savonius in a circulating water channel. It was found that whilst the starting torque increased, the power coefficient decreased by 30%.

For the Savonius-type turbines, research in the wind turbine applications have shown that its performance is critically affected by three particular parameters. They are aspect ratio, overlap ratio and stacking configuration. An initial experimental study on marine turbine application described by Yaakob et al. [13] concluded that overlap ratio is one important factor to determine the performance of the Savonius rotor. This concurred with findings of Menet [17] who reported that previous experiments of Savonius-type wind turbine by a number of researchers have shown significant relationships between maximum power coefficient of turbine and the overlap ratio (β). Gupta et al. [19] found that the maximum power coefficients were obtained at overlap ratio between 0.20 and 0.25. The numerical study showed that the optimum performance was obtained for a two stack, four-bladed Savonius rotor with overlap ratio of 0.21. This paper describes the experimental work to validate the results of numerical work.

2. MATERIALS AND METHODS

A 1/10th scaled model of a Savonius rotor used in CFD simulation reported by Yaakob et al. [14] was built and tested in Marine Technology Laboratory, Universiti Teknologi Malaysia.

2. 1. Dimension of Savonius Rotor Determination of main dimensions is important in order to estimate the result of turbine power. The main dimensions are height, aspect ratio and diameter of rotor. Height of rotor (H) is determined based on depth of location and the mechanical design of rotor such as design of shaft, draft of platform and support design of rotor. H of turbine is also used in aspect ratio calculation to get the diameter of turbine. Aspect ratio (α) is one of the important criteria for an aerodynamic performance of Savonius rotor. In general, the high value of α should significantly improve the efficiency. According to Menet [17], when the values of α is four, it will provide the best power coefficient for a conventional Savonius rotor.

The relationship between aspect ratio, height and diameter is shown by:

$$\alpha = \frac{H}{D} \tag{1}$$

Using dimensional analysis, the following relationships are obtained:

$$\gamma = \frac{L_p}{L_m} = \frac{d_p}{d_m} \tag{2}$$

$$\frac{V_p}{V_m} = \sqrt{\gamma} \tag{3}$$

The dimensions of the full-scale prototype and scaled model of the rotor are shown in Table 2.

One of the important parameter of Savonius rotor must be considered is overlap ratio. Overlap ratio β is comparison between the overlap (e) and diameter of the paddle (d). Figure 2 shows the scheme of Savonius rotor where:

$$\beta = \frac{e}{d} \tag{4}$$

The best efficiencies were obtained for values of overlap ratio (β) between 0.20 and 0.30. Gupta et al. [20] reported the maximum power coefficient in the overlap ratio of 0.20 – 0.25. The CFD simulation study by Yaakob et al. [14] concluded that the maximum torque of Savonius model of marine current application occurred where overlap ratio is 0.21 at static conditions.

TABLE 2. Specification of Savonius rotor prototype and scaled model [14]

No	Specification	Prototype	Model
1	Height of rotor (*Hp*)	15 *m*	1.5 *m*
2	Diameter of paddles (*dp*)	3.75 *m*	0.375 *m*
3	Aspect ratio (α)	4	4
4	Nominal speed (*Vp*)	0.56 *m/s*	0.17 *m/s*

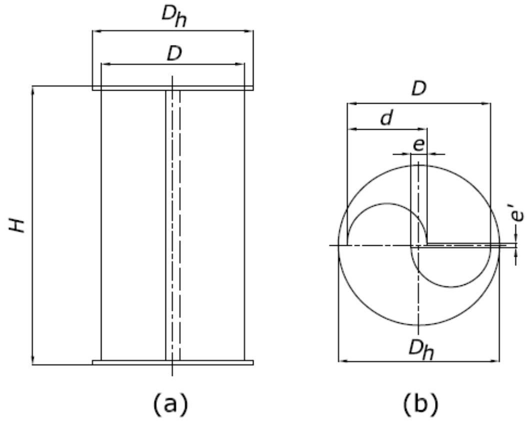

Figure 2. Scheme of a single stacking Savonius rotor. (a) Front view; (b) Top view [14]

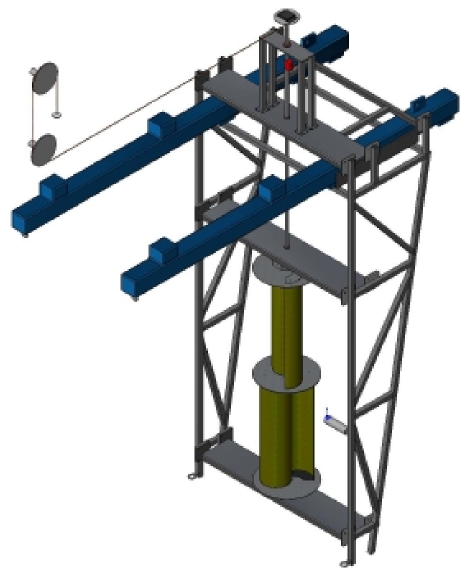

Figure 3. Isometric view of Savonius rotor and support structure with load

2. 2. Model Construction Rotor construction can be divided into 3 parts, which are 4 paddles, holder of paddle and shaft of rotor. Its holder is constructed using 5mm plates. Shaft of rotor part is hot dipped galvanized steel shaft. The support of rotor is constructed by carbon steel square tube. All materials for rotor of turbine have been laminated by hot dipped galvanization to prevent corrosion. Bearings are put between shaft rotor of turbine and support structure to reduce friction between rotor and support structure.

The Savonius rotor is enclosed in a support structure, supported by a thrust bearing as shown in Figure 3. Figure 4 shows the picture of the model above the towing tank.

Figure 4. Savonius rotor model

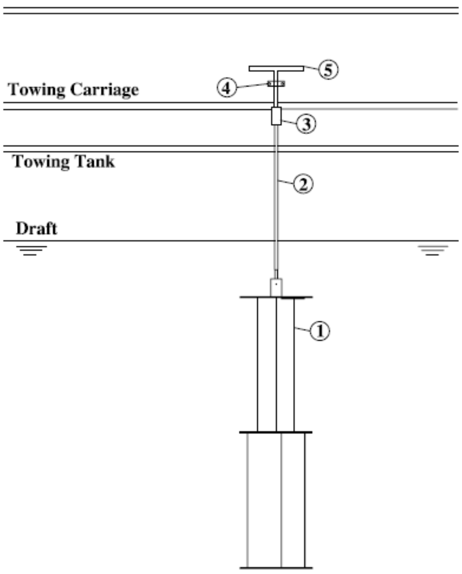

Figure 5. Schematic representation of the model experiment at static condition

2. 3. Experimental Set-up The experiment was conducted in the towing tank in Marine Technology Laboratory, UTM, which had 120 m length, 4 m breadth and 2.5 m water depth. The model was towed at speeds equivalent to the required marine current speeds while the torque and RPM values were measured. A torque meter was put on top of shaft to measure torque (Nm) and angular velocity (RPM). The experiment was run at two conditions; static and rotational conditions.

2. 4. Static Condition The objective of this condition was to enable comparison with CFD simulation results. The experiment was run with overlap ratios of 0.10, 0.15, 0.21, 0.25 and 0.30 at static condition.

In static condition, the rotor is imposed to stop using the fix load. That meant, the rotor did not rotate at the carriage moved. Figure 5 shows the set-up position of model at static conditions.

The rotor was locked at various angles similar to that in the numerical analysis. The rotor positions of this test were 0º, 45º, 90º and 135º representing condition of rotor for one rotation (360° revolution). Figure 6 shows angle positions of lower stack of the Savonius rotor used in this experiment. The net torque on the rotor was calculated using methods explained by Yaakob et al. [14].

2. 5. Rotational Condition The performance of the rotor can be evaluated by this condition. The experiment provided the data of torque and RPM from zero until maximum loads. Thus, from that data, the performance parameter of rotor in the form of coefficients of torque (*Ct*), tip speed ratio (λ) and coefficient of power (*Cp*) could be analyzed. To measure the desired torque, a load mass system was applied as shown in Figure 7.

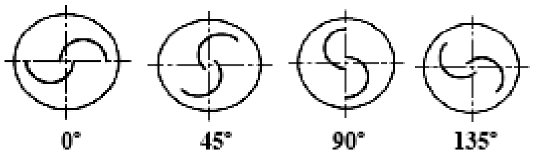

Figure 6. Angular positions at lower stack of Savonius rotor [14]

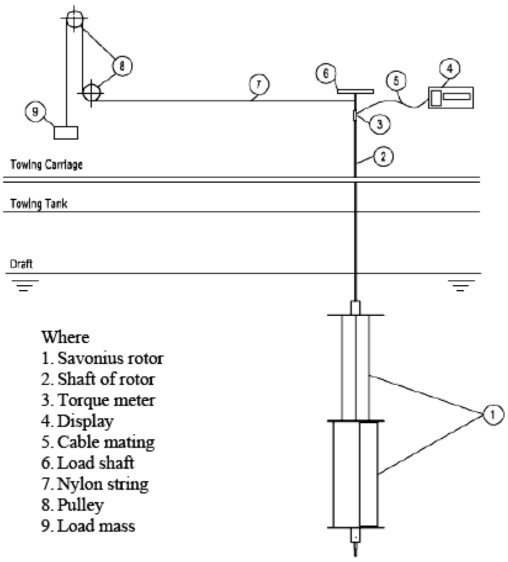

Figure 7. Schematic representation of model experiment at rotational condition

Based on the results from static tests, the dynamic condition tests were carried out at an overlap ratio of 0.21 at various velocities. For each velocity, the experiment was run at three conditions of load mass; non-load (zero loads), varying load and maximum load (fix load). In non-load condition, the RPM of the model at constant current velocity was recorded. In varying load condition, torques were applied by adding weights from zero to maximum load while the sensor measured the associated torque and RPM. At maximum load condition (fix load), the rotation stopped, because the torque which was provided by rotor of turbine and load shaft were in equilibrium. The time duration was 30 s for every run experiment.

3. EXPERIMENTAL RESULTS

Figure 8 shows comparison of torque between experiment and CFD results [14] at static conditions.

The validation of CFD results was based on comparison with manual calculations to determine the best computational domain of simulation. The description about computational domain of simulation was given by Yaakob et al. [14].

Although the absolute values of the torques were slightly different, the experimental and CFD simulation results were comparable in terms of trends and showed that the maximum torque occurred at overlap ratio of 0.21. This confirms the earlier results from Gupta et al. [19] and Yaakob et al. [14].

The differences in the results between experimental and CFD simulation were due to the following factors. First, in the CFD simulation process, the turbine was divided into 2 parts; the upper and lower rotor [14], thus the effects of the rotation between the parts could not be considered. Second, the CFD software used generated the mesh using an automatic meshing process leading to the same shape of elements and size of meshing (square) in all areas. Whereas, the simulation will get optimum result if make the detail of type element mesh in critical area. This process cannot be provided by the software [14].

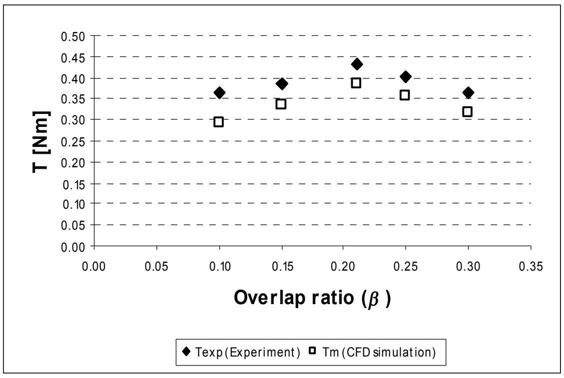

Figure 8. Comparison of torque between experiment and CFD simulations (Vm = 0.17 m/s)

TABLE 3. Torque and RPM of Savonius rotor with overlap ratio of 0.21 and Vm = 0.17 m/s

No	Load mass (*L*) [*gram*]	Texp [*Nm*]	STDEV texp	RPM	STDEV RPM
1	0	0	0	11.97	1.23
2	500	0.13	0.03	9.96	0.72
3	750	0.15	0.03	9.06	0.8
4	1000	0.18	0.03	8.36	0.92
5	1250	0.22	0.03	8.45	1.11
6	1500	0.23	0.03	7.27	0.93
7	1600	0.27	0.04	5.88	1.35
8	1650	0.27	0.04	6.84	0.7
9	1700	0.28	0.04	6.43	1.23
10	1800	0.29	0.03	5.06	1
11	2000	0.31	0.03	6.49	1.21
12	2300	0.36	0.03	3.38	1.75
13	2500	0.34	0.03	4.44	1.88
14	2600	0.36	0.03	0	0

The rotational conditions tests were carried out only at overlap ratio of 0.21. Table 3 shows data of torque and angular speed (RPM) for several load mass configurations at model current velocity of 0.17 m/s.

The performance parameters of the turbine such as coefficients of torque (Ct), tip speed ratio (λ) and coefficient of power (Cp) can be obtained from the experimental results. The parameters are calculated using Equations (5, 6 and 7) [19]:

$$C_t = \frac{4.T}{(\rho.V_m^2.D_m^2.H)} \tag{5}$$

$$\lambda = \frac{\omega.r}{V_m} \tag{6}$$

$$C_p = C_t.\lambda \tag{7}$$

From the above equations, performance of the turbine can be found as shown in Figure 9. The maximum Cp of the turbine is quite low, just below 0.16 at the tip speed ratio (λ) of 0.79. Nakajima et al. [15] also carried out experiments on the Savonius turbine with horizontal axis. The result of the coefficient of power (Cp) was higher than vertical axis turbine. However, the overlap ratio of the cross-flow turbine was 0.36 compared to the overlap ratio of 0.21 used in the present study.

The coefficient of power (Cp) data between vertical and horizontal axes are superimposed and compared with existing Cp-λ performance curves of several types of turbines taken from the work of Guidice et al. [18] in Figure 10. The current experimental results are given as the black dots. It shows that our results are closer to the conventional Savonius *Cp* originally given by Guidice. Our results are also similar to the efficiencies of Darrieus-Savonius turbine given by Kyozuka [16] which are also in the range of 0.15 to 18.

Based on Figure 10, the marine Savonius turbine has similar coefficient of power (*Cp*) with conventional Savonius turbine for wind application. It shows that efficiency of the Savonius turbine is not affected by the fluid medium or its speed.

At a scale of 1:10, the estimated dimensions, current velocity, torque, angular speed and power of rotor full-scale prototype are shown in Table 4. Current velocity of model 0.17 m/s is equivalent to the actual current velocity prototype 0.56 m/s or 1.1 knots at the location of research. Table 5 shows the estimated power provided by prototype is about 1426.28 *W*.

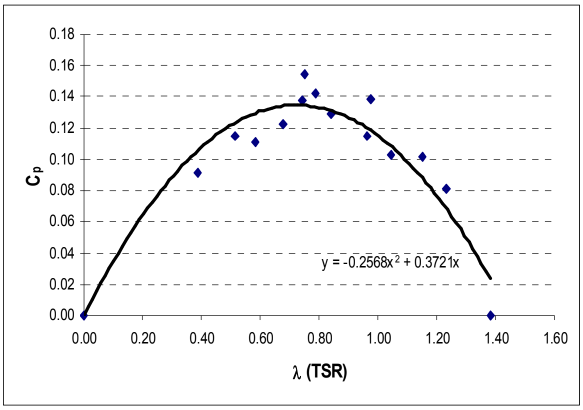

Figure 9. Coefficient of power and tip speed ratio of experiment with overlap ratio of 0.21 and Vm = 0.17 *m/s*

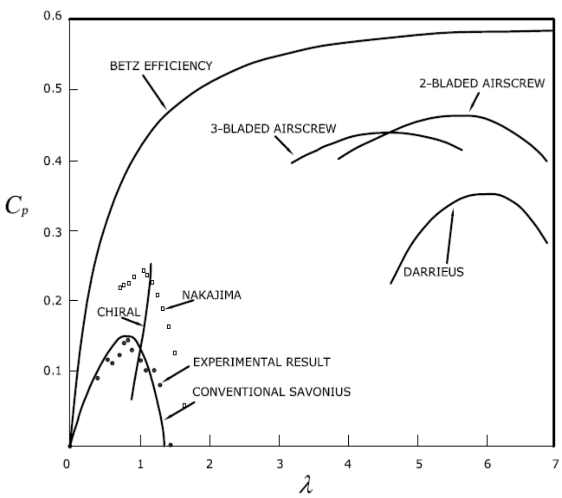

Figure 10. Comparison of Cp-λ performances curves [18]

TABLE 4. Result of Savonius turbine for marine current application

No	Description	Model	Full-scale prototype
1	Torque (*T*)	0.36 *Nm*	3600 *Nm*
2	Angular speed (ω)	11.97 *rpm*	3.79 *rpm*
3	Angular speed (ω)	1.25 *rad/s*	0.4 *rad/s*
4	Power (*P*)	0.45 *W*	1426.28 *W*

4. CONCLUSIONS

Although many researches have proposed the Savonius rotor for wind turbine applications, the work presented in this paper is one of the few dealing with marine current applications. The study provides a new concept of Vertical Axis Marine Current Turbine (VAMCT) especially for low current velocity. Previously developed VAMCT are all based on the minimum current velocity of more than 2 knots full-scale. The prototype of Savonius rotor developed in the present study will operate even with low current velocity of 0.56 *m/s* or 1.1 knots.

The experimental work has confirmed the findings of earlier numerical simulation studies, indicating that the best overlap ratio is in the region of 0.20 – 0.25. Our studies have shown that with its low starting torque, this rotor can work at low speed marine current velocity. Hence, this condition is suitable with Malaysia ocean which have low speed current (0.56 *m/s*). The low current speed and higher density of water has no effect on the coefficient of power of the turbine, which is similar to wind turbine efficiencies of around 0.16 to 0.18.

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چکیده

جهت پاسخگویی به تقاضای روزافزون انرژی، لازم است منابع انرژی تجدید پذیر کشف و جایگزین سوخت های فسیلیِ درحال پایان گردد. مالزی، با سواحل طولانی، آمادگی دارد از این منابع انرژی بهره برداری کند. هدف از این کار تحقیقاتی، طراحی یک دستگاه مناسب برای استخراج انرژی از جریان های دریایی می باشد. سرعت جریان آب دردریاهای اطراف مالزی بطور متوسط ۰,۵٦ متربرثانیه بوده و کمتر ازسرعت مورد نیاز برای کار دستگاه های موجود میباشد. برای غلبه بر این محدودیت سرعت، توربین محورقائم دریایی (VAMCT) از نوع Savonius ارائه شده است. آزمایش اندازه گیری گشتاورروی توربین مذکور، که تا کنون برای انرژی باد استفاده می شده است ، در این مقاله ارائه شده است. انجام تستهای آزمایشگاهی در حوضچه کشش دانشگاه صنعتی مالزی (Universiti Teknologi Malaysia) صورت گرفته است. مدل توربین به سیستم یدک (Carriage) وصل وجهت شبیه سازی جریان، درآب آرام کشیده شده است. نتایج نشان داده است که توربینهای حاوی دو روتورکه روی هرکدام ازآنها دو پدال وجود داشته و نسبت همپوشانی آنها ۰,۲۱ میباشد، عملکرد بهتری دارند.

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