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Experimental Study of a Hybrid Turbine for Hydrokinetic Applications on Small Rivers in Malaysia

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ABSTRACT

Energy consumption has become a primary commodity due to technological revolutions in developing countries, such as the expansion of the hydrokinetic turbine as a renewable energy source to mitigate environmental issues. However, conventional vertical axis turbines in hydrokinetic applications particularly for small rivers with low speeds, have limited capabilities such as great power but poor self-start or vice versa. Therefore, the current study aims to address this issue by investigating a hybrid turbine through quantitative and qualitative wind tunnel experiments to improve the performance and self-start capability by integrating Savonius and Darrieus turbines. The findings discovered that the maximum torque coefficient of the hybrid turbine is 37% higher than that of a single conventional Savonius turbine. The integration of the hybrid turbine has resulted in a higher torque coefficient which has enhanced the self-start performance. The hybrid turbine achieved a maximum power output improvement of 30% at a low Reynolds number of 89500, typically representing the small river flow conditions. The presence of a substantial wake captured by the smoke generator at the rear part of the hybrid turbine signifies large drag resulting in power loss and a subsequent decrement in power output. The hybrid turbine has demonstrated its potential to be implemented in hydrokinetic applications in developing countries such as Malaysia for sustainable energy generation.

Keywords:
Savonius; hybrid turbine; vertical axis turbine; power; hydrokinetic

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1. Introduction

The increasing usage of online platforms particularly in education due to the recent COVID-19 pandemic has profoundly changed the way people learn globally. The need for power has become critical to accessing online learning, especially for those living in rural areas and off the grid who have been living without any power supply, including Malaysia. Non-renewable energy has currently become the primary source of energy generation in Malaysia but this has resulted in environmental issues such as increased carbon dioxide emissions, greenhouse effects, and global warming [1-3]. Therefore, these issues have become the main concerns in exploring other alternatives and the hydrokinetic turbine has demonstrated the potential for renewable energy and sustainability due to the vast river network in Malaysia [5,6].

Salleh *et al.,* [6] have established that the vertical axis turbine seems to be the most viable option for installation in a small river compared to the horizontal axis turbine. This is due to the nature of the river in

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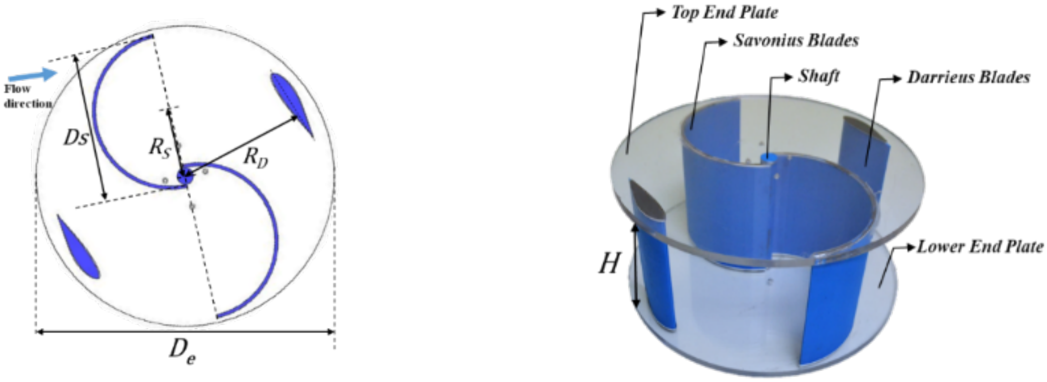
Malaysia which has a low flow rate, and the most common types of vertical axis turbines are the Darrieus and Savonius types. The Darrieus type provides high power efficiency but has poor self-starting torque [7], whereas the Savonius type usually provides good starting torque but has low power efficiency [8]. Although the Savonius type appears to be more practical for hydrokinetic applications, particularly in rural areas due to its simpler design with low development and maintenance costs [9], its limitations in producing adequate power have hindered it from being implemented in practical applications.

Therefore, several attempts were performed to improve the turbine performance and overcome its limitations such as combining the Savonius and Darrieus turbine features, also known as a hybrid turbine. The combination has significantly enhanced the turbine performance [10] compared to a conventional Savonius or Darrieus turbine on its own or 2 or 3-stage modified Savonius turbine [11]. However, most of the established studies on hybrid turbines have mainly focused on higher Reynolds numbers above 200 000 and there is a lack of studies conducted for hydrokinetic applications particularly for low Reynolds numbers. Therefore, the present study aims to address this missing gap with quantitative and qualitative measurements to improve the performance of the turbine. The experimental investigation on the hybrid turbine in the present work was performed at a low Reynolds number of 89 500 for hydrokinetic applications to make it more practical for a small river with low flow rate typically ranging from a speed of 0.2 m/s to 0.5 m/s in Malaysia.

2. Methodology

2.1 The Hybrid Turbine Model

A hybrid turbine in the present study consists of a combination of conventional Savonius and Darrieus blades. The Savonius blades were incorporated with a Darrieus blade to produce a better performance at a low tip speed ratio [12,13]. The Darrieus airfoil blade profile was AH93W215 which has a maximum lift-to-drag ratio of approximately 6.70 [14]. The physical dimension parameters are illustrated in Fig 1 and the geometric configurations of the turbine are tabulated in Table 1.



(a) (b)

Fig. 1. The geometric parameters of the hybrid turbine. (a) The top-view of the hybrid turbine model and (b) the assembly of the hybrid turbine

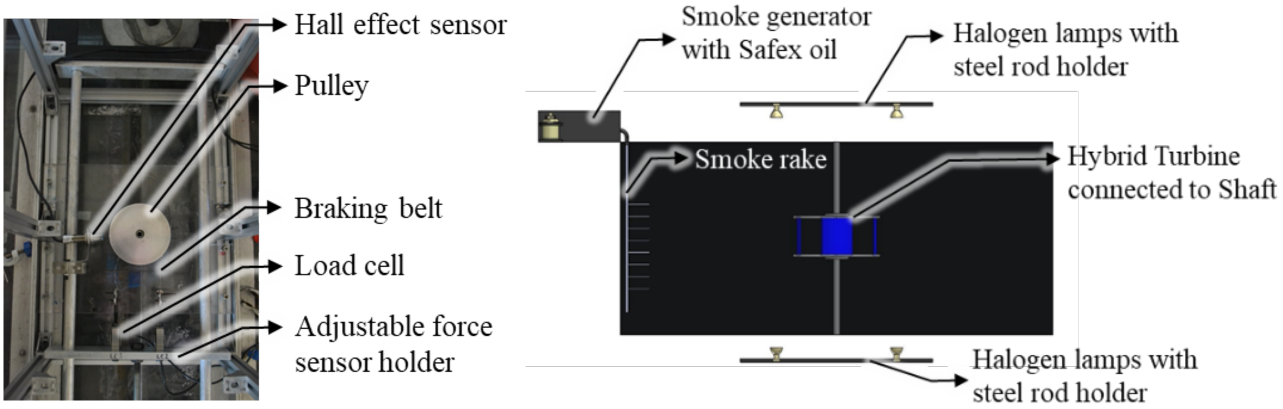
2.2 Experimental Setup

The experimental setup for both quantitative and qualitative measurements is shown in Fig 2. The experiment was carried out in the closed-circuit wind tunnel with a test section size of *1.8m* x *1.0m* x *0.8m* at a Reynolds number of 89 500. The Prony dynamometer setup for quantitative measurement consisted of a Hall effect sensor to detect the magnetic field with the magnet attached to the pulley and two load cell sensors capable of detecting forces acting on the pulley. To complement the quantitative analysis, a flow visualization image of the hybrid turbine was captured to provide the flow structure of the hybrid turbine. A three-dimensional (3D) printer was used to fabricate the turbine blades using polylactic acid (PLA) as the material.

The endplates for the turbine were made of a 10 mm acrylic plate and the slots for the Savonius and Darrieus blades were created using a Computer Numerical Control (CNC) machine.

Table 1
The dimension parameter of the hybrid turbine design

Parameters	**Value (units)**
Height of turbine, H	0.1500 (m)
Diameter of turbine, D	0.3600 (m)
Diameter of blade, d	0.1850 (m)
Diameter of shaft, d_s	0.0100 (m)
Diameter of end plate, D_E	0.3610 (m)
Thickness of blade, t_b	0.0040 (m) Savonius blade 0.0196 (m) max thickness of Darrieus blade
Thickness of end plate, t_E	0.0100 (m)
Radius Ratio, $RL = R_S/R_D$	1.1500 (-)
Aspect ratio, $AR = H/D$	0.4166 (-)
End plate ratio, $OR = D_E/D$	1.0027 (-)
Blockage ratio, $\mathrm{BR} = HD/ H_{WT}W_{WT}$	0.0767 (-)



(a) (b)

Fig. 2. The experimental setup consists of (a) The Prony-dynamometer and (b) The side view flow visualization of the components arrangement illustration

2.3 Equations

The Reynolds number, *Re,* of the flow in the present study was calculated from equation (1). Based on the output from the experimental setup of the hybrid turbine, the dynamic torque, *T,* is calculated by using equation (2) with the radius of the pulley, r_p =0.03 m. The angular speed, ω of the turbine is obtained in equation (3) with the revolution of the turbine in a minute, RPM value detected from the Hall effect sensor.

$$Re = \frac{\rho V_\infty D}{\mu} \tag{1}$$

$$T = \Delta F \times r_p \tag{2}$$

$$\omega = \frac{2\pi}{60} \times RPM \tag{3}$$

$$C_T = \frac{4T}{\rho H D^2 {V_\infty}^2} \tag{4}$$

In equation (4), the torque coefficient is calculated as a non-dimensional parameter using the torque value obtained from equation (1). Then the power coefficient was then calculated by dividing the turbine's power generated, $P_{out} = T\omega$ by the incoming flow speed, $P_{in} = \frac{1}{2}\rho H D {V_\infty}^3$. The power coefficient equation was generalized as follows:

$$C_P = \frac{2T\omega}{\rho H D {V_\infty}^3} \tag{5}$$

The coefficient of torque and power value is plotted against the tip speed ratio, λ where:

$$\lambda = \frac{\omega D}{2V_\infty} \tag{6}$$

2.4 Uncertainty Analysis

According to the method described in Moffat [14], the general uncertainty analysis is shown in equation (8) with the relative sensitivity shown in equation (9). Table 2 illustrates the uncertainty of the parameters under conditions of maximum power coefficient at 4 m/s airflow speed.

$$U_R = \pm\frac{\delta R}{R} = \left\{\left(a\frac{\delta X_1}{X_1}\right)^2 + \left(b\frac{\delta X_2}{X_2}\right)^2 + \cdots + \left(n\frac{\delta X_n}{X_n}\right)^2\right\}^{1/2} \tag{8}$$

$$a = \frac{X_1}{R}\frac{\partial R}{\partial X_1}; b = \frac{X_2}{R}\frac{\partial R}{\partial X_2}; n = \frac{X_n}{R}\frac{\partial R}{\partial X_n} \tag{9}$$

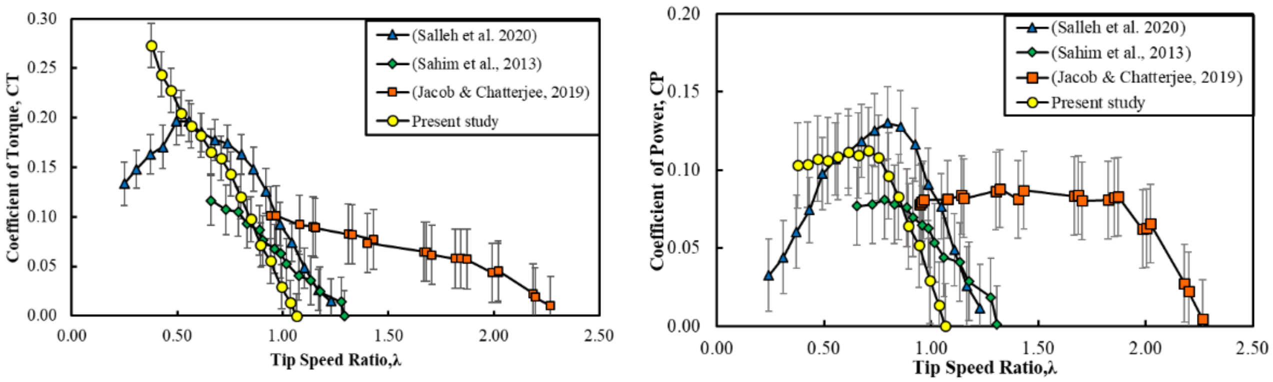
Table 2
The values of uncertainty percentage of the parameters

Parameters	Uncertainty value	Uncertainty percentage
Tip speed ratio, λ	±0.0131	1.30%
The coefficient of torque, C_T	±0.0304	3.04%
The coefficient of power, C_P	±0.0414	4.14%

3. Results and Discussion

3.1 The Performance of the Hybrid Turbine

The performance of the hybrid turbine is represented in the torque and power coefficient against the tip speed ratio illustrated in Fig 3. The hybrid turbine generated a more significant torque coefficient value than the conventional Savonius turbine [16] with a C_T value of 0.27 at a tip speed ratio of 0.38. The result demonstrates that the peak of the torque coefficient is higher despite having a low Reynolds number compared to the other hybrid turbines from the previous studies. This analysis reveals that the torque behaviour of the hybrid turbines is crucial in overcoming the self-starting issues as more torque was generated at a lower tip speed ratio. Meanwhile, the power coefficient curve of the hybrid turbine exhibits an increment along with the tip speed ratio until the peak point is reached, and subsequently the power coefficient decreases with the increment of the tip speed ratio. The power coefficient of the hybrid turbine shows the peak value at 0.11 at the tip speed ratio of 0.7 with an improvement of 37% and 22% compared to [17] and [18] respectively.



(a) (b)

Fig. 3. (a) The torque coefficient and (b) The power coefficient of the turbine

In addition, the smoke flow visualization image captured to illustrate the flow structure of the hybrid turbine as shown in Fig 4 indicated a stagnation point with maximum pressure in this region. A relatively large white region with a circulation flow at the rear part of the turbine indicates the wake generated behind the rotating turbine with streamlines at the top and bottom of the turbine as a result of low pressure [19]. The wake size downstream of the hybrid turbine is larger than the overall height due to pressure drag indicating a more significant energy loss in the flow [20]. This pressure drag due to the flow separation could be the reason for the deterioration of performance of the hybrid turbine that was lower than the conventional Savonius turbine [16,21,22] despite its higher torque coefficient values.

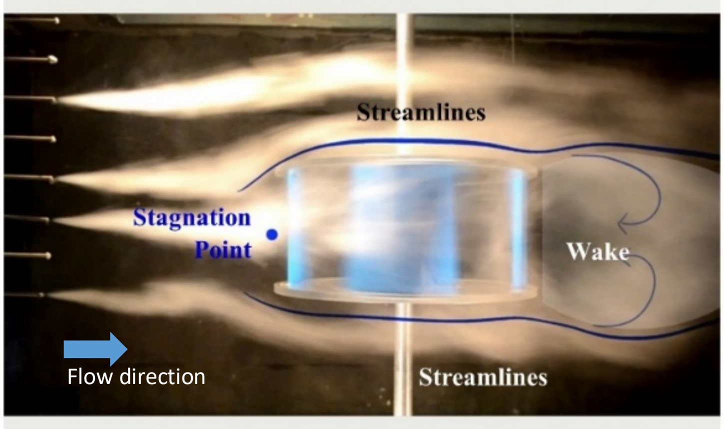


Fig. 4. The side view flow visualization of the hybrid turbine

4. Conclusions

The present study investigates the performance of a hybrid turbine consisting of a combination of conventional Savonius and Darrieus blade configurations at a wind speed of 4 m/s, corresponding to a Reynolds number of 89 500 and equivalent to a river flow speed of 0.2 m/s. The results revealed that the maximum power coefficient deteriorated by 15.38% compared to the baseline conventional Savonius turbine from the previous study, although it produced a significantly large torque coefficient trend with a maximum torque coefficient of 0.27. The smoke flow visualization showed the presence of the downstream wake, which was evident to affect the power coefficient of the hybrid turbine as the large wake represents a significant pressure drag due to flow separation.

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