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Tests on a non-clogging hydrokinetic turbine

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ABSTRACT

Hydrokinetic turbines (HKTs) are a promising technology for electrical power supply in small remote villages located in fairly flat, high rainfall country where other renewable energy technologies such as wind, solar and conventional micro-hydro are not suitable. However, clogging by floating debris has been identified as a major problem for HKTs in many waterways, and particularly in tropical rivers. To overcome this problem, an axial flow HKT has been designed using conventional wind turbine blade element theory and modified so as to minimize clogging by allowing one or more blades to swing back and forth in its plane of rotation. A 0.8 m diameter prototype has been constructed using low cost materials and simple tools. The final design was observed to shed long stringy algae and operate normally where a maximum coefficient of performance of 0.25 and a water-to-wire efficiency of just under 20% were achieved.

Introduction

The need for small scale electrical power supply in remote villages and the limitations of current means of supply have been documented in Anyi et al. (2010). Cheap diesel engine-powered gensets are commonly used, but fuel is expensive and difficult to transport, and these gensets typically fail after a year or two due to poor quality manufacture and/or lack of maintenance. The well-known renewable energy technologies are not suitable in high rainfall, densely forested country where (i) there is not enough wind for wind turbines, (ii) long periods of dense cloud cover limit photovoltaic production and high humidity and fast-growing fungus and vegetation can cause premature failures, and (iii) there is not enough static head for conventional micro-hydro.

Fig. 1 shows a typical village in Sarawak located right next to a large, fast-flowing river which is used for water supply, fishing and transport. Such rivers could also supply power via hydrokinetic turbines if the problem of clogging by floating debris could be overcome. According to Tyler (2011),

> *"Perhaps the greatest obstacle that confronts the implementation of commercial scale hydrokinetic devices in rivers is debris. Until recently, this problem has been largely avoided by installing devices in areas where debris is not a factor. This practice significantly limits the possible locations for deployment…."*

This is particularly true of tropical rivers which carry large amounts of vegetation during floods, but can be a problem in any waterway carrying floating debris. Fig. 2 shows driftwood piled up on a HKT pontoon and anchor cable in Alaska.

A screen in front of a turbine as proposed in Tiago (2003) is itself likely to become clogged by debris, thereby reducing or completely blocking flow into the turbine. Variants on the traditional undershot water wheel have been built and should shed debris under normal flow conditions because they are drag machines in which the paddles move with the water and debris should simply pass through with the water. Any debris sticking to the paddles will increase drag and should not adversely affect performance unless it damages the turbine or gets wound around the shaft. However these are large, cumbersome, inefficient devices requiring a very large wheel to generate useful power and a very large gear ratio to drive a generator. Existing HKTs have been reviewed in Anyi and Kirke (2010a, 2010b) and it was concluded that it should be possible to design a reasonably efficient axial flow HKT with blades that would "roll with the punches" and shed debris.

The clog-free rotor design concept

Besides aiming for a clog-free characteristic, the rotor must also be reasonably efficient and able to survive impacts. The banana-shaped blades used on some sewage treatment impellers (see for example in

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0973-0826/

Fig. 1. A typical village in Sarawak, located right next to a river (Flicker, undated).

ITT, undated) are designed to shed debris, but they are motor-driven impellers designed for mixing, which they will do to some extent even if there is some debris on them. They are not lift type turbines designed to generate power, whose blades must be reasonably efficient to generate any power. Also, being rigidly fixed to the hub, these blades would be prone to damage from floating logs.

One possible way to avoid both impact damage and clogging would be to use flexible blades, but these would be difficult to design and construct in such a way that they operate efficiently under normal conditions but are flexible enough to avoid damage and shed debris. A simpler and better way appeared to be to mount blades on hinges so they could swing back on impact, or to allow debris to slide off. The obvious way would be to allow them to swing back in about a tangential axis as shown in Fig. 3, i.e. “cone” as shown in Fig. 4(c), with spring preload preventing the coning action under normal operating conditions. This would also limit blade loading in floods by reducing the turbine swept area causing it to shed some power, saving turbine blades and structures from over stress and damage. However the direction of flow relative to a blade traveling at a tipspeed ratio of about 4 is more tangential than axial over most of its length, so allowing blades to swing back in the plane of the rotor as shown in Figs. 3 and 4(b) should have a better self-cleaning action and would also cushion impact.

During normal operation the blades would be held in the radial position by stops, but if a blade becomes clogged to the point where it no longer generates forward torque it would be free to swing back so that the relative flow acts to slide the debris out along the blade and off the tip so that the blade again generates forward torque and swings

Fig. 2. Driftwood on hydrokinetic turbine pontoon and anchor cable in Alaska (Tyler, 2011).

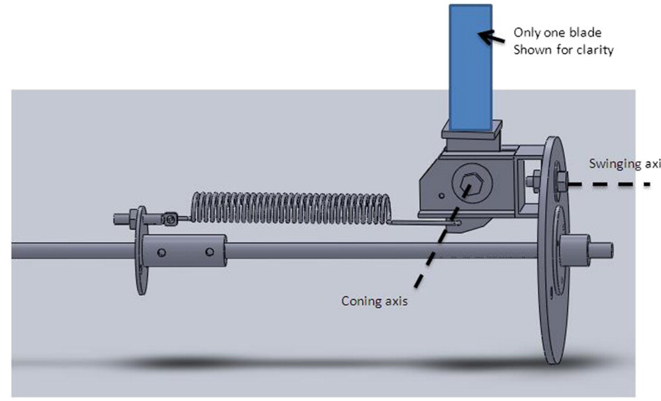

Fig. 3. Conceptual design for swing and cone blade motions.

forward into its normal operating position. However this mechanism would not limit blade loading in floods, so a combination to the two mechanisms would seem ideal.

Construction of a rotor with folding and swinging blades

After experimenting with a number of blade folding and swinging geometries, one potential design concept was chosen and further developed. Design of a blade geometry using conventional wind turbine blade element theory and its construction from timber using a simple router has been described in Anyi and Kirke (2010a, 2010b). Assuming a flow velocity of 1 m/s, a water-to-wire efficiency of 21% and a 200 W electrical output, it was determined in Anyi and Kirke (2010a, 2010b) that a turbine diameter of 1.6 m would be required.

A set of blades was designed and constructed using the techniques set out in Anyi and Kirke (2010a, 2010b), and another set was made out of cambered sheet aluminum to compare both performance and ease of construction. The coning and swinging mechanisms as originally constructed are shown in Fig. 5. There is a means of adjusting blade pitch and a means of adjusting coning spring tension. The non-rotating nose cone was intended to keep weeds out of the hub mechanisms.

Initial testing

The work was done in South Australia, the driest state of the driest inhabited continent, and in contrast to Sarawak, it was difficult to find a suitable waterway in which to test the turbine. There were no suitable laboratory facilities in South Australia and funding was not available to hire the large laboratory towing tank at the Australian Maritime College, which would have been ideal. Several possibilities were assessed and found to have either too low flow velocity or not enough flow area. The final choice was a 2.1 m wide concrete channel at Bolivar wastewater treatment plant which carries secondary treated sewage effluent (i.e. no solids, clear but nutrient-rich water with lots of long stringy sticky algae). Flow depth and velocity varied slightly with time of day, but average depth was about 1 m and average velocity was about 1 m/s. Although not ideal, this channel was available at no cost and is fairly close to the university campus, making logistics relatively simple. The 1 m/s flow velocity was considered representative of typical sites in Sarawak, but the 1 m depth meant that the original design, which called for a 1.6 m diameter turbine to deliver 200 W in a 1 m/s current, had to be reduced to 0.8 m diameter. The expected power was now reduced to about 50 W, calculated as below.

$$P = 1/2\,\rho A V^3 \times C_p \times \eta$$

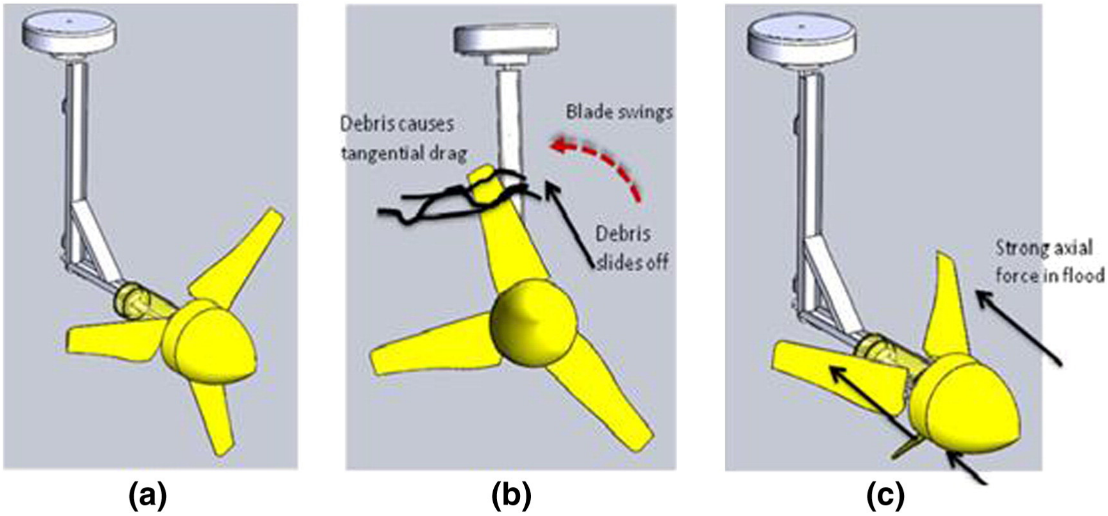

Fig. 4. (a) Normal operation, (b) one blade swings back in plane of rotation and (c) coning downstream.

where P = power, ρ = water density = 1000 kg/m^3, R = turbine radius = 0.4 m, V = flow velocity = 1 m/s, C_p = turbine power coefficient and η = transmission and generator efficiency. Assuming $C_p\eta$ = 0.21 as in, we have

$$P = 1/2(1000)\left(\pi R^2\right)\left(1^3\right) \times (0.21)$$

$$P = 1/2(1000)(\pi)\left(0.04^2\right)\left(1^3\right) \times (0.21)$$

$$P = 52.78 \quad W \approx 53 \quad W.$$

Although this is hardly enough for a village, it was considered enough to test the clog-free concept.

The turbine was mounted on a frame with adjustable height which was initially attached to an inflatable boat as shown in Fig. 6, with power transmission via a shaft with a 45° gearbox from a brush cutter. In later tests the 45° gearbox was replaced with a 90° gearbox and the frame was mounted vertically on a bridge across the channel. Net torque after gearbox losses was measured with a Prony brake system comprising a cord wrapped 180° around a pulley with a pair of spring balances, angular velocity was measured initially with a digital tachometer but this was unreliable in bright sun, and it proved easier to simply count revolutions per minute. Mechanical power in Watts is given by

$$P_{Mech} = T\omega$$

where T = torque in Nm and ω = angular velocity in radians/s = rpm × π/30.

The Prony brake was then replaced with an electric motor driven as a generator as shown in Fig. 6 and electrical power was measured. Two types of motor were bench tested, a brushless Smartdrive multi-pole low speed motor from a washing machine, of the type often advocated for small owner-built wind turbines, and a 36 V geared brushed DC motor. The rationale behind using the Smartdrive motor was to generate a high enough voltage to run 240 V appliances at the lowest rpm possible in order to match the low rpm of the turbine. However it did not perform as well as the brushed motor, even after modification. Performance details will be reported in another paper.

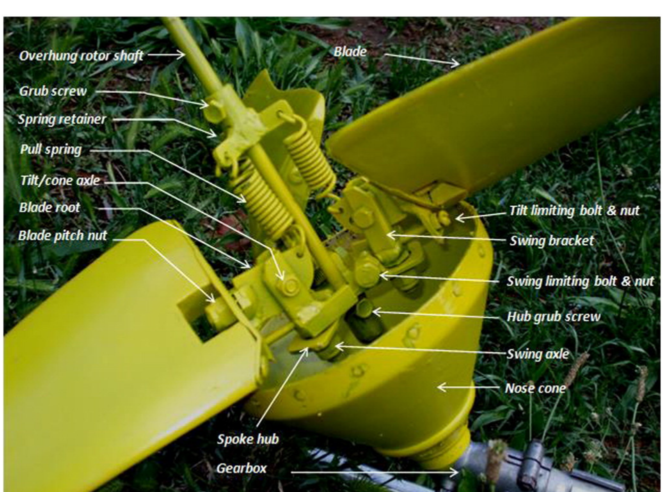

Fig. 5. Hub as originally constructed, complete with coning and swinging mechanisms, blade pitch adjustment and nose cone (nacelle).

Fig. 6. Turbine and generator mounted on inflatable boat in Bolivar channel.

Fig. 7. Weed/algae tangled in turbine hub and gearbox.

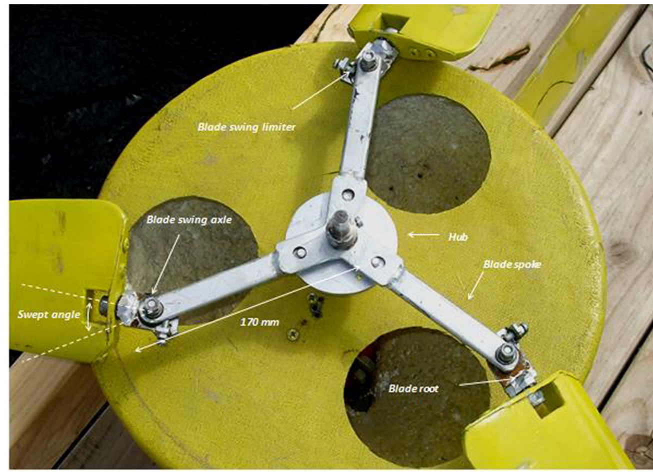

Fig. 9. Swing axes mover further from turbine axis, necessitating a bigger nose cone.

Initial results and design modifications

Weed/algae soon accumulated around the turbine shaft in its original form as shown in Fig. 7, and it was clear that modifications were needed.

It was realized that location of the blade swing axes meant that even when a blade swung back, it was still in an almost radial orientation as shown in Fig. 8, so that there was little cleaning effect.

But if the swing axes were to be moved further out as shown in Fig. 9, a blade carrying debris would swing into a more nearly tangential orientation as shown in Fig. 10, thus facilitating self-cleaning.

The larger nose cone shown in Fig. 9 was required to deflect flow around the swing axes, and the tail cone shown in Fig. 10 was added in the expectation that this would ensure smoother flow through the turbine. This meant that the coning mechanism could no longer be used, and it was decided to concentrate on the swing action and leave coning for later. Moving the swing axes out also required that the blades be shortened to maintain the 400 mm radius limit imposed by the depth of the water. To maintain correct taper and twist, they should ideally have been cut off at their inner ends, but to save time it was decided to cut off the outer ends and accept a reduction in efficiency, since the primary purpose was to test the turbine's non-clogging capability.

The larger nose cone looks out of proportion to the blades and it might be expected that this would reduce the effective swept area and severely reduce the turbine efficiency, but in fact its 300 mm diameter is only $(3/8)^2 = 14\%$ of the swept area, and the central part of a normal axial flow turbine contributes little to the power output. Flow is accelerated as it is deflected around the nose cone, augmenting the kinetic energy available to the outer part of the truncated blades, so there should be little loss in efficiency in the present arrangement.

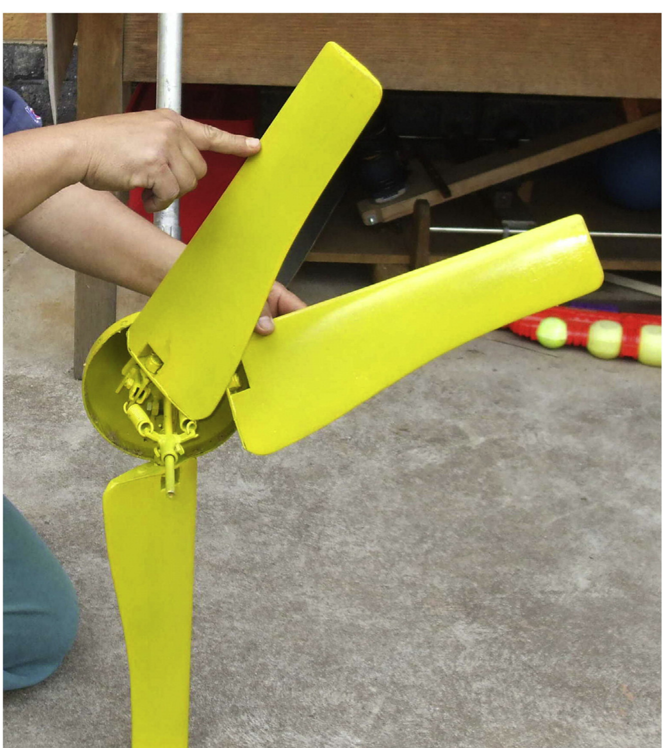

Fig. 8. Blade still in an almost radial orientation when swung back.

Further testing and final non-clogging results

The turbine was tested with the complete egg-shaped hub enclosure shown in Fig. 10. Unlike in the first test, weed was not found sticking to the blades while in operation. A small amount of weed did find its way into the space between the two cones but did not affect the performance of the turbine significantly.

The downstream cone was then removed, which was found to reduce drag by about 40%, from 250 N to 150 N and the turbine rpm was found to increase quite significantly. Removal of the downstream cone meant that

Fig. 10. Modified turbine with larger nose cone (below) and tail cone (above), showing a blade swung back in nearly tangential orientation to facilitate self-cleaning.

a blade coning mechanism was again possible, but it has not yet been implemented. Although the blades were found to shed debris effectively, some weed still wrapped around the shaft, as shown in Fig. 11.

A ring was then added behind the nose cone as shown in Fig. 12 to prevent weed winding around the shaft. This version of the turbine remained virtually weed-free.

Hydrodynamic performance

Although the primary aim of the work was to develop a non-clogging HKT rotor, the mechanical shaft power and electrical power output were measured. The Prony brake arrangement used to measure torque enables the maximum power output to be measured but not the full C_P–tipspeed ratio curve, since the turbine starts by freewheeling and torque is increased until the turbine stalls. It is possible to get the full C_P–tipspeed ratio curve with a controllable electrical load mounted on bearings so that the reaction torque on the generator can be measured, but that equipment was not available for these tests and was not considered necessary since only the maximum power output is of interest.

The mechanical power output is shown in Table 1. The maximum coefficient of performance or "efficiency" $C_{P\ max}$ was 0.25 for the wooden blades and 0.19 for the cambered sheetmetal blades, measured in both cases at the point of maximum torque just before the rotor stalled. The theoretical maximum C_P for a HKT is the Betz limit of 0.593, and 0.3 to 0.35 under real field conditions is considered reasonably good, so 0.25 for the wooden blades at close to the design tipspeed ratio of 4 is acceptable, given that it could certainly be improved with correct taper and twist. There is clearly room for a lot of improvement in the sheetmetal blade performance.

Some possible reasons for the less than ideal performance of the wooden blades include

i. Friction loss in shafts and the right angle gear box. This could be eliminated by placing the generator in the nose cone.
ii. Losses due to blade modification (outer ends cut-off)
iii. Losses due to clog-free mechanisms (large nose cone)
iv. Losses due to errors during blade construction and inconsistency in wood material.

Electrical performance

Two low cost, low power motors were acquired and tested as generators:

(i) A brushless Smartdrive motor with 42 coils and 56 magnetic poles, rated 230–240 V, 165 W and 50 Hz.

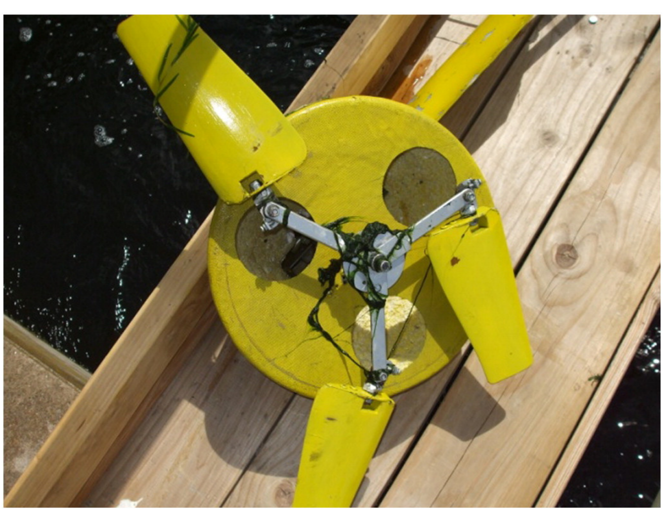

Fig. 11. Blades virtually weed-free but some weed still wrapped around the shaft.

Fig. 12. Final design with ring behind the nose cone to prevent weed winding around the shaft made the turbine remained virtually weed-free.

(ii) A brush commutated geared 24 V DC motor rated at 250 W at 320 rpm on the input shaft with a 7:1 gear ratio.

These machines were bench tested. By rewiring the Smartdrive so all coils were in series it was hoped that it would generate a high enough voltage to directly run some small 240 V 50 Hz appliances which are insensitive to frequency, to avoid the need for battery storage and inverters, but this was not achieved. At 275 rpm and 125 Hz it produced 240 V on open circuit, but when loaded with 2×100 W 240 V light globes the voltage dropped to 150 V, and with $2 \times 100 + 3 \times 40$ W globes the voltage dropped to 100 V, so this was clearly not an option. The 24 V motor is a much more straightforward machine but would require a battery and inverter to run 240 V AC appliances, and the brushes would need periodic replacement.

The electrical output of each generator was measured with the more efficient wooden blades fitted. Fig. 13 shows the on-site electrical performance test setup used with the Smartdrive. A bank of low wattage globes was used as a load and a clamp current meter and a voltmeter were used to measure power. However the Smartdrive in the configuration tested was clearly not well matched to the turbine and it stalled with very little electrical load. It may be possible to improve this matching and achieve good efficiency, and this remains an aim for future work, but for the time being the focus switched to the 24 V motor, which was connected to the turbine via a 3:1 chain drive.

Table 1
Hydrodynamic performance of turbine with 2 types of blade.

ΔF (kg)	ΔF (N)	n (rpm)	Ω (rad/s)	T (Nm)	PMech (W)	C_p	tsr
Wooden blades							
4.40	43.12	108	11.31	3.23	36.57	0.15	4.52
5.70	55.86	136	14.24	4.19	59.66	0.24	5.70
6.80	66.64	120	12.57	5.00	62.80	0.25	5.03
7.40	72.52	100	10.47	5.44	56.95	0.23	4.19
8.20	**80.36**	**100**	**10.47**	**6.03**	**63.11**	**0.25**	**4.19**
Cambered sheet aluminum blades							
4.20	41.16	92	9.63	3.09	29.74	0.12	3.85
5.00	49.00	88	9.22	3.68	33.86	0.14	3.69
6.00	58.80	80	8.38	4.41	36.94	0.15	3.35
7.00	68.60	72	7.54	5.15	38.79	0.15	3.02
8.00	**78.40**	**76**	**7.96**	**5.88**	**46.79**	**0.19**	**3.18**

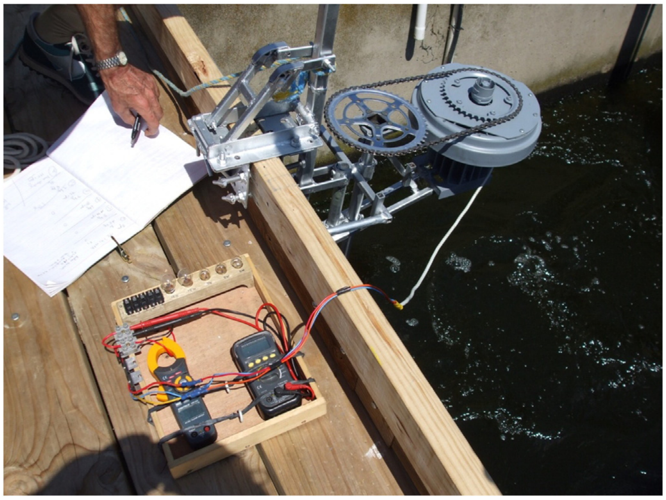

Fig. 13. On site electrical performance test setup.

It produced a maximum of 49 W, as shown in Table 2, close to the 53 W predicted in Section 4, giving an overall water to wire efficiency just under 20%.

Discussion

Although types of debris vary widely in different environments and the turbine was tested with one type of debris only, the sticky stringy weeds encountered in these tests are likely to be as difficult as any to shed. If the turbine can shed this material and operate normally in such severe conditions, then it is expected to be able to operate in equatorial rivers.

Impact by floating logs is another issue. It was not practicable to throw logs into a channel in a wastewater treatment plant but it is hoped that testing in rivers in Sarawak will provide data on the turbine's ability to survive such impacts. If the swinging action proves inadequate for this, then the coning option will be investigated.

A maximum C_P of 0.25 for the turbine is comparable with some other well-known HKTs such as the Gorlov Helical Turbine, and the water-to-wire efficiency of just under 20% is comparable with that reported for some other HKTs.

Table 2
Electrical output of 24 V DC motor as generator.

Revolution (rpm)	Volt (VDC)	Elect current (A)	Elect power (W)	Water power (W)	Water to wire efficiency (η_{wtw})
96	18.17	2.44	44.33	251.00	17.66
	18.6	2.36	43.90	251.00	17.49
	18.5	2.5	46.25	251.00	18.43
	15.6	2.9	45.24	251.00	18.02
80	**14.5**	**3.37**	**48.87**	**251.00**	**19.47**
	14.2	2.5	35.50	251.00	14.14
	18	2.1	37.80	251.00	15.60
	16	2.6	41.60	251.00	16.57
	16	3	48.00	251.00	19.12
	15	2.8	42.00	251.00	16.73
	12	3.78	45.36	251.00	18.07

Conclusion

A small axial flow hydrokinetic turbine (HKT) with swinging blades has been designed and constructed using only low cost workshop equipment which could be used in a remote village. It has been shown to avoid clogging by long, stringy, sticky water weed which would quickly clog a normal HKT, while achieving a coefficient of performance C_P of 0.25 and a water-to-wire efficiency just below 20% which is comparable with other small turbines of its type. It is expected that the efficiency can be improved with further development. Although the output power of about 50 W from a 0.8 m diameter turbine in a 1 m/s flow is only enough to trickle charge a battery bank, a scaled up version of this turbine should be suitable for deployment in tropical rivers for small remote village power supply, either singly or as a bank of turbines.

References

Anyi M, Kirke B. Evaluation of small axial flow hydrokinetic turbines for remote communities. Energy Sustain Dev 2010a;14(2010):110–6.

Anyi M, Kirke B. Hydrokinetic turbine blades: design and local construction techniques for remote communities. Energy Sustain Dev 2010b;14(2011):223–30.

Anyi M, Kirke B, et al. Remote community electrification in Sarawak, Malaysia. Renew Energy 2010;35(2010):1609–13.

Flicker. Farm4. Retrieved 29 July, 2013, from http://farm4.static.flickr.com/3244/2746605306_02dba4e09a.jpg. [undated].

ITT. Flygt low-speed mixers. Retrieved 2 July, 2013, from http://www.flygtus.com/3339510.pdf. [undated].

Tiago G. The state of art of hydrokinetic power in Brazil. Buffalo, New York: Waterpower XIII; 2003.

Tyler RN. River debris: causes, impacts, and mitigation techniques; 2011.