Experimental Testing of the Transverse Horizontal Axis Water Turbine

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Abstract

This paper outlines the procedures and preliminary results for a set of experiments on the Transverse Horizontal Axis Water Turbine (THAWT), which is a variant of a Darrieus turbine. Testing of a 1/20th scale device was conducted in the combined wind, wave and current tank at Newcastle University. Flow depth and velocity were varied over a range of realistic Froude numbers for tidal streams. Various configurations of the device were tested to assess the merits of the THAWT design. Variants included a parallel bladed device, a "truss" device and a parallel bladed device configured with blades pitched relative to the pitch circle tangent. Experiments were carried out using a speed controlled motor, allowing quasi-steady results to be taken over a range of tip speed ratios. Preliminary results demonstrate that, over a range of flow conditions, the device is capable of exceeding the Lanchester-Betz limit for kinetic efficiency. This is principally due to the relatively high blockage ratio which can be achieved with such a device.

Keywords: Darrieus, Horizontal axis, THAWT, Tidal stream

Nomenclature

A	= Cross sectional area of turbine
c	= Blade chord length
D	= Mean diameter of turbine
Fr	= Dimensionless Froude number
h	= Depth of flow
n	= Number of turbine blades
P	= Measured power produced by turbine
Re	= Dimensionless Reynolds number
s	= Turbine solidity
U	= Flow velocity
η	= Turbine efficiency
μ	= Kinematic viscosity of water
ρ	= Density of water

Subscripts

∞	= far field, upstream flow
k	= based on the change in kinetic flux

1 Introduction

The rapid development of devices for tidal energy exploitation is being encouraged by government initiatives and by private investment. The horizontal axis, axial flow turbine is the most common design of a tidal stream turbine. A number of variants of this type of device, which incorporate features such as flow-guiding shrouds or specific mounting techniques, have been proposed by different developers, but the underlying hydrodynamics remain similar for these devices. However, a drawback with such designs is that their size cannot be increased significantly, because of the limited depth of flow at most sites. It would be more efficient to stretch a device laterally across a tidal flow. This paper presents the Transverse Horizontal Axis Water Turbine (THAWT) as an alternative design that can be stretched in this way. This device is a variant of the Darrieus concept, and incorporates a (patent pending) truss design to increase the stiffness and strength of the structure (see Fig. 1). This increased stiffness and strength allows longer units to be constructed, and reduces the overall costs of foundations, bearings, seals and generators. A full scale device might have a diameter of 10 – 20 m and would operate in a flow depth of 20 – 50 m.

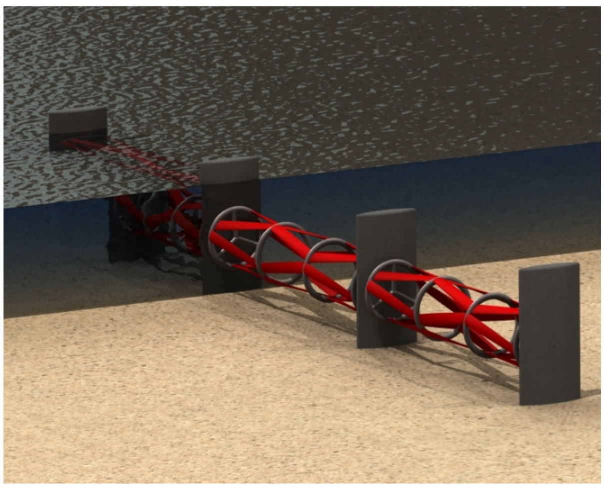

Figure 1: Rendered image of a string of THAWT devices with water cut away.

The primary scope of this work was to test the performance of a 0.5 m diameter scale model of the THAWT device experimentally in a range of realistically scaled flow conditions. While a significant amount of research has been performed on vertical axis wind turbines [1, 2], little research has been performed on Darrieus type turbines in a marine environment [3] and no research appears to have been performed on horizontal axis Darrieus turbines in water.

The main objectives were to explore the power curve characteristics of the THAWT device in a range of flow conditions, and to vary aspects of the device configuration to optimise the design. Turbine solidity and self starting performance have previously been explored by [3], but only for a single set of unspecified flow conditions and in a vertical axis configuration.

2 Newcastle University flume

Previous experiments performed in a small flume at Oxford University had proven the potential of the THAWT concept, but the low Reynolds number of the flow caused poor performance on small bladed device configurations. For the larger scale tests, the combined wind, wave and current flume tank, located in the Armstrong building of the Marine Science and Technology Department at Newcastle University was chosen. The flume is 1.8m wide, 11.25m long, and supports a flow depth of up to 1m and flow velocity of up to 1m/s. A full scale THAWT device would feature several turbine units attached end-to-end, creating a long, multi-bay rotor. To simulate this in a scale model a single bay is isolated, minimising the flow that may pass around the sides of the device, and only allowing flow to pass above and below the rotor. This was achieved by narrowing the span of the flume, as shown in Fig. 2, to the length of the device, which was limited to 0.875m due to structural constraints.

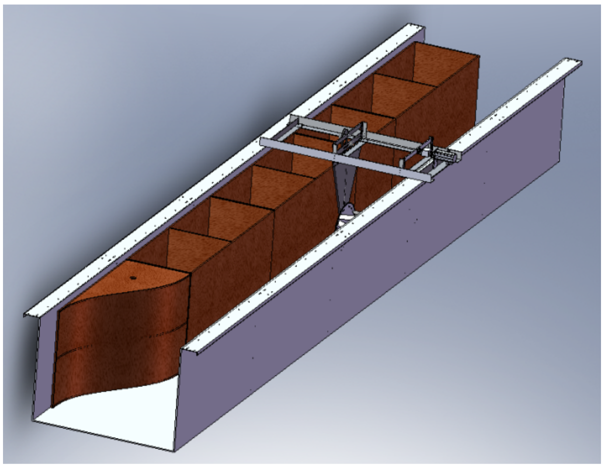

Figure 2: CAD image of flume, showing partition detail and turbine placement.

The flow is narrowed using a 5th order polynomial inlet contraction [4], which, along with a honeycomb flow straightening device installed in the flume, significantly reduced the flow turbulence, as well simply narrowing the channel.

3 Turbine Variants

The “truss” THAWT device is the main focus of the research, but two other configurations of turbine were chosen as variants for comparison. A six parallel-bladed device, shown in Fig. 3, is simply a horizontal implementation of the Darrieus concept, and is the main variant for comparison. By removing half of the blades, a three parallel-bladed variant of half the turbine solidity is also available.

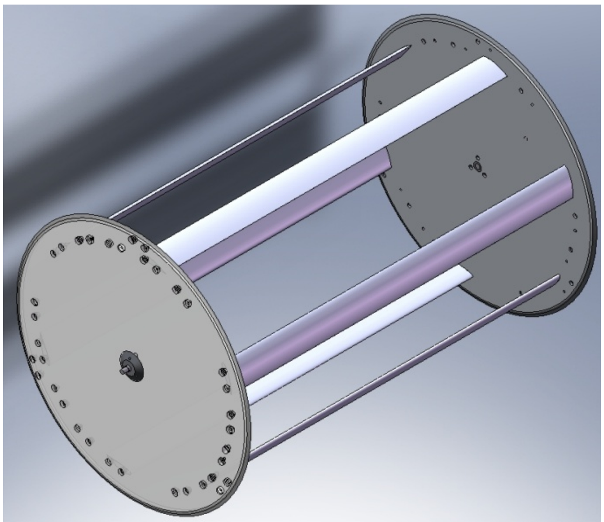

Figure 3: CAD image of a parallel six-bladed variant.

All of the tested turbines are of a bay length 0.875m and mean blade diameter D = 0.5m. The six-bladed devices have a solidity s = 0.25, defined as:

$$s = \frac{nc}{\pi D}$$

With half of the number of blades, the solidity of the three-bladed device is s = 0.125.

The carbon fibre blades were formed by pressing a closed cell foam core wrapped in a carbon fibre layup in between a set of moulds. The blades of the truss THAWT device follow a straight line through the quarter chord point, but twist so that the chord line is tangential to the pitch circle at all points. Pinned ends allow a simple fixing to a set of endplates, which feature holes for several configurations of turbine. Slotted holes allow for a fixed pitch to be applied to the blades on the parallel-bladed variant.

4 Test Apparatus and instrumentation

The turbine is mounted in the flume using a frame constructed from aluminium angle section and mounted in the flume as shown in Fig. 4.

The power is transferred from the turbine using a toothed pulley system to a shaft, which is flexibly coupled to a rotary torque and speed sensor and a motor-generator. A gap in the wooden partition allows the pulley system to operate in the still water of the partitioned section so that the free stream flow is undisturbed. Using a speed-controlled motor the power required to drive the turbine or absorbed by the motor is calculated from the recorded speed and torque information.

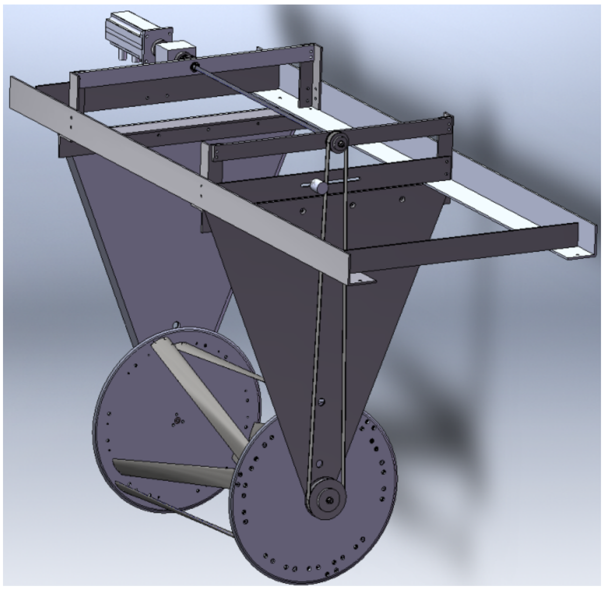

Figure 4: CAD image of turbine support frame.

A 2:1 gearing ratio in the toothed pulley system is used to double the angular velocity at the torque sensor so that the torque is reduced to within the accurate range of the sensor.

4.1 Flow instrumentation

Depth and velocity data is taken at key points along the flume using a velocity probe and three wave probes as shown in Fig. 5.

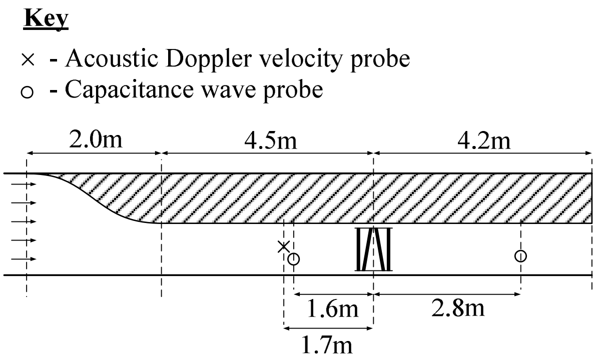

Figure 5: Plan view of flume setup and instrumentation.

The acoustic Doppler velocity probe is positioned far enough after the contraction to experience a smooth laminar flow, and far enough upstream from the device so that waves generated by the turbine do not have a significant effect on the velocity measurement. Capacitance wave probes are placed at two positions in an attempt to measure the uniform flow depth upstream and downstream of the turbine. Data acquired from the flow sensors as well as the rotary torque and speed sensor is recorded digitally.

5 Experimental schedule

There are two main factors which affect the performance of scale model water turbines; the Reynolds number and Froude number, defined respectively as:

$$Re = \frac{U_\infty c \rho}{\mu}$$

$$Fr = \frac{U_\infty}{\sqrt{g h_\infty}}$$

The Froude number and Reynolds number cannot both be scaled simultaneously, so when scaling it must be decided whether to maintain a realistic scaled Froude number or Reynolds number. There is a trade-off between free surface effects and local blade effects, which has been encountered by ship designers for decades.

Variations in the Reynolds number of a flow will cause variations in the lift and drag produced by a hydrofoil. If a turbine of a relatively small blockage ratio were used in a relatively low velocity tidal channel, variations in the flow velocity and Reynolds number would have a significantly larger effect on the performance of the turbine than variations in the Froude number. However, the performance of a turbine of a relatively large blockage ratio in a relatively high velocity channel would be dominated by variations in the Froude number rather than the Reynolds number. This is because the effect of variations in the Reynolds number on hydrofoil lift and drag coefficients decreases as the Reynolds number increases [2]. The Froude number is a non-dimensional ratio of the kinetic and gravitational potential energy in a fluid flow. Assuming a negligible effect from varying Reynolds number, using LMADT for open channel flow [5] it is possible to show that the power available to a turbine is a function of Froude number only.

At the scale of the Newcastle turbine, it was felt that the effects of both Froude number and Reynolds number were significant. However, limitations on flow velocity meant that in the Newcastle flume it would not be possible to replicate flow conditions of a Reynolds number consistent with those experienced by a full scale device. For this reason it was decided to scale within a realistic range of Froude number, $0.1 < Fr < 0.22$, which could be experienced in a full scale tidal stream.

By scaling with Froude number, the power produced by the turbine would be conservative, as the relatively low Reynolds number would reduce the performance of the turbine when compared to a full scale device.

5.1 Blade pitching

It can be shown that a fixed pitch Darrieus device, which does not disturb the pattern of the surrounding uniform flow, has an optimum blade pitch angle of 0° (relative to the tangent of the pitch circle). If this assumption were true then the upstream and downstream halves of the device would contribute an equal proportion of the total power output.

Basic momentum theory suggests that the flow experiences a deceleration through the turbine, which results in a lower flow velocity incident on the downstream turbine blades. It can therefore be assumed that the optimum blade pitch angle is one which maximises the power takeoff by the upstream half of the device.

To explore this experimentally the apparatus allows for the turbine blades to be pitched by 2° both positively and negatively (a positive pitch acting to increase the angle of attack on the upstream half of the turbine).

5.2 Reversing the flow

By swapping the attachments at each end of the turbine, and turning it around so that the device rotates in the opposite direction, it is possible to test the turbine in reverse without changing the direction of the flow in the flume. (By "forward" flow we mean that the bottom of the turbine rotates in the same sense as the flow.) Tests were performed with a "reversed" device to show that the performance of the turbine does not significantly differ when the direction of the tidal flow is reversed. The experiments performed are outlined in Table 1:

$h_\infty[m]$	1.0				0.8		
$U_\infty[m/s]$	0.3	0.4	0.5	0.7	0.3	0.4	0.5
Truss	*	*	*	*	*	*	*
Reverse Truss	*		*				
Parallel six	*	*	*	*	*	*	*
Reverse six	*		*				
Pitched six	*		*				
Parallel three	*	*	*	*	*	*	*

Table 1: Chosen tests for experiment.

Ideally, for each set of flow conditions and configuration, a power curve would be produced in which each point represents the performance of the turbine at a steady state. To test in steady state conditions at regular increments of tip speed would be very time consuming, and due to limited time in the Newcastle facility a more convenient scheme was required. The chosen solution was to use the motor controller to accelerate the turbine gradually using a low gradient ramp, as shown in Fig. 6, so that the system had time to react continuously and simulate steady state conditions.

To check that the results from these experiments would represent a device operating in steady state, a test was also performed with a ramp of half the gradient. With no visible difference between the results, it was assumed that the quasi-steady assumption was valid.

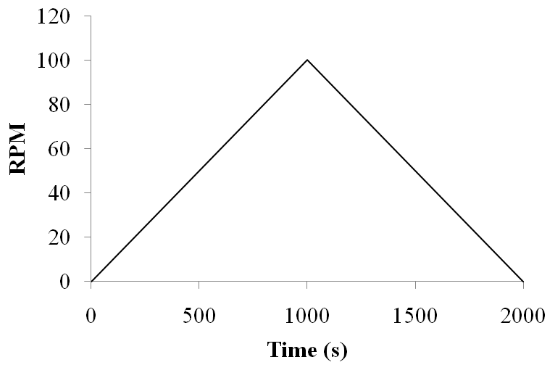

Figure 6: Example of ramping speed control.

6 Data Calibration

After the raw experimental data had been recorded it was resampled down to 20Hz using linear interpolation, before a 500 sample width Hamming window was applied to smooth the data. Post smoothing, the data was corrected using calibration values taken for the:

- reduction in torque due to friction in the test apparatus.
- change in (apparent) depth due to drift on the instrument amplifier.
- change in depth due to the head loss generated by a moving flow.
- mean velocity value, as opposed to the value of the velocity at the acoustic Doppler measurement point.

7 Results

7.1 Truss THAWT device performance

Throughout this section the performance of the different device configurations will be compared in terms of power produced and kinetic efficiency, defined as:

$$\eta_k = \frac{P}{1/2\, \rho A U_\infty^3}$$

Fig. 7 demonstrates that the truss THAWT device produces a peak in power at a consistent tip speed ratio. It is also clear that, as the Froude number is increased, the turbine produces positive power up to a greater tip speed ratio. Unfortunately the low tip speed ratio data for the higher Froude number flows is unavailable due to a poor frequency response of the motor controller at the low tip speeds, where the turbine behaviour is highly unsteady. Future experiments will attempt to improve the motor controller characteristics to allow results to be recorded at all tip speed ratios.

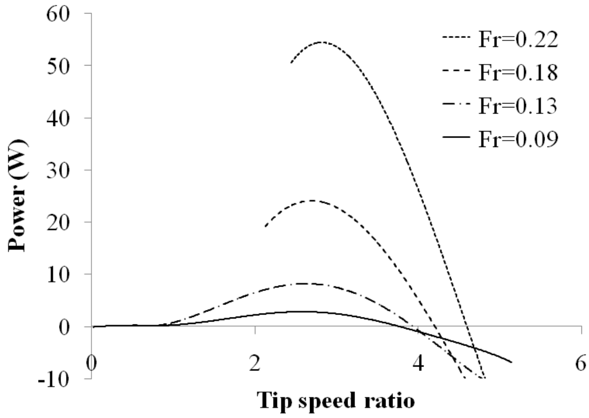

Figure 7: Power curves produced by the truss THAWT device over the range 0.09 < Fr < 0.22.

Fig. 8 illustrates that the THAWT device exceeds the Lanchester-Betz limit for kinetic efficiency for flows with a Froude number greater than roughly Fr = 0.16. This compares favourably to experimental results performed on more conventional horizontal axis devices [6].

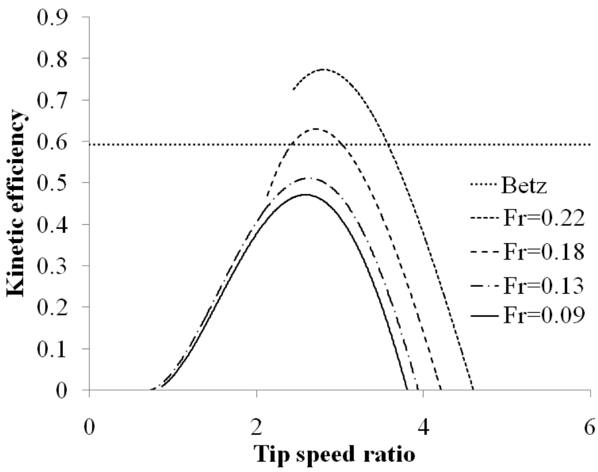

Figure 8: The efficiency of the truss THAWT device over the range over the range 0.09 < Fr < 0.22.

A kinetic efficiency greater than the Lanchester-Betz limit is possible due to channel blockage effects and the sub-critical nature of the flow. A tidal turbine differs from the conditions analysed in the classical Lanchester-Betz solution in that (a) the flow is of finite depth, (b) gravitational effects need to be taken into account [5,7]. When these effects are taken into account, a greater amount of power can be extracted than indicated by the simple Betz analysis. For instance, at a Froude number of 0.14 and a blockage ratio of 50%, the modified analysis [7] suggests that up to 4.6 times as much power could be extracted than would be indicated by the Betz formula. The phenomenon of increased power in tidal flows has previously been experienced in tests on standard horizontal axis tidal devices [8].

As described by [7], not only is the power available to the device a function of the Froude number of the flow, the efficiency with which that power may be extracted increases as the blockage ratio is increased. This trend is confirmed experimentally as, for both the truss and parallel bladed devices, at a range of Froude numbers, when the blockage ratio was increased from 50% to 62.5%, the kinetic efficiency increased by a factor between 1.66 and 2.13.

The depth of the flow decreased across the turbine, confirming that potential energy is being extracted as well as kinetic energy. These findings suggest that a more extensive study of the blockage effects in open channel flow is required to accurately assess the true efficiency of open channel tidal devices.

7.2 Comparison of truss and parallel bladed devices

Figs. 9-10 illustrate that, over the range of studied Froude number flows, the parallel-bladed device produces power with an efficiency of 3 - 11% greater than the truss configured device. Whilst the reduced efficiency of the truss is not favourable, it is felt that the economic gains that will occur by utilising the truss structure will outweigh the effects of the reduction in device efficiency.

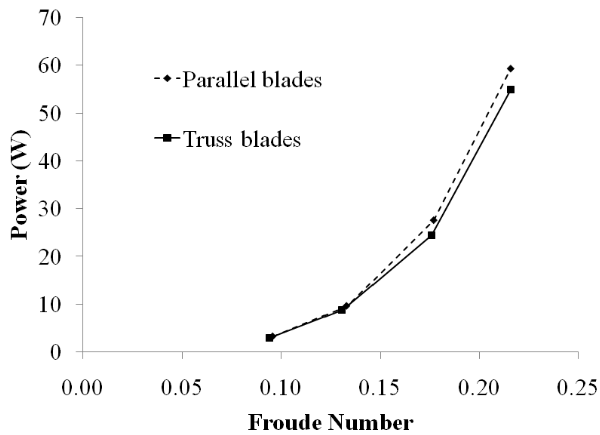

Figure 9: Truss and parallel bladed device power output with a varied Froude number.

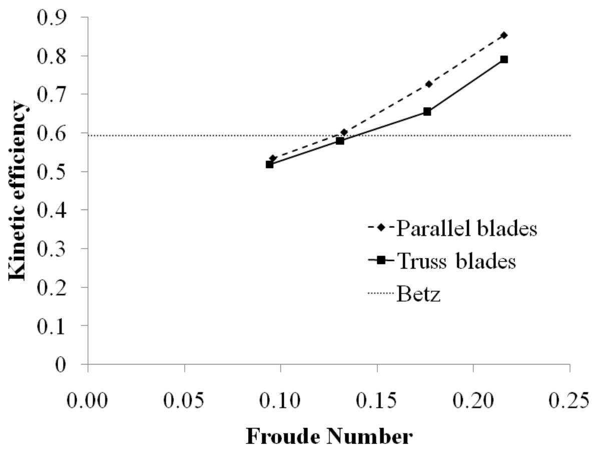

Figure 10: Truss and parallel bladed device efficiency with a varied Froude number.

The parallel three-bladed configuration produced power with a 19-65% greater efficiency than the

parallel six-bladed device, suggesting that a reduction in the solidity of the device would increase the power output.
Reducing the solidity of the device would result in thinner more flexible blades, which may require expensive structural materials. A structural analysis of the turbine is required to assess the optimum design in terms of economic feasibility.

7.3 The effect of reversing the flow direction

As illustrated in Fig. 11, a reversed configured device at a flow velocity of 0.5m/s produces an average of 98% of the power produced by the standard configuration of device. This suggests that the performance of the turbine is not significantly affected by the direction of the tidal flow.

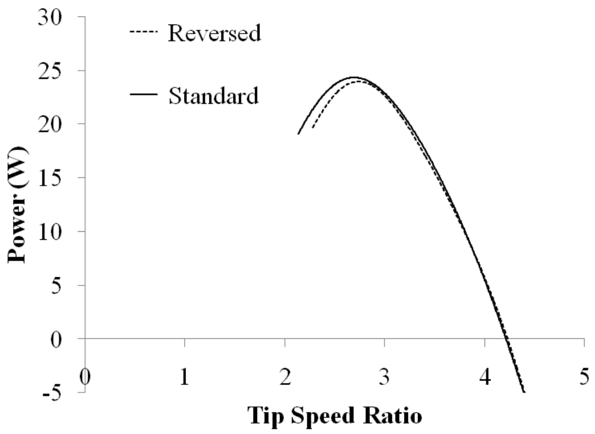

Figure 11: Truss device performance at 0.5m/s in a standard and reversed configuration.

7.4 Applying a fixed pitch to the turbine blades

Table 2 shows that the kinetic efficiency of the THAWT device can be increased by up to 8.4% by applying a 2° negative pitch to the turbine blades. A more thorough study is required to find the optimum pitch angle for this configuration of device.

U_∞[*m/s*]	-2° pitch	0° pitch	+2° pitch
0.3m/s	61.7%	53.3%	47.7%
0.5m/s	77.9%	72.6%	65.7%

Table 2: Efficiency of the parallel bladed device with a varied blade pitch angle.

8 Conclusions

This paper demonstrates that in a series of scale model experiments the truss variant of the THAWT produces power with a kinetic efficiency close to that of the conventional parallel-bladed device. Results show that both the parallel and truss-bladed devices are capable of producing power at efficiencies greater than the Lanchester-Betz limit and that the power available to the device is not simply a function of the incident kinetic flux, but is increased because of blockage effects.

The effects of reversing the flow direction have been shown to have a negligible effect on the power produced by the turbine. Results confirm that a fixed negative pitch (relative to the tangent of the pitch circle) increases the power produced by the turbine.

It is anticipated that blades on a full scale device will experience flows of a greater Reynolds number, resulting in improvements in the lift and drag characteristics of the hydrofoil, and an increase in the efficiency of the device. The results of this paper can therefore be assumed to represent a conservative estimate of the full scale performance of the turbine.

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References

[1] I. Paraschivoiu. Aerodynamic loads and performance of the darrieus rotor. *Journal of Energy*, 6(6):406–412, 1982.

[2] R. E. Sheldahl and P. C. Klimas. Aerodynamic characteristics of seven symmetrical airfoil sections through 180- degree angle of attack for use in aerodynamic analysis of vertical axis wind turbines. *Technical Report Unlimited Release*, *Sandia National Laboratories*, SAND80-2114, 1981.

[3] M. Shiono, K. Suzuki, and S. Kiho. An experimental study of the characteristics of a darrieus turbine for tidal power generation. *Electrical Engineering in Japan*, 132(3), 2000.

[4] J. H. Bell and R. D. Mehta. Contraction design for small low-speed wind tunnels. *Technical Report* NASA-CR-177488, 1988.

[5] J. I. Whelan, J. M. R. Graham and J. Peirò. A free-surface and blockage correction for tidal turbines. *Journal of Fluid Mechanics*, 624(-1): 281-291

[6] A. S. Bahaj, A. F. Molland, J. R. Chaplin, and W. M. J. Batten. Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank. *Renewable Energy*, 32(3):407 – 426, 2007.

[7] G. T. Houlsby, S. Draper, and M. L. G. Oldfield. Application of linear momentum actuator disc theory to open channel flow. *Technical Report* OUEL 2296/08, University of Oxford, 2008.

[8] L. Myers and A. S. Bahaj. Wake studies of a 1/30th scale horizontal axis marine current turbine. *Ocean Engineering*, 34(5-6):758–762, 2007.