Review of experimental studies on Transverse Axis Crossflow Turbines

Rónán Gallagher, Carwyn Frost, Pál Schmitt, Charles Young and John Doran

Abstract—**Transverse Axis Crossflow Turbines (TACTs) are a niche subset of tidal turbines. TACTs are not as well understood as the more traditional horizontal axis turbine and associated flow theory which leans heavily on advances in wind energy and marine propulsion. This paper reviews laboratory and field based experimental fluid dynamics work from the perspective of turbine performance. The available literature deviates significantly in perspective and scope since it is found that not all papers declare a full complement of parameters, thereby making it difficult to check or validate the respective results. Therefore, identifying trends amongst the variable and sparse datasets is difficult. None of the papers reviewed cite adherence to the recommended tank testing guidelines. The work reviewed analyses aspects such as mounting supports, solidity, blockage and blade support locations in isolation, but the cumulative impact of these variables is unknown. Arising from the analyses carried out as part of this review, blade loading, solidity and blockage were identified as key parameters and are the subject of planned research. Trends between solidity and blockage with tip speed ratio were identified. This paper contributes to the understanding of TACT performance through the tidal turbine performance curve and highlights the need for comprehensive physical testing and model validation.**

Keywords—**experimental, blockage, solidity, tip speed ratio, transverse axis crossflow turbine, turbine performance**

I. Introduction

THERE is an insatiable demand for electricity and non-renewable electricity sources are the preferred option presently. Tidal stream technologies have immense potential and are receiving increased attention. Until recently the costs and engineering challenges associated with tidal stream energy capture were prohibitively high. By 2030 [1] predicts that there will be approximately 2.9 GW of ocean energy devices installed globally by which time the costs of tidal stream energy will reduce to €110/MWh which will bring it in line with the costs of other renewable sources.

Crossflow hydrokinetic turbines range from lift or drag devices to hybrid configurations [2]. TACTs are a niche category of lift based hydrokinetic current turbines whose low rectangular profile are ideally suited to relatively shallow unconfined sites. TACTs operate in an environment with low head and relatively fast water and are an example of a device that could be deployed in remote marine and riverine sites to help meet the growing demand for electricity. The potential of energy security and independence offered by distributed indigenous renewable energy sources is attractive to remote communities. Distributed energy infrastructure incorporating renewable sources will be essential to satisfy the growing demand for electricity and enable universal access in the future.

There are two distinct TACTs designs featuring either helical or straight blades. The benefit of the helical over the straight bladed design is that it is self-starting and smooths torque during operation [2], [3]. Despite producing more variable torque, straight bladed turbines are more efficient [4]. Many different configurations have been explored including variations in turbine dimensions, blade profiles, number of blades, blade profile symmetry, cambered

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blades, blade pitch, mounting supports and mounting positions.

The hydrodynamics of crossflow turbines is not well understood. The flow passing through a crossflow turbine is complex as the downstream sweep of the blades must pass through the wake of the upstream sweep as well as the wake and shadow of the rotating shaft. Many numerical studies have been produced with relatively few experimental studies to validate results. An exception to this is [5] which reports good agreement for the performance of a straight 3 bladed Darrieus turbine versus tip speed ratio (TSR) for both experimental and three-dimensional CFD work with peak performance occurring in the tip speed ratio range ~1.5-2.

II. LITERATURE REVIEW

The pool of published experimental work in the area of TACTs and crossflow turbines is relatively small in comparison to the horizontal axis tidal turbines (HATT). As a result, pertinent numerical studies and experimental work outside of the scope of this paper may be relied upon in order to clarify a point or support an argument position.

In this study 25 lab and 10 field-based studies were identified (thus far) as being suitable as they matched specific criteria. This selection process utilised the following terms/criteria – Scopus search terms, peer reviewed, complete dataset and water as a working fluid. Numerical work and unpublished postgraduate theses around TACTs were identified but are not included in this review. The selected laboratory and field publications are listed with localised reference, L for laboratory studies and F for field studies, in Table I and II, respectively. Although, 35 publications were identified initially, many field study datasets were either partially complete or did not declare key performance parameters and could not contribute to the high-level summative overview of turbine performance characteristics (the aim of this paper). On this basis, the field studies had to be largely excluded and the reasons for including or excluding them are listed in Table III. Hence, based on the peak performance data (points) reported in the remaining publications, a series of scatterplots were prepared to try and identify trends in the data and establish knowledge gaps.

The areas of study of the selected laboratory publications included turbine performance, wake, blade supports, shaft, operation, blockage, free surface effects, hydrodynamic loading and blade profile.

The theme of field studies identified included investigating turbine performance, controller optimisation as well as wake characterisation. Each of the selected works has their own agenda and as a result not all publications report the same set of parameters. The combined result is an eclectic series of turbine experiments each with different parameters and permutations of parameters varied between each batch of runs. It is worth noting that not all the selected publications feature in each of the plots compiled as part of this review. For example, the field study in [6] does not declare the blade profile, chord length or number of blades in the turbine but does declare the maximum turbine performance coefficient and optimum tip speed ratio.

A. *Lack of Design and Analysis Convergence*

There is global design consensus regarding horizontal axis wind turbines and the three bladed design has recently been applied to tidal electricity generation. However, this is not the case with crossflow turbines as borne by the array of designs encountered in this study. The literature search yielded a variety of different types of crossflow turbine ranging from the Darrieus turbine [7], Lucid Spherical Turbine (LST) [8], Gorlov Helical Turbine (GHT) [3] to the Transverse Horizontal Axis Water Turbine (THAWT) [9].

Akin to the lack of design convergence there is also an absence of analysis convergence for TACTs. A review of hydrodynamic analysis models for the design of Darrieus type vertical axis tidal turbines has been carried out in [10]. The suggested analysis models range from streamtube to computational fluid dynamics models. The study in [10] recommends that blade performance, turbine configuration, solidity and tip speed ratio is crucial to the performance of the turbine and concluded that apart from resource hungry computational fluid dynamics (CFD) simulations, none of the existing theoretical models truly captures the performance of the vertical Darrieus device.

Aggregating the performance of a variety of fundamentally different types and configurations of turbines into easily interpreted infographics is not straightforward. Several data points are necessary to create a plot, however, when grouping many different types of turbine together concessions must be made as adhering to strict selection criteria when creating a summary plot would yield very few data points. Hence, in this review, performance data from crossflow turbines with different designs, types of blades, blade profiles and even number of blades has been assembled to provide an overview of the research carried out on TACTs.

TABLE I
LABORATORY WORK REVIEWED

Ref	Citation	Paper Theme
L1	Bachant and Wosnik, 2016 [48]	Effects of Re on turbine performance
L2	Polagye et al., 2013 [41]	Turbine performance and wake characterization
L3	Bachant, 2015 [53]	Wake investigation
L4	Strom et al., 2018 [38]	Effect of mounting structure on performance.
L5	McAdam et al., 2013a [16]	Parallel bladed Darrieus turbine performance
L6	McAdam et al., 2013b [17]	Hydrodynamic loading
L7	McAdam et al., 2013c [18]	High blockage – device exceeds Betz limit
L8	McAdam et al., 2009 [19]	Parallel bladed Darrieus optimum blade pitch 0°
L9	McAdam et al., 2011 [9]	Parallel bladed Darrieus V THAWT
L10	Gunai et al., 2016 [42]	Variable chord length helical turbine
L11	Pongduang et al., 2015 [40]	Investigation of helical angle
L12	Bachant and Wosnik, 2011 [27]	LST V GHT
L13	Bachant and Wosnik, 2014 [47]	ReD independence O(10^6)
L14	Provan et al., 2019 [39]	Flow straighteners
L15	Shiono et al., 2002 [4]	Helical V straight blades
L16	Shiono et al., 2000 [23]	Characteristics of Darrieus turbine
L17	Mannion et al., 2018 [50]	Vertical axis turbine with flow accelerator
L18	Bachant and Wosnik, 2015 [8]	Estimate of exergy efficiency
L19	Sun et al., 2019 [37]	C_P with angular speed variation
L20	Hunt et al., 2020 [26]	Investigation of AR on turbine performance
L21	Takamatsu et al., 1991 [25]	Non-cambered blade with long chord gives best efficiency
L22	Takamatsu et al., 1985 [36]	Chord mounting point – 50%
L23	Birjandi et al., 2013 [45]	Blockage and free-surface effect increases Cp
L24	Ross and Polagye, 2020 [52]	Confinement asymmetry investigation
L25	Hill et al., 2014 [13]	NREL Reference Model 2

TABLE II
FIELD WORK REVIEWED

Ref	Citation	Paper Theme
F1	Forbrush et al., 2016 [6]	Non-dimensional performance curve in sheared flow
F2	Guerra Paris and Thomson, 2016 [43]	Turbine wake characterization
F3	Donegan et al., 2017 [51]	Use of turbine controller to optimise LCOE
F4	Bibeau et al., 2009 [46]	Cold climate operation of 5kW turbine
F5	Grabbe et al., 2009 [44]	Optimisation of turbine generator configuration
F6	Han et al., 2009 [29]	Analysis of helical turbine
F7	Talukdar et al, 2017 [35]	Investigation of model helical turbine
F8	Gorlov 1998 [3]	Gorlov helical turbine analysis
F9	Sahim and Jaini, 2015 [49]	Investigation of Darrieus turbine blade configuration
F10	Birjandi et al., 2012 [45]	Macro-turbulent flow 25kW turbine

TABLE III
FIELD WORK EVALUATION

Ref	Citation	Parameters not declared	Included/ Excluded
F1	[6]	B, TI, U_∞, C_P, TSR	Included
F2	[43]	c, S, C_P, TSR	Excluded
F3	[51]	N, c, B, S, TI, U_∞, C_P, TSR	Excluded
F4	[46]	c, B, S, TI, U_∞, TSR	Excluded
F5	[44]	B, S, TI, U_∞, TSR	Excluded
F6	[29]	c, B, S, TI, U_∞, TSR	Excluded
F7	[35]	B, TI	Included
F8	[3]	B, TI	Included
F9	[49]	B, TI	Included
F10	[45]	c, B, S, TI, U_∞, C_P, TSR	Excluded

B. *Turbine Power Equations*

The power available in a flow is proportional to the cube of the free stream velocity and the turbine frontal area, as given by (1). The power output by the turbine, P_{out}, is given by the product of shaft torque, T, and the angular velocity, ω. The performance of the turbine is more commonly characterised by the non-dimensional coefficient of power, as given by (2).

Blockage and solidity are dimensionless numbers that are often used in conjunction with the coefficient of performance to qualify turbine performance. Blockage is the ratio of the frontal area of the device plus supports and the channel cross section and solidity is the ratio of the total length of blades chords to the turbine circumference.

$$P_{avail} = \frac{1}{2}\rho A U_\infty^3 \tag{1}$$

$$C_p = \frac{P_{out}}{P_{avail}} = \frac{T\omega}{\frac{1}{2}\rho A U_\infty^3} \tag{2}$$

III. TURBINE PERFORMANCE

Using the peak performance data points for each of the TACTs reviewed, a tidal turbine performance rating curve (C_P V TSR) was compiled and is shown in Fig. 1. The plot shows non-blockage corrected peak turbine performance point data versus tip speed ratio for the various crossflow turbine configurations reviewed along with the whole performance curve for the Sandia National Laboratory reference models, RM1 [11] and RM2 [12].

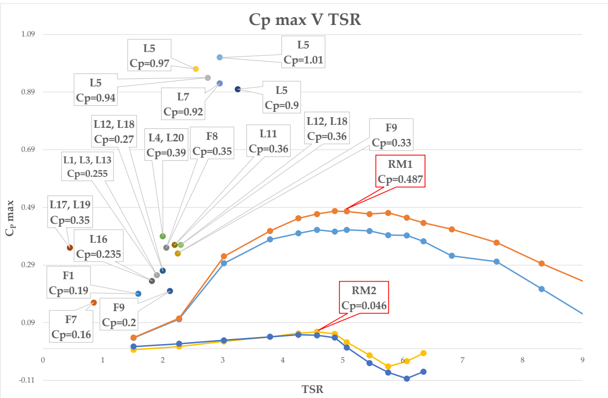

Fig. 1. Non-blockage corrected tidal turbine performance versus tip speed ratio. Solitary data points indicate maximum coefficient of power at optimum tip speed ratio. Data point labels are based on local referencing in Table I and II. Entire performance curves for RM1 and RM2 are shown for context.

Blockage ratios greater than 5% affect the tangential and normal forces and thus the development of power and thrust [13]. Blockage ratios greater than 20% should be avoided according to [13] as turbine performance characteristics should be established in unblocked flow. Data points from field studies (F8, F9) where blockage has not been declared and presumably quite low are included in Fig. 2. It can be seen from the plot that both straight bladed and helical turbines have a CP max value of up to 0.40 in the 1.5~2.5 TSR range.

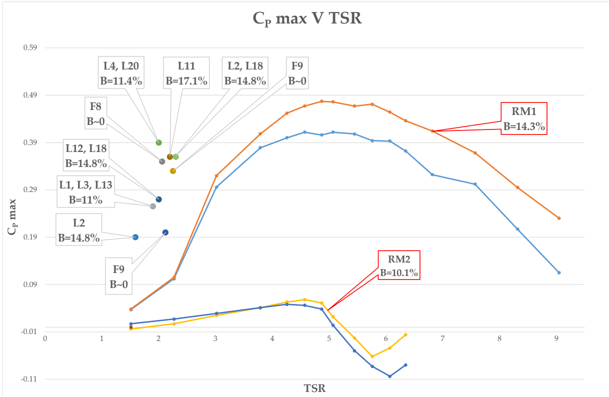

Fig. 2. Tidal turbine performance with blockage factors less than 20% and TSR>1. Solitary data points indicate maximum coefficient of power at optimum tip speed ratio. Data point labels are based on local referencing in Table I and II. Entire performance curves for RM1 and RM2 are shown for context.

Along with the peak point data retrieved from the current review, Fig. 1 and Fig. 2 also depict the entire performance curves for the Sandia National Laboratory reference models, RM1 [11] and RM2 [12]. The RM1 and RM2 turbine sets comprise two counter rotating horizontal axis and vertical axis crossflow tidal turbines, respectively. A difference in performance of each turbine within each set was detected, hence the pair of lines for both RM1 and RM2 in Fig. 1 and Fig. 2. This difference was attributed to flow asymmetries in the laboratory [11], [12]. The performance of the crossflow turbine (RM2) with a blockage of 10.1% is less than 5% at a tip speed ratio, λ=2.2, and places the peak performance data compiled in this study in context. Wosnik et al. [14] attributed the poor performance of the RM2 device to the drag of the rather large shaft diameter.

A. *Turbine Operation*

The performance of a turbine is governed by six non-dimensional groups, including the number of blades, solidity, blockage, tip speed ratio (TSR), Reynolds number (Re) and Froude number (Fr). Tip speed ratio is the ratio of the blade tip to the inflow and the Reynolds and Froude number become important when similarity and scaling problems arise when transitioning from tank testing to full scale deployment.

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) \tag{3}$$

$$w = u_\infty\sqrt{1 + 2\lambda\cos\theta + \lambda^2} \tag{4}$$

As a TACT rotates the angle of attack of the blades, α, given by (3), continuously changes as a function of the rotation of the turbine, θ, as shown in Fig. 3. This variation in blade angle of attack consistently exceeds the static stall angle of attack (typically ±15°) as shown in Fig. 4.

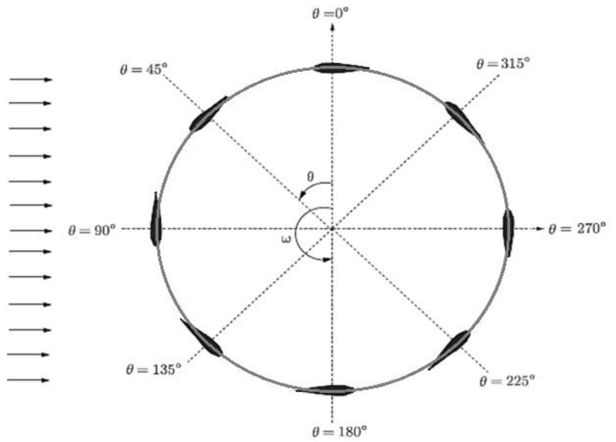

Fig. 3. Schematic of inflow and turbine rotation

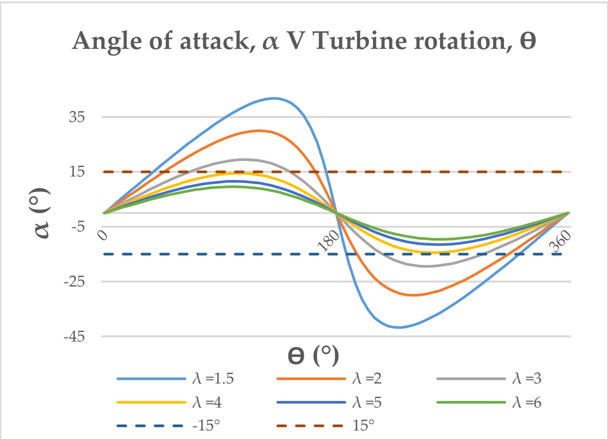

Fig. 4. Variation in angle of attack as a function of turbine rotation.

For a turbine blade with a fixed angle of attack, the static stall angle is the angle of attack above which the coefficient of lift rapidly decreases. However, in a dynamic case with varying angle of attack over a complete rotation, the lift continues to increase beyond the static stall angle of attack. The faster the turbine rotates, the more the range of variation in angle of attack decreases. For tip speed ratios greater than four, the dynamic angle of attack recedes below the static stall angle. This analysis would appear to recommend that the faster a turbine rotates then the more efficient it will be as the static stall angle of attack will not be exceeded. However, the evidence presented in Fig. 2 contradicts this theory whereby the maximum coefficient of performance falls in the TSR range 1.5~2.5, which means that CP max occurs when dynamic stall occurs. It can be concluded that dynamic stall does not adversely affect peak performance of the TACTs reviewed in this study. Dynamic stall may not be a problem in laboratory sized turbines where the drag of the blade support structure has a larger proportional influence on turbine performance in comparison to full scale devices.

The flow through a TACT varies spatially and temporally as the turbine rotates. A schematic of a typical turbine rotation is presented in Fig. 3. Reynolds number is the ratio of inertial resistance to viscous resistance of a fluid and is used to characterise fluid flow based on a characteristic length of the system. In the case of turbines, either blade chord length or turbine diameter is used.

The varying relative velocity of the flow passing through a TACT, as given by (4), means that the relative Reynolds number also varies as a function of turbine rotation. The variation in relative chord and device Reynolds numbers (Re_{rel}) for a typical inflow is shown in Fig. 5. Reynolds number is an important parameter when scaling from a prototype in the laboratory to full size in the field and is also used to categorise flow and report the operating range of blade profiles. Rapid variation in Re means that the theoretical static lift values for a blade profile calculated in the laboratory, such as those by [15], are not likely to translate to rotating turbine blades in laboratory testing or in the field, thereby making the prediction of turbine performance problematic.

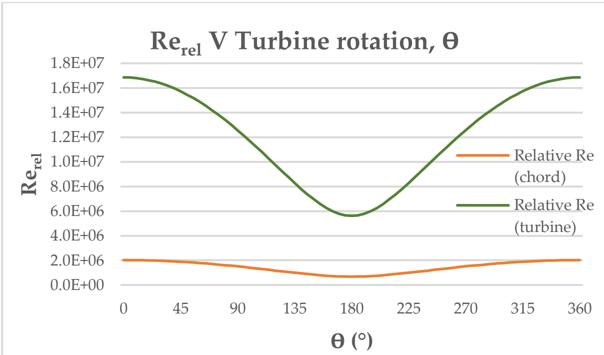

Fig. 5. Variation in relative Reynolds number (Re_{rel}) as a function of angle of rotation for a 1m diameter turbine with an angular velocity of 20rad/s, TSR of 2 chord length of 0.12m and inflow velocity of 5m/s.

B. *Appraisal of TACT Performance Parameters*

A total of 35 laboratory and field-based studies relating to TACTs were identified in this study. The reviewed work investigated many parameters and employed straight, helical and spherical blades with different types of supports as listed in Fig. 6. Each combination of support and blade type is unique and deserving of their own series on the summary plots. However, in order to simplify the turbine performance plots only two series are used in Fig. 6 to Fig. 10, namely, straight blade and other along with the local referencing declared earlier in Table I and Table II. The plots aggregating the TACT performance parameters are presented in the following sections (see Fig. 6 to Fig. 12). For clarity, data point labels were used sparingly in Fig. 6 to Fig. 10 and any untagged data points belong to the dataset tagged by the nearest label.

Any excessive values for key turbine performance which deviates from thresholds identified in literature have been omitted. For example, L5, L6, L7, L8 and L9 (see Table I) originating from [16], [17], [18], [19] and [9], respectively, all cite Cp values greater than the Betz limit as can be seen in Fig. 1. This superior performance is attributed to high blockage and was not corrected for same. In addition to purging data with C_{Pmax} that exceeded the Betz limit, restrictions were also imposed on blockage and tip speed ratio. All datasets with blockage ratios greater than 20% were omitted as according to [20], only data with 5%<B<20% should be corrected to free stream conditions using an empirical correction method. Also, datasets with TSR<1 were omitted as TACTs are lift based devices.

IV. Comparison of Performance Parameters

Maximising turbine performance is critical. There are many elements that can contribute to the successful deployment and in-service operation of a turbine. Some of the features relating to the turbine design and optimisation are discussed in this paper, however, many elements remain outside the scope of this review including losses due to end tip losses, friction and blade fouling [21].

The most obvious element of a turbine to vary and assess its influence on turbine performance is its blade profile. The most popular blade profile used in the experimental work reviewed is the NACA0018 profile. However, experimental work can sometimes contradict numerical studies and [22] in a numerical study found that the thinner NACA0012 blade profile offered superior performance. Other blade characteristics that have been investigated experimentally include, camber, inverted camber and even rectangular cross section blades by [23] and [24]. A symmetrical blade with a long chord was found to be most efficient in experiments carried out by [25].

At a much more elementary level, researchers have varied the blade length as well as the number of blades to optimise turbine performance. Increasing blade length, whilst keeping the chord length and number of blades constant, should improve overall turbine performance as the percentage of losses attributable to blade ends is smaller by proportion with longer blades and an increase in blade surface area would mean more power is extracted from the flow. The coefficient of performance, C_P versus blade length is shown in Fig. 6, which contains several clusters of data and is dominated by blades with two strut end supports. In this review, L2, L15 and L18 (highlighted in Fig. 6) realised an increase in C_P with an increase in blade length. However, no increase in C_P max was found by L20 due to an increase in blade length under strict laboratory conditions, as highlighted in Fig. 7. It is extremely difficult to evaluate the effect of a single variable on C_P in isolation as documented by [26]. Assessing the relationship between turbine performance and aspect ratio was the sole objective of their study and involved a straight bladed device with two blades and end strut supports. The blade length was increased from 0.163m to 0.280m in five increments, the turbine diameter was kept constant at 0.172m and the inflow velocity was varied. The kinematic viscosity of the water in the test tank was manipulated by lowering the water temperature to keep Fr and Re constant. The study resoundingly concluded that C_P was not a function of aspect ratio, as highlighted in Fig. 7. This finding, albeit under extreme controlled conditions, is at odds with the studies highlighted in Fig. 6. It can therefore be concluded that an increase in blade length does not automatically translate to an improvement in turbine performance.

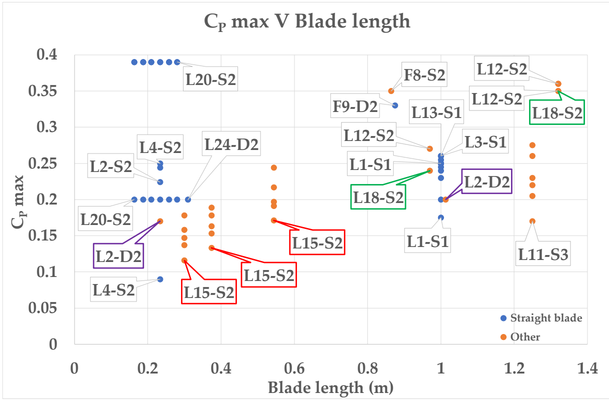

Fig. 6. Purged coefficient of performance versus blade length and blade support types. S1 – 1 no. mid span strut, SM2 – 2 no. mid span struts, S2 – 2 no. end struts, S3 – 2 no. end and mid span struts, D2 – 2 no. end disks. Untagged data points belong to the set identified by the adjacent label.

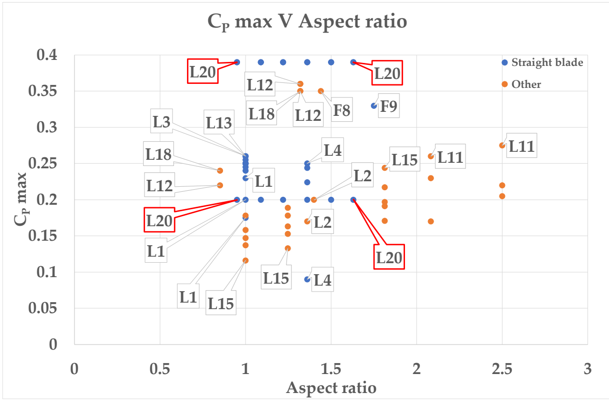

Fig. 7. Purged coefficient of performance versus aspect ratio. Untagged data points belong to the set identified by the adjacent label.

The length of a helical blade impacts the wrap of the blades and may impact the angle of helicity (ψ). Investigating the influence of blade length on a helical blade is much more complex than for a straight bladed turbine. However, by increasing the angle of helicity from 43.7° to 60°, [4] found that C_P increased from 0.116 to 0.244. They also found that as the blade inclination angle was increased, the efficiency and torque output of the helical bladed turbine approached the performance of a straight bladed turbine. Based on the evidence presented in Fig. 7, straight bladed turbines tend to have a higher coefficient of performance that non-straight bladed turbines of a similar aspect ratio.

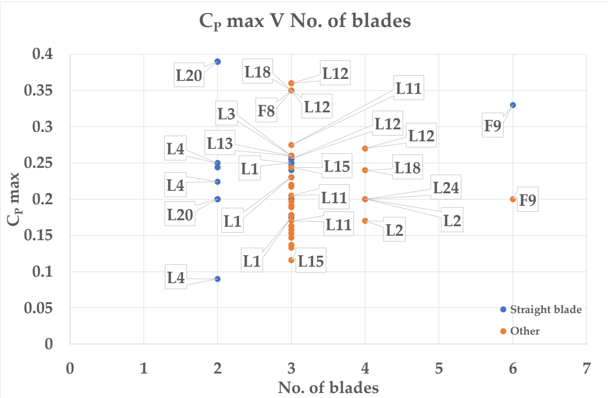

Fig. 8. Purged coefficient of performance versus number of blades. Untagged data points belong to the set identified by the adjacent label.

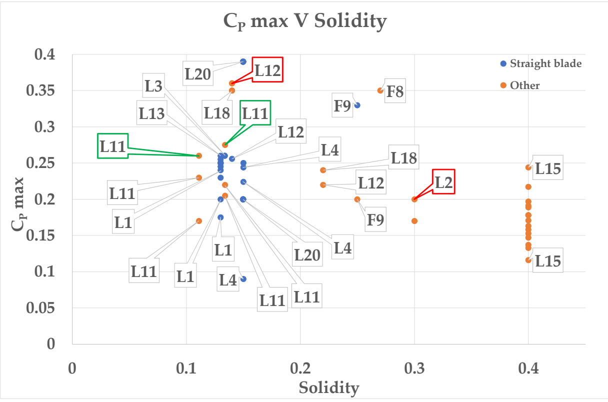

Fig. 9. Purged coefficient of performance versus solidity. Untagged data points belong to the set identified by the adjacent label.

Analogous to blade length, increasing the number of blades, as shown in Fig. 8, does not immediately translate to superior turbine performance. Some turbines with two blades, such as L4 and L20, have higher C_P values than those with more blades. Non-straight bladed turbines tend to have three blades whereas the number of blades for straight bladed turbines varies. The number of blades on any given turbine is not driven solely by performance but also other design parameters such as smoothing torque, structural blade loading and cost.

Solidity, S, is typically varied by changing the number of blades and/or changing the chord length. Increasing the number of blades changes the characteristics of a turbine by physically introducing more blades and supports into the water and hence more losses due to viscous effects and parasitic drag. Hence, it is unsurprising to see in Fig. 9 that some turbines, such as L12, with lower solidity have superior performance than those (such as L2) with higher solidity. Not all data follows this trend, however.

Increasing the number of blades on a turbine increases solidity. In a study of the impact of solidity and number of blades on turbine performance [27] and [8] found that both C_P and TSR decreased with an increase in number of blades. However, [28] found the opposite effect in increasing the number of blades from 2 to 4 (with S=0.019 and 0.038) led to an increase in $C_{P\,max}$ from 0.43 to 0.53 and shifted the power curve to a lower range of tip speed ratios. The same shift in power curve due to an increase in solidity is evident in the well-known coefficient of performance versus TSR for wind turbines. However, unlike [28], C_P decreases with solidity from a two bladed airscrew to a three bladed device in wind turbines. Whilst comparing a 3 and 6 blade turbine design, [29] found that performance decreased with increasing solidity and reported that the 3-blade turbine had the maximum efficiencies of about 30% whereas the 6-blade turbine had maximum efficiencies of about 25%. Shiono et al. [23] carried out a study to find the most suitable values of solidity and number of blades for a Darrieus turbine in water. The study kept solidity constant by increasing chord length whilst reducing the number of blades from 3 to 1. It was found that $C_{P\,max}$ was obtained at an optimum solidity of 0.179. Hence, whilst keeping the solidity constant at 0.179, the experiment was repeated for chord lengths of 168.8mm, 84.4mm and 56.3mm for one, two and three bladed turbines, respectively. It was found that both the one and two blade turbine had similar values for torque and efficiency, but the three-bladed turbine had 40% lower torque and 20% lower efficiency. The increase in number of blades and solidity shifted the power curve to lower tip speed ratios.

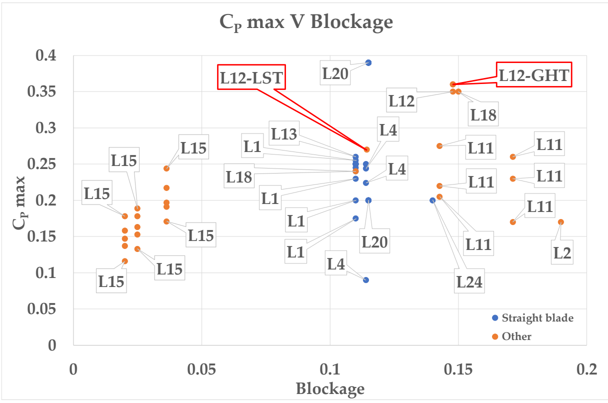

Fig. 10. Purged coefficient of performance versus blockage. Non-blockage corrected. GHT - Gorlov Helical Turbine, LST - Lucid Spherical Turbine. Untagged data points belong to the set identified by the adjacent label.

In laboratory testing blockage is typically increased by reducing the channel width. Blockage is a key parameter in laboratory testing as it has a massive effect on turbine performance. In commercial deployments, developers actively seek to exploit blockage to their advantage. Turbine performance typically increases as blockage is increased since the water is forced to pass through the turbine [30]. Good practice suggests that blockage correction factors should be applied to turbine laboratory performance data before field deployment. According to [20] blockage ratios, between 5% and 20% should be corrected to free stream conditions. Only one publication reviewed, [27], applied a blockage correction factor to the turbine performance data gathered, L12 as highlighted in Fig. 10. According to [27], the blockage correction factor decreased C_{Pmax} for the GHT from 0.36 to 0.28 and for the LST from 0.27 to 0.21. This translates to a ~30% and ~18% reduction for the helical and spherical turbine, respectively. Similar downward revisions should be made to the remaining entries in Fig. 10 and all of the entries in Fig. 2.

Turbine blade loading is one topic that was found not to have been addressed very well during the literature review. Blade loading was not reported by any of the field studies reviewed, however, it was reported by [9] and [18] from the same set of lab experiments. In these experiments, the turbine blades were instrumented with strain gauges to compare the stresses induced in a parallel bladed and truss type turbine. Extremely high blockage values in the range, B=0.47-0.58 and coefficients of performance in the range, C_P=0.79-0.92 were reported by [9] and [18]. High blockage values would mean the hydrodynamic loading on the turbine blades would be higher due to the increase in water velocity than in a low blockage environment.

V. Comparison of Dimensionless Parameters

The data presented in Fig. 6 to Fig. 10 all display the coefficient of power on the y-axis. Due to high degree of variability, it is difficult to identify trends and draw meaningful insight from the point clouds of data in these plots. The large variability and absence of trends may be due to the volatility of the coefficient of performance for each turbine configuration. As a result, additional plots of the purged dimensionless parameters were prepared.

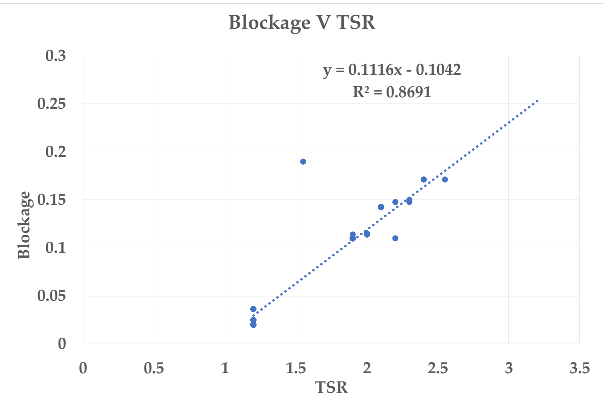

Fig. 11. Blockage V TSR (combined data) with fitted line.

Fig. 11 shows blockage versus TSR for the combined dataset (both straight and non-straight blades) and includes a linear trendline fitted to the data. The high correlation value, R^2=0.8691, suggests that there is quite a strong linear relationship between blockage and tip speed ratio. This linear relationship makes sense from a flow physics standpoint because when blockage increases, the water is forced to move faster around and through the turbine, thereby increasing the tip speed ratio.

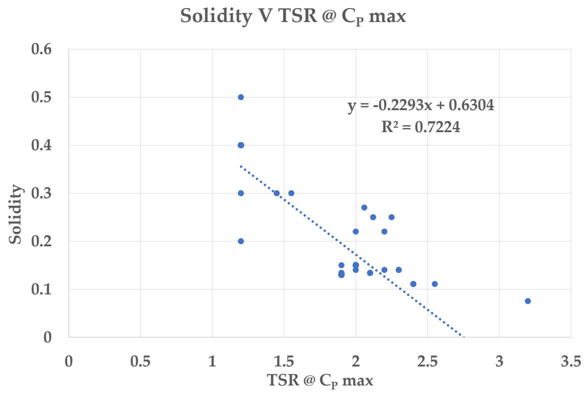

Fig. 12. Solidity V TSR (combined data) with fitted line.

An inverse linear relationship between solidity and tip speed ratio was identified for the combined purged dataset, which is shown in Fig. 12. The strong correlation between solidity and tip speed ratio is signified by the high R^2 value of 0.7224. It was noted earlier in the discussion surrounding Fig. 9 and the relationship between solidity and C_P that the optimum TSR tended to decrease in tandem with C_P as the solidity was increased. Han et al. [29] found that the tip speed ratio of peak turbine performance decreased from 2.4 to 1.9 for the 3 and 6 bladed turbines, respectively. The inverse linear trend identified in Fig. 12 concurs with this evidence. Both relationships and associated equations identified in the review between solidity, blockage and TSR can be used by turbine designers to optimise their designs.

VI. The Need for Experimental Work

Numerical studies offer great promise as many permutations of turbine design and configuration can be simulated. A lot of CFD work is carried out in two dimensions since 3D analyses is resource intensive and is obviously a simplification of the real-world three-dimensional flows that a turbine experiences in operation. 2D numerical studies often only focus on the centre shaft and the orbiting foils and omit the blade mounting structure. The inclusion of blade mounting supports (in 3D) would obviously further complicate the meshing requirements and hence slow down the analyses. On the other hand, the absence of mounting supports does not reflect reality and can have a significant effect on the turbine performance as demonstrated by [24] in the lab.

Blockage correction factors have generally been developed from actuator disc theory. The original actuator disc theory was developed to establish the theoretical limit of power that can be extracted from unconfined flow. Originally developed for wind power and rotorcraft applications, Betz's limit was derived using the conservation of mass and momentum of an inviscid incompressible flow [31]. Many researchers have modified the actuator disc theory approach taken in the development of the Betz limit to serve other applications such as marine hydrokinetic turbines [31], [32], [33].

Blockage correction factors have optimum ranges of operation as identified by [32] who investigated the applicability of a number of blockage correction factors to crossflow turbines. They found that no single correction factor accounted for the full physics of the crossflow geometry and stressed the need for caution when applying correction factors to TACTs. They also stated that at transitional Reynolds number, the effect of blockage was likely to be convolved with the Reynolds number dependence on unsteady lift and drag. The development of a blockage correction factor from experimental fluid dynamics studies specifically for crossflow turbines is necessary.

VII. Discussion

In order to realise the full potential of electricity production from tidal resources, significant investment and research is required as demonstrated by this review. The current published knowledge bank dealing with TACTs is relatively small and erratic as many publications simply do not declare a full set of parameters and had to be omitted from an already small dataset in this review. Some of the variability in reporting may be explained by the fact that none of the work reviewed cited adherence to either of the two testing protocols relevant to TACTs prepared by the University of Southampton for the Department of Energy and Climate Change [20] and that by the International Towing Tank Commission [34].

Further field and lab testing and reporting is required. Numerical studies can offer some assistance but must be supported with experimental validation. Adherence to testing protocols will not diminish some of the difficulties likely to be encountered. For example, some field conditions such as lateral shear as encountered by [6] are difficult to recreate in laboratory environments. Variation of lateral inflow would be difficult to recreate in the lab but a condition that in-service turbines are likely to experience. Conventional limits and formulae derived for horizontal axis turbines are automatically applied to TACTs. Alternate factors specifically for crossflow turbines should be developed.

VIII. Conclusion

The objective of this paper was to conduct a literature review of published work on TACTs. The literature survey of transverse axis crossflow turbines identified a relatively small body of published work in this niche area. Plots of key turbine performance parameters were compiled to identify trends in the data and extrapolate gaps that could be addressed by a targeted research plan. Trends were difficult to identify amongst the experimental point clouds. Despite this, strong relationships were identified between some of the dimensionless turbine parameters. These correlations identified between solidity and blockage with tip speed ratio can be used by designers to optimise their turbine designs.

The main findings of this work are that there is a relatively small variable dataset concerning TACTs which is largely incomplete, there is a lack of design consensus and an absence of an analytical model for TACTs. The lack of adherence to testing standards and application of unconfined flow correction factors is also a concern.

A strong rationale for experimental work to validate numeric simulations was also developed. Hydrodynamic blade loading was only considered in two lab publications which reported very high levels of blockage and coefficient of performance. None of the field studies reviewed reported on the structural loading on the turbine blades. It is concerning that only one of the publications reviewed applied a blockage correction factor to their results and none cited the recommended testing protocols. TACTs must be evaluated at small scale employing international best practice to develop renewable energy strategies and infrastructure that can go some way to meeting the demand for electricity.

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