Journal of Hydro-environment Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydro-environment Research

journal homepage: www.elsevier.com/locate/JHER

Research papers

# An investigation of the wake recovery of two model horizontal-axis tidal stream turbines measured in a laboratory flume with Particle Image Velocimetry

Stephen M. Simmons [a,*], Stuart J. McLelland [a], Daniel R. Parsons [a], Laura-Beth Jordan [a], Brendan J. Murphy [a], Lada Murdoch [b]

[a] School of Environmental Sciences, University of Hull, Cottingham Road, Hull HU6 7RX, UK
[b] CFD People Ltd., North Lanarkshire, UK

ARTICLE INFO

*Article history:*
Available online xxxx

*Keywords:*
Renewable
Power
Tidal
Turbine
Flow
Wake

ABSTRACT

The uptake of tidal stream-turbine (TST) technology lags other renewable energy sources despite the advantages of predictability, stability and increased power output in comparison to wind turbines of the same dimensions. There remains a need to address environmental concerns about the potential impacts of TSTs including the suspension and deposition of bed sediments if TSTs are to be more widely accepted and deployed. Sediment mobilisation and persistent flow vortices will also adversely affect the performance of other TST devices in an array downstream of the wake. The focus of this work is to improve our understanding of the wake recovery structure of a TST to build on the limited field and laboratory data currently available in order better predict the impact of TSTs on flow and sediment transport. Detailed measurements of the wake flow structures generated by scaled TST devices are presented. These results are the first to be derived from the application of high spatial resolution stereoscopic Particle Image Velocimetry (PIV). Two scale model horizontal-axis TSTs were manufactured and deployed in a laboratory flume (11 m long, 1.6 m wide and 0.6 m deep) at different flow speeds and heights above the bed. The results demonstrate greater wake recovery lengths for the rotor design with wider blade tips, despite the higher wake turbulence generated by the blades. Wake recovery is more rapid at the higher flow speed when greater turbulence from the tips is observed, but wake recovery lengths increase when both rotors are positioned closer to the bed.



## 1. Introduction

Horizontal-axis TSTs can harness energy from a current stream without the requirement to either channelize or impound the flow stream (Khan et al., 2009). TSTs generate more power than equivalent-sized wind turbines due to the higher density of water compared with air but consequently, there are greater structural stresses placed on the turbine rotor and supporting structures (Bahaj et al., 2007). Another advantage that makes tidal stream devices desirable as a renewable energy source is the repeatability and predictability of the power generation of bi-directional TSTs that are able to harness both ebb and flood currents (Charlier, 2003). Tidal power generation has the potential to become a major source of renewable energy, particularly in the UK (Burrows et al., 2009). However, take-up of the technology remains slow, due partly to concerns about adverse environmental impacts on the sea-bed ecosystem (e.g. Cada et al., 2007; Couch and Bryden, 2007).

TST wakes are characterised by a reduction in flow velocity downstream of the rotor and accelerated flow around the rotor (McCombes et al., 2011). For an array of TSTs, the wake effects of the upstream turbines affect the inflow conditions for downstream turbines causing a potential decrease in kinetic energy available to the rotor and an increase in unsteady flow velocity fluctuations. Turbulence generated at the rotor blade tips increases the bed shear stress downstream of the TST (Jordan et al., 2015) with potential adverse impacts on sediment transport and scour in the vicinity of the downstream TST supports. A good understanding of the wake development is therefore necessary to determine the

* Corresponding author.
*E-mail addresses:* s.simmons@hull.ac.uk (S.M. Simmons), s.j.mclelland@hull.ac.uk (S.J. McLelland), d.parsons@hull.ac.uk (D.R. Parsons), L.Jordan@2013.hull.ac.uk (L.-B. Jordan), b.j.murphy@hull.ac.uk (B.J. Murphy), lada@cfdpeople.com (L. Murdoch).

http://dx.doi.org/10.1016/j.jher.2017.03.003
1570-6443/

optimal distance between TST devices in an array. Wake widths expand with distance downstream of the turbine but may become constrained by the water surface, altering the wake structure when compared with unconstrained flows (Myers et al., 2008). The lateral spacing of TST devices is also an important consideration as the wake recovery length has been shown to decrease as a result of the increased mixing caused by higher turbulence generated between the two adjacent TST wake structures (Stallard et al., 2013). Physical modelling of TSTs has previously focused on wake characterisation and the influence of turbulence on generating performance (e.g. Maganga et al., 2010) and, more recently, on scour development (Hill et al., 2014). Measurement of flow in laboratory flumes has tended to focus on the central vertical plane of a single rotor design using Acoustic Doppler Velocimeters (ADV) to obtain point measurements of flow across planes intersecting the TST wake (e.g., Chamorro et al., 2013; Maganga et al., 2010). More recently, Simmons et al. (2015) demonstrated the importance of the rotor design on the generation of vortices at the blade tips and the influence of those vortices in the development of turbulent flow structures several rotor diameters downstream of the TST using Particle Image Velocimetry (PIV). Similarly, Jordan et al. (2015) reported on the wake asymmetry that arose from the deployment of one design of rotor positioned close to a roughened bed using PIV.

This study utilises a PIV system to measure flow velocity vectors in high resolution within 2D vertical interrogation areas at different positions across the channel. This enables an improved characterisation of the turbulent wake structure downstream of the TST rotor and the recovery of the structure through interaction with the surrounding flow. Results are presented from an examination of factors thought to affect wake recovery downstream of the rotor including comparisons between two different rotor designs, two different rotor heights above the bed within the turbulent boundary layer and two different inlet flow speeds. A discussion of the effect of these factors on the wake structure is presented that focusses on differences in mixing related to the structure and magnitude of turbulent kinetic energy in the downstream wake.

## 2. Experimental setup

Experiments to quantify the impact on flow structure of two contrasting model rotors were conducted at the Total Environment Simulator (TES) at the University of Hull. The TES is a re-circulating flume and a working channel of 1.6 m width was constructed using partition walls to give a working section of 11 m length with a water depth of 0.6 m. The channel width minimised the side-wall effect and enabled the PIV camera housing to be mounted on a traverse in a separate section of still water outside the experimental channel. The bed of the channel was constructed from varnished, plywood boards and the flow depth ensured that the 0.2 m diameter rotors were sufficiently separated from flow surface effects (Stallard et al., 2013). Two flow regimes were used in the experiments with depth-averaged streamwise flow speeds of 0.26 $ms^{-1}$ and 0.50 $ms^{-1}$. These are referred to herein as low flow and high flow respectively. The high flow regime flow rate was chosen as it was the highest flow rate at which the rotational speed of the motor, used to control the speed of the rotor, could be kept constant.

Two different rotor models were designed at the University of Strathclyde for the experiments and are shown in Fig. 1. Both horizontal-axis three-bladed rotors have a diameter of 200 mm. Rotor A has a twist of 17.6° and 5° fixed blade pitch, NACA 63-415 aerofoil and a tip thickness to blade radius ratio of 0.05. The blade design for Rotor B is based on that described by Vybulkova et al. (2015). It has a blade twist of 18.58° from root to tip (including blade pitch angle that was fixed), aerofoil NACA 0012 aerofoil and a tip thickness to blade ratio of 0.141. The rotor designs are available as stereolithography (STL) files in the supplemental material. Both rotors have comparable power coefficients but different aerofoil and blade-tip shapes to provide a comparison between the impact of narrow-bladed and wide-bladed rotors on flow structure. In practice, TSTs are likely to be designed with wider blade tips than similar horizontal-axis wind-turbine rotors in order to provide structural strength to withstand the greater forces placed on them (Fraenkel, 2010). The model rotors used in the flume were manufactured from these designs using stereolithography and were mounted on an 8 mm diameter shaft attached to a motor through a watertight seal and flexible coupling. The rotor speed was controlled by the 25 W DC motor that enabled the tip-speed ratio of the rotor to be set and controlled remotely. The motor was chosen to provide sufficient stability and power to control the rotor at a tip-speed ratio of 5.5, chosen to represent the maximum of the power curve, for the low flow regime (137 RPM) and high flow regime (263 RPM) but with a small diameter to minimise the impact of the motor housing on the flow. The motor housing and support were designed as a solid piece with a 32 mm diameter housing attached to a 68 mm × 6 mm solid fin that enabled the rotor to be supported from above and positioned at different heights above the channel bed. The rotor was supported from above to enable quantification of the rotor's impact on flow without the impediment of a bed-mounted support. The rotor was positioned ~6.5 m from the inlet to allow the flow to become fully developed before encountering the rotor. Fig. 2(a) shows Rotor B attached to the housing from a position upstream in the channel looking towards the channel outlet. The power and control cables exit the housing through a seal at the downstream end of the housing.

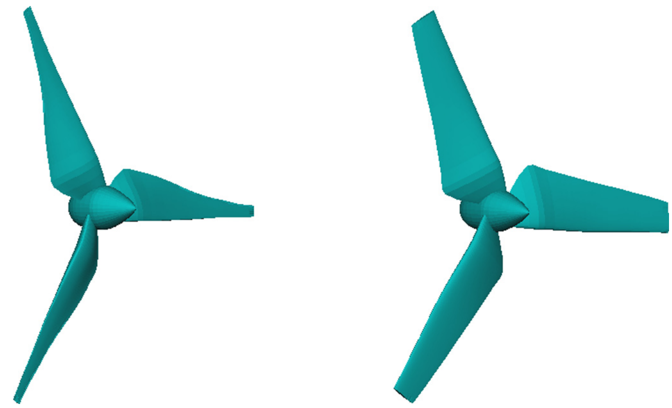

**Fig. 1.** CAD images of the two rotor designs: (a) Rotor A and (b) Rotor B.

Images of the laser-illuminated, seeded flow downstream of the rotor were captured with two submersed cameras that formed a stereoscopic, dual-pulse laser PIV system. The system thus enabled the derivation of 3-component velocity vectors across a 2D interrogation area aligned with the streamwise axis. The laser was positioned downstream of the rotor on a frame mounted above the channel. The laser beam was directed through an optic, positioned approximately 0.2 m above the channel bed at around 2 m downstream of the rotor, which created a vertical, light-sheet orientated parallel to the channel centreline. The intersection of the light-sheet with the channel bed and the cylindrical camera housing is seen in Fig. 2(b) before the tank was filled with water. The laser-mounting and the camera housing traverse allowed the light-sheet to be re-positioned at different locations across the channel whilst maintaining the geometrical arrangement between the light-sheet and the two cameras, which captured images through