Flow boundary interaction effects for marine current energy conversion devices

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1 Introduction

Marine current energy conversion technology is presently at the prototype stage where single devices are deployed, or planned for installation, at isolated testing sites. The flow conditions for marine devices are distinctly different than for similar technologies such as the wind energy industry. One of the principle differences is the constrained nature of the operating fluid in the vertical plane. This is likely to introduce some interesting flow effects for Marine Current Energy Converters (MCECs) where fluid can be constrained/accelerated either above or below the region of energy capture.

The close proximity of both the seabed and water surface will have a significant effect upon the structure of the downstream flow field of the rotor. Fluid passing through a horizontal axis MCEC will experience a reduction in velocity across the rotor plane. Downstream of the rotor this region of fluid is moving at a lower velocity than the free stream fluid (that passed around the rotor) and hence must expand in order to conserve momentum. This takes the form of a gradually expanding cone-shaped region downstream of the rotor that is better known as the wake. Turbulent mixing in the boundary region between the wake and the faster moving free stream fluid serves to re-energise the wake, breaking it up and increasing the velocity. At a distance far downstream the wake will have almost completely dissipated and the flow field will closely resemble that which existed upstream of the rotor disk.

Marine current energy converters open up new areas of open channel hydraulics and fluid dynamics in that they could potentially occupy a significant fraction of the total height of the operating fluid. Initial estimates were that the top 8m and bottom 25% of the depth would be avoided due to surface wave effects and the steeper section of the boundary layer respectively [1]. For a typical first-generation site with depths close to 30m this would equate to a horizontal axis rotor of 12-15m diameter. As the technology matures devices may increase the energy capture region to include more sheared and turbulent flows close to the sea bed and surface. The non-uniform nature of the vertical velocity profile in the sea has implications for both rotor loading and initial wake profile/recovery due to unequal mass flow rates above and below the rotor disk.

The vertical velocity profile has been measured in a few cases in UK waters where reasonably strong tidal streams exist [2, 3]. The latter study was conducted as part of a prototype MCEC testing programme. Measurements of the inflow velocity profile were made at a site near Lynmouth North Devon where a 300kW prototype device was installed by Marine Current Turbines Ltd in 2003. One published velocity profile taken at a surface flow speed slightly greater than 2m/s shows a very close resemblance to the modified $1/7^{th}$ power law [1] running from seabed to surface.

Whereas the seabed is a solid flow boundary the water surface is able to deflect. Results arising from previous work indicate that unless flow speeds become very rapid and blockage ratios are excessive there may not be any measurable change in water surface elevation [4]. Thus the wake flow downstream of the rotor disk may deflect or be constrained by both the bed and water surface altering the wake structure in comparison to a rotor operating in unconstrained or infinite flow field. This was postulated as one of the reasons for the discontinuity between rotor thrust and power in a study of a horizontal axis rotor test at shallow immersion in a towing tank [5].

Lateral blockage could also have a significant effect upon the downstream flow field either as a dual-rotor device or as a row of single rotor devices closely spaced perpendicular to the incoming flow.

2 Materials/Methods

In order to conduct work at a manageable scale porous mesh disk rotor simulators (often referred to as actuator disks) were used. Discussion regarding the use of actuator disks for small-scale reproduction of far-wake conditions has been addressed previously [4, 6]. There is also evidence of previous investigations [7, 8] concerning the study of flow fields around horizontal axis rotors using mesh disk simulators.

The principle differences between the flow fields of actuator disks and horizontal axis rotors have been shown to dissipate in the near wake region generally less than 4 rotor diameters downstream [9, 10].

Actuator disks most accurately replicate the far-wake region where ambient turbulence is the principle mechanism of rotor wake recovery. To this end, the principle parameters that require accurate scaling are:

a) Accurate replication of rotor disk thrust controlled through the level of porosity (ratio of open to closed area)

b) Linear scaling of length ratios such as disk diameter to water depth and channel width.

c) Replication of ambient flow field conditions such as Froude number, vertical velocity profile and turbulence intensities. Full-scale and model Reynolds numbers cannot achieve parity at very small scales but should still lie within the turbulent classification.

100mm diameter disks were mounted on a thin steel support arm which was part of a pivot arrangement to mechanically amplify the small thrust forces on the disks (figure 1). A 10N button load cell was used to measure the total thrust force whilst a small deduction was made for the drag of the exposed section of the support arm. Time-averaged thrust readings were recorded using a Keithley 2700 multimeter/data acquisition system with 22-bit resolution.

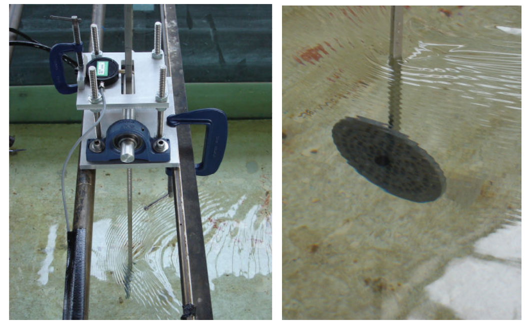

Fig 1. View of disk rig showing load cell (left). Porous mesh disk immersed in the flume (right).

Experimental work was conducted at two indoor facilities. The first was the Chilworth hydraulics laboratory at the University of Southampton, UK. The working section of this flume is 21m in length, 1.35m width and maximum depth 0.4m for steady operation. It is a gravity fed flume whereby water is lifted from a sump via 3 centrifugal pumps and deposited at the upstream end of the working section through 2 diffusers. Flow rate is controlled by utilising a number of these pumps each having a control value on the feeder pipe running to the upstream end of the flume. At the downstream end of the working section an overflow tailgate exists to control the water level. The Chilworth flume was used for studies where the downstream flow field was expected to interact with the bed and water surface.

The second facility was the IFREMER circulating channel at Boulogne sur Mer, France. The channel has a working section 18m in length, 4m wide and 2m deep. The channel is a closed loop system with 2 large variable-speed axial flow pumps providing the thrust to circulate the water. Disks could be positioned at much greater depths than could be attained at the Chilworth flume thus eliminating or minimising any interaction with either the bed or water surface.

In order to visualise the flow field around the mesh disk rotor simulators a large number of point measurements were taken. A Nortek Vectrino Acoustic Doppler Velocimeter

(ADV) was used for high frequency velocity sampling. The functionality and general accuracy of ADV devices has been addressed elsewhere [11-14]. The Vectrino ADV used for this work incorporated advanced firmware and was set to sample at 50Hz with a sample volume of 0.15cm^3. Sampling periods were set to 180 seconds providing 9000 discrete velocity samples in 3-dimensions.

Fig 2. View downstream of the IFREMER water channel (left), installed mesh disk rig and ADV mounted on 3-dimensional axis

Due to the high concentration of suspended solids in the Chilworth flume, no doubt arising from being located in a hard water area, ADV acoustic signal strengths and device correlation scores were consistently high. The correlation coefficient (R^2) can be expressed in terms of the dimensionless spectral width (φ_r):

$$R^2 = e^{-2\pi^2 \varphi_r^2} \quad (4)$$

The dimensionless spectral width is the product of the received signal width and the sample time interval. Higher correlation values are generally indicative of greater measurement accuracy. A value of correlation greater than 0.7 (or 70 if expressed as a percentage) is recommended by Nortek for measurement of turbulent velocities. During experimental work typical device signal to noise (SNR) ratios were above 22 and correlation >90%. However these are not definitive measurements of sample accuracy and can only be used as an approximate guide to ADV performance.

The water in the IFREMER facility was much clearer with a lower concentration of suspended solids. This resulted in lower device correlation and SNR so the water was seeded with 15 micron diameter polyamide seeding particles.Data was passed through a number of different filters to remove noise and spurious points. Filtering is generally necessary for analysis of higher order flow effects such as turbulence intensity, Reynolds stresses etc. but for mean flow velocity filtering has a very small effect.

3 Results

The experimental domains at both the Chilworth and IFREMER channels are detailed in table 1.

Table 1. Physical properties of two experimental facilities used for experiments

	Chilworth flume	IFREMER channel
Total water depth	4 Diameters	20 Diameters
Channel width	13 Diameters	40 Diameters
Disk centre from surface	2 Diameters	2 Diameters
Depth-Averaged Froude No.	0.118	0.113
Depth-averaged Reynolds No.	9.2×10^4	9.9×10^5

The principle difference is that the Chilworth experimental domain consists of the both the free surface and channel bed at 2 diameters from the disk centerline; the IFREMER setup is similar except that the channel bed is very far below the disk such that there are no interaction effects. Previous experiments at the Chilworth facility have focused upon disk diameter/water depth ratios closer to 3 which are expected to be similar for first-generation MCEC devices. The closer proximity of the bed at the Chilworth facility influences the vertical velocity profile across and close to the disk.

Figure 3 shows both normalized vertical velocity profiles for the Chilworth and IFREMER experimental domains. Depth is expressed in disk diameters (D). Whilst the velocity profile at Chilworth is well-developed the close proximity of the bed induces a more pronounced gradient that leads to disparate mass flow rate above and below the disk. Flow speed at the IFREMER channel is more similar above and below the disk.

Ambient turbulence intensity is the principle mechanism for wake dissipation far downstream of the rotor disk. A comparison of

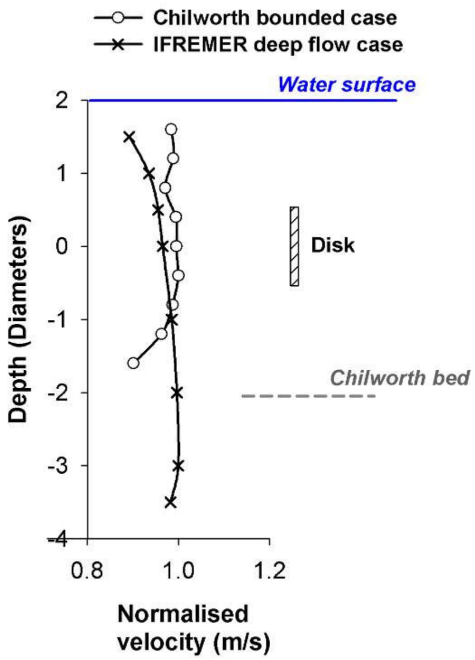

Fig 3. Normalised vertical velocity profiles at the Chilworth and IFREMER water channels

the ambient conditions is presented in figure 4 where turbulence intensity is defined as:

$$I = \frac{\sigma}{\overline{U}}$$

Where σ is the standard deviation of the velocity in each component and U is the Reynolds-averaged mean flow velocity. Figure 4 shows the ambient turbulence intensities in all 3 planes (U,V,W; Longitudinal, lateral and vertical) for both experimental facilities. At the Chilworth facility the presence of the flume bed 2-diameters below the disk causes an increase in turbulence intensity immediately above the bed. U and V components are of a similar magnitude at 6-7% whilst the turbulence intensity in the vertical plane is

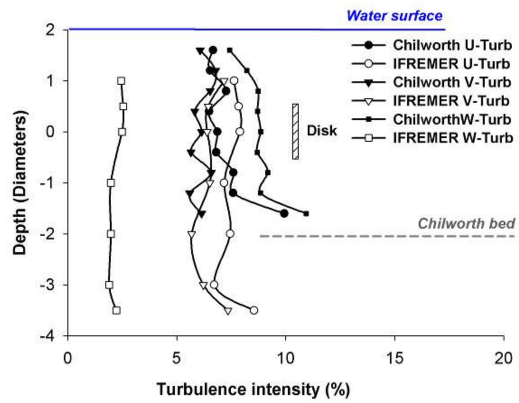

Fig 4. Turbulence intensities for the Chilworth and IFREMER channels under experimental conditions

slightly greater. At the IFREMER facility the turbulence intensity is more constant with depth close to the disk. The turbulence intensity in the vertical plane is much lower than at Chilworth. This difference could be due to the design of both facilities and the nature in which water is delivered to the upstream end of the working section.

Horizontal axis wake recovery can be defined in terms of velocity deficit, which is a non-dimensional number relative to the free-stream flow speed at hub height (U_0) and the wake velocity (U_W):

$$U_{deficit} = 1 - U_w / U_0$$

Figure 5 shows the longitudinal centre plane velocity deficits for the experiments conducted at IFREMER and Chilworth. There is a degree of flow acceleration above and below the disk in the 4D deep flow that appears to persist far downstream close to the bed and water surface. The wake in the deeper flow appears to persist much further downstream; the deficit at 10-

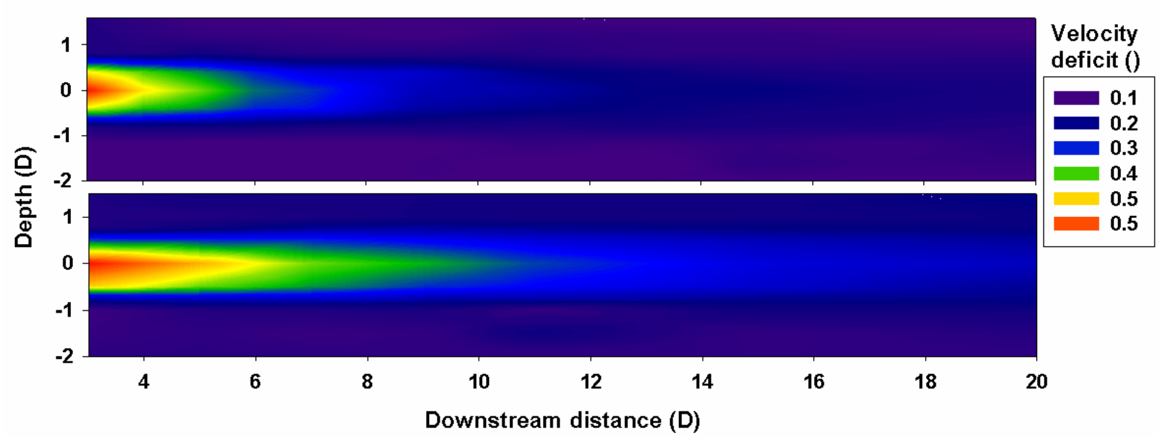

Fig 5. Centre plane velocity deficit profiles; Chilworth (top) IFREMER (bottom).

diameters is far stronger than for the shallower, constricted flow. Figure 6 shows vertical line plots of velocity deficit. The accelerated flow can be seen for the bounded conditions where the deficits close to the bed and water surface are very small or negative, the latter implying flow acceleration.

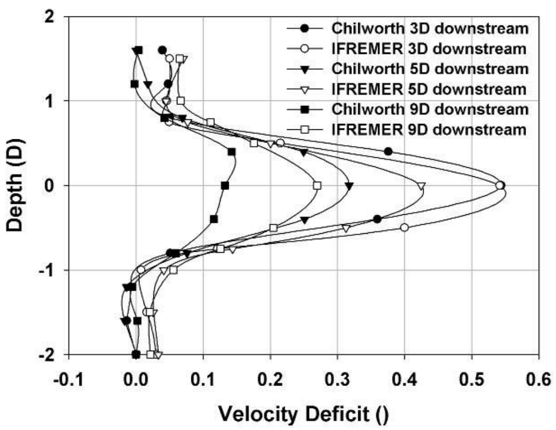

Figure 6. Measured vertical velocity deficit profiles at discrete distances downstream

Figure 7 shows the downstream centerline deficits. As suggested in figure 5 the wake recovers much faster in the more constrained flow. This may appear counter-intuitive as one might think that in a more open flow regime the wake is more free to expand. The principle reason could be due to the flow acceleration around the disk in a shallower flow pulls the wake downstream inducing increased shear forces that serve to break the wake up more rapidly. Flow in the deeper scenario does not accelerate above and below the disk to the same degree and the wake persists further downstream.

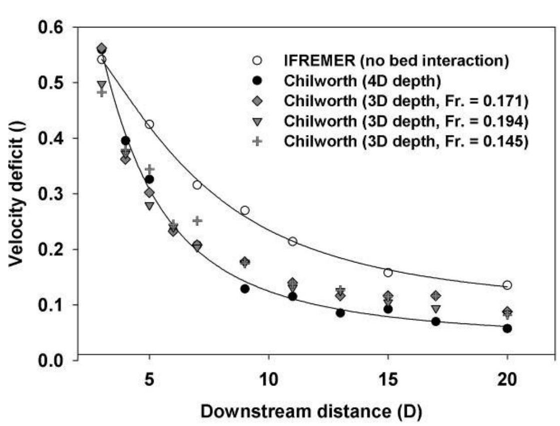

Fig 7. Centreline velocity deficit comparison

Data is included in figure 7 for 3 other flow mapping experiments conducted at the Chilworth facility. These were conducted with a water depth of 3-disk Diameters and disks located at centre-depth. Results for varying flow speed or Froude number are presented to show that this parameter has little effect upon downstream centerline wake recovery. The reason for the slightly larger wake deficits at 3D compared to the 4D case in the same flume was due to the much larger difference in mass flow above and below the disks. Figure 6 demonstrates that the wake is symmetrical in the horizontal plane when the disk lies within a flow depth of 4D. For the 3D-depth the wake was suppressed downwards by the faster flow over the disk whilst increased velocity shear beneath the disk lead to a much lower mass flow passing beneath the disk. This reduced the amount of high-energy flow on the underside of the wake that would serve to re-energise and break up the wake. Full results of experiments conducted in the Chilworth flume can be found elsewhere [4, 6].

Thus the lower ambient turbulence in the vertical plane at the IFREMER facility can be ruled out as the reason for the lower rate of wake recovery. The lack of flow acceleration around the disk causes the wake to persist further downstream than for conditions where the disk is in closer proximity to both the water surface and bed.

4 Conclusions

MCEC's operating in shallow fast-moving flow regimes will see a difference in the downstream flow field compared devices installed in deeper water. The breakdown of vertical symmetry in the wake has been addressed in previous work by the authors [4] and appears to occur for water depth/rotor diameter ratios less than 4. Experiments to remove the effect of sea bed proximity have shown that wake recovery is not as favourable when the flow field is in effect infinitely deep beneath the rotor disk. In a symmetrical constrained flow there is acceleration around the rotor disk that reduces the length of the near wake where stronger velocity deficits exist. This faster moving flow persists into the far-wake region aiding breakdown of the wake and centreline velocity recovery. For flow depths shallower than 4-diameters the rotor disk is positioned closer to the more sheared section of the vertical velocity profile. This limits mass flow beneath the disk and reduces the rate of recovery on the underside of the wake. The work described in this paper provides an insight into the flow effects around MCECs operating in a constrained flow field.

Acknowledgements

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References

[1] European Commission, 'The Exploitation of Tidal Marine currents', Report EUR16683EN, 1996.

[2] Rippeth, T.P., Williams, E., Simpson, J.H., Reynolds stress and turbulent energy production in a tidal channel, Journal of physical oceanography, Vol. 32, pp 242-1251, 2002.

[3] DTI report, Development, installation and testing of a large scale tidal current turbine, Contract number T/06/0021/00/Rep, October 2005.

[4] Bahaj, A.S., Myers, L.E., Thomson, M.D., Jorge, N., Characterising the wake of horizontal axis marine current turbines, *Proc.* of the European Wave and Tidal Energy Conference, Porto, Sept. 11-13, 2007.

[5] Bahaj, A.S., Molland, A.F., Chaplin J.R., Batten, W.M.J., Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, Renewable Energy, Vol. 32, pp. 407-426, 2007.

[6] Myers, L.E., Bahaj, A.S., Rawlinson-Smith, R.I., Thomson M.D., The effect of boundary proximity upon the wake structure of horizontal axis marine current turbines, *Proc.* of the 27th International Conference on Offshore Mechanics and Artic Engineering, June 15-20, 2008, Estoril, Portugal.

[7] Sforza, P.M., Sheerin P., Smorto, M., Three-dimensional wakes of simulated wind turbines, AIAA Journal, V. 19, No. 9, p. 1101-1107, 1981.

[8] Builtjes, P.J., The interaction of windmill wakes, Proceedings of the 2nd Int. Symposium on wind energy systems, Amsterdam, 1978.

[9] Connel J.R., George, R.L., The wake of the MOD-0A1 wind turbine at two rotor diameters downwind on 3 December 1981, Report no. PNL-4210, Pacific Northwest Laboratory, Battelle, U.S, 1982.

[10] Vermuelen, P.E.J., Mixing of simulated wind turbine wakes in turbulent shear flow, TNO report 79-09974, 1979.

[11] Lohrmann A., Cabrera R., Kraus N.C., "Acoustic Doppler velocimeter (ADV) for laboratory use", Proceedings of symposium on fundamentals and advancements on hydraulic measurements and experimentation. ASCE, pp 351–365, 1995.

[12] Voulgaris G., Trowbridge J.H., "Evaluation of the Acoustic Doppler Velocimeter (ADV) for turbulence measurements", journal of atmospheric and oceanic technology, V. 15, pp 272-289, 1998.

[13] Rusello, P.J., Lohrmann, A., Siegel, E., Maddux, T., "Improvements in acoustic doppler velocimetry", The 7th Int. Conf. on Hydroscience and Engineering, ICHE-2006, Sept. 10-13, 2006.

[14] Blanckaert, K., Lemmin, U., "Means of Noise Reduction in Acoustic Turbulence Measurements", Journal of hydraulic Research, Vol. 44, pp 3-17, 2006.