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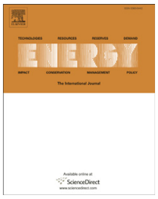

Shaping array design of marine current energy converters through scaled experimental analysis

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ABSTRACT

Marine current energy converters or tidal turbines represent an emerging renewable energy technology that can provide a predictable supply of electricity. Single devices are in operation around the world with aspirations to deploy farms or arrays of multiple devices.

We present an experimental study that has characterised the downstream wake flow around a 1/15th-scale turbine in a large circulating water channel and a series of experiments involving static actuator disks at 1/120th-scale allowing simulation of multiple-device layouts.

Our analysis demonstrates that the near wake is highly turbulent with structures generated by the rotor and support structure. This region of flow may prove difficult to numerically simulate with a high degree of accuracy. In the far wake the performance of static actuator disks can be matched to mechanical rotors reducing scale and cost facilitating replication of complex array geometries. Here the ambient turbulence and geometric properties of the device/channel drive the wake recovery towards free stream conditions.

Devices operating downstream of others will be subject to a non-steady flow field making comparative performance difficult. We discuss the possibility of unequal device specification and rated power within an array (unlike wind farms) providing a more representative measure of array performance.

1. Introduction

Whilst the concept of extraction of the kinetic energy available in marine currents is a relatively old idea achieving this on a commercial scale has only become a reality in more recent years. Technical advances in related industries such as offshore hydrocarbon extraction and offshore wind energy have increased the knowledge and competency associated with operating in the sea, including underwater actions such as drilling, cable laying and performance of subsea structures. In addition, global desire to reduce the carbon intensity of electricity production provides a clear opportunity to look at natural resources such as marine energy to part of our energy production mix. Previously the drivers for renewable energy arose from the oil crisis of the early 1970's for wind energy and in the 1980's for wave energy where several demonstrator projects were developed. Tidal energy, specifically extracting kinetic energy from flowing waters in the sea (marine currents), represents a recent addition in activities in marine energy conversion. In such conversion, most devices have similar appearance to wind turbines and act in much the same way. However, operation of such underwater turbines is subjected to the strong tidal flows that exist in estuaries, constrained between landmasses and around headlands which are the prime sites for energy conversion. Extraction of kinetic energy from such sites does not require impounding of the operating fluid and as such will have minimum environmental impact as it will maintain almost all of the dynamic nature of the flow. In addition, tidal or marine current energy conversion offers a resource that is predictable in terms of direction and speed translating into a more reliable and quantifiable form of electricity generation compared to more other intermittent renewable energy technologies. Significant resources lay in waters around the United Kingdom [1], North East and North West coasts of the United States and Canada [2], the Philippines and South Korea [3].

1.1. Operations in arrays

Over the last 10 years technology progress of MCEC (Marine Current Energy Converter) technology has undergone various

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development stages from small-scale tank testing through to offshore devices prototype deployment in open seas. Marine energy test centres have been created such as the European Marine Energy Centre in the North of the UK that offer offshore grid-connected berths for tidal turbines in order to test devices, to develop the necessary in-situ knowledge and expertise to quantify performance and energy yields of devices. Recently, successful applications have been made for seabed leases around the UK and elsewhere in the world for MCEC arrays. The projects planned in the UK alone represent an expected installed capacity of over 600 MW by 2020 [4].

The evolution of MCEC arrays is addressed by the authors within the EquiMar protocols on marine energy [5]. Part IIC of these protocols discusses the layout of MCEC arrays with increasing scale of deployment. The most efficient layout in terms of maximising energy extraction and minimising negative device interaction is a single row of devices aligned orthogonal to the mean flow direction (Fig. 1(a)). Unlike wind energy many sites with strong tidal flows are relatively compact in nature often with constrained bathymetry meaning that optimised device layout and packing density is required to extract the maximum amount of energy from a specific site. Hence, a second row can be deployed in an offset manner (Fig. 1b) that will avoid operation in the slower, more turbulent wake flow generated by another device within the array. Depending upon the lateral constraints at any tidal site eventually the increasing number of MCECs will require some devices to operate longitudinally downstream of another (Fig. 1c). Here the inflow conditions are likely to be different to those intercepted by the upstream devices.

Unlike wind energy conversion, the tidal energy resource often has low directionality with flow often reversing by (or very close to) 180° in direction between the flood to ebb tides. Therefore highly geometric array layouts may proliferate if bathymetry is constant across a site. Thus whilst the resource available to each device within the array may vary, the temporal nature will be quite predictable. However, the issue still arises that energy (power) production (whilst predictable) will vary depending upon device position within the array. This predictability might warrant (a) varying device designs, (b) an appropriate control strategy of the array and (c) the quantification of inflow conditions to each device (especially important to those at the centre of the array).

MCEC devices operate by extracting the kinetic energy from the tidal flow and therefore the velocity downstream of the devices will be reduced. This region of slower-moving fluid is termed the ‘wake’. Immediately downstream of the device the wake will be at its strongest; a slow, highly turbulent volume of fluid. Fluid mixing will occur between the outer surface of the wake and the free stream fluid that passed around the MCEC. High shear forces at this boundary caused by the disparity in velocity between the wake and ambient flow is one mechanism the second being the turbulent mixing of flow structures present in both the ambient flow passing around the MCEC and structures generated by the device itself (from the rotor blades and device support structure). As we move further downstream the wake becomes wider and the velocity increases such that at a point far downstream the wake has almost completely dissipated and the flow field closely resembles that which existed upstream of the MCEC. A key question is at what longitudinal separation distance should we employ in order to maximise energy capture, minimise operation in turbulent wake flow and hence minimise the cost of electricity generation?

Many different mechanisms and drivers define the structure of the wake as it forms and propagates downstream. The initial strength of the wake principally depends upon the amount of energy extraction but other factors also contribute. As the wake expands downstream the turbulence present in the ambient flow is the key driver for wake dissipation. Other drivers acting to characterise the strength and shape of the wake include the length scales of the system (depth, location and shape of MCEC energy extraction) any bathymetry or seabed roughness features that might affect the global flow field and the form/shape of the MCEC device itself. As such it is a complex flow field; initially it might appear very similar to that downstream of a wind turbine but very different turbulent features and the highly constrained nature of the overall flow field (especially in the vertical plane) have led to highly varied and different wake structures [6].

1.2. Scope of this work

In order to understand the issues mentioned above and pertinent to the MCEC array operation, experimental studies have been conducted to investigate aspects of the flow field that are likely to occur in large arrays. A model (1/15th-scale) horizontal axis MCEC was designed and constructed at the University of Southampton and tested in a large open re-circulating water channel facility. The purpose of this work was the investigation of the near-wake properties of devices and to quantify the longitudinal decay of the wake. This work was augmented by conducting further experiments at 1/120th-scale using static porous membranes or actuator disks. Here the focus was on the characteristics of the far wake region and the performance and flow effects of positioning devices directly downstream of one another as is likely to occur in large MCEC arrays.

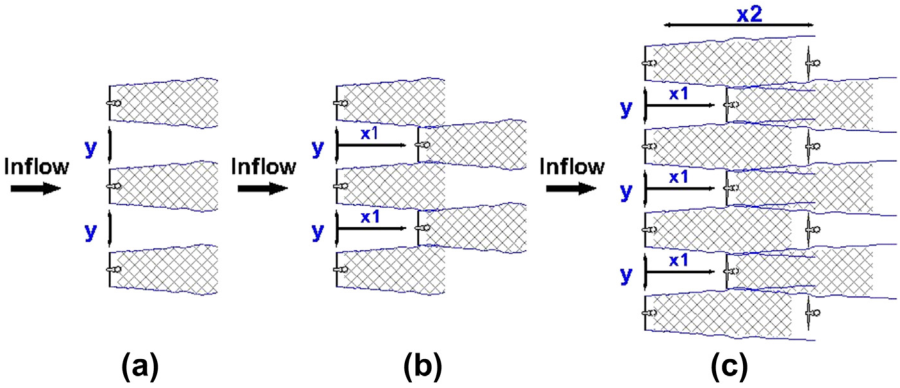

Fig. 1. Plan view of MCEC arrays. (a) Single row, (b) offset dual row, (c) multi-row.