International Journal of Marine Energy 10 (2015) 39–51

Contents lists available at ScienceDirect

International Journal of Marine Energy

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

# Investigation of tidal turbine array tuning using 3D Reynolds-Averaged Navier–Stokes Simulations

William Hunter [a,*], Takafumi Nishino [b], Richard H.J. Willden [a]

[a] *Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK*
[b] *Centre for Offshore Renewable Energy Engineering, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK*

ARTICLE INFO

*Article history:*
Received 2 September 2014
Revised 12 December 2014
Accepted 5 January 2015
Available online 22 January 2015

*Keywords:*
Tidal energy
Efficiency
CFD
Actuator disk
Array

ABSTRACT

Three-dimensional incompressible Reynolds-Averaged Navier–Stokes (RANS) computations are performed of water flow past an array of tidal turbines, modelled as actuator disks. While recent analytical models provide useful insight into the limit of power extraction and efficiency of tidal turbine arrays, they assume that the turbines are operated uniformly across the entire array. This study presents results of tuning operating conditions across arrays of four and eight turbines, and also the effect of staggering an array of turbines into upstream and downstream sub-arrays. The results show that the power coefficient of a non-staggered array of turbines is maximised when the turbines are operated with a uniform local resistance coefficient across the entire array. This operating condition results in a non-uniform distribution of thrust and power coefficient across the array. For the staggered array, it is found that for a given streamwise separation of sub-arrays the power coefficient is maximised by differential tuning of the front and rear rows, but that the maximum power coefficient does not exceed that achieved by the equivalent non-staggered array. Additionally, for a given efficiency of extraction, i.e., the power extracted by the turbines relative to the total power removed from the flow, the non-staggered array is shown to have a higher power coefficient than the staggered arrays.

---

* Corresponding author.
*E-mail address:* william.hunter@eng.ox.ac.uk (W. Hunter).

http://dx.doi.org/10.1016/j.ijome.2015.01.002

## 1. Introduction

Most successful attempts to harness tidal stream energy so far have resembled modern wind turbines, i.e. a horizontal axis two or three bladed rotor mounted on a supporting tower, e.g. [1]. It has been known for almost a century that the power extractable by a wind turbine can be estimated using linear momentum actuator disk theory (LMADT). By modelling the turbine as a step drop in static pressure over the swept area of the rotor in the axial flow direction, LMADT combines control volume analysis of momentum, mass and energy and the assumption of an incompressible, inviscid fluid to estimate the power that can be extracted from a flow. For wind turbines, the maximum power that can be extracted, normalised by the kinetic energy flux of the undisturbed flow through the equivalent rotor swept area is now known as the Betz limit [2]:

$$C_{P\max} = \frac{P_{\max}}{\frac{1}{2}\rho A U_{\text{in}}^3} = 16/27 \tag{1}$$

where $A$ is the rotor swept area, $U_{\text{in}}$ is the undisturbed upstream velocity and $\rho$ is the fluid density. At this maximum, the velocity at the disk plane $U_d = 2/3U_{\text{in}}$, or the so-called "induction factor" $a = 1 - U_d/U_{\text{in}} = 1/3$.

The same limit of power extraction may apply to an isolated tidal turbine in a very large channel. However, tidal turbines are expected to be located in tidal streams where the depth of the flow is typically $1.5D$–$5D$, where $D$ is the diameter of the rotor. The flow will therefore be constrained vertically by the sea bed and the free surface [3], and possibly also laterally in narrow tidal channels. By considering an additional stream-tube for the accelerated flow bypassing a turbine, Garrett and Cummins [4] found that the $C_{P\max}$ of a tidal turbine in a constrained channel is increased by a factor of $(1 - B)^{-2}$ where $B$ is the blockage, defined as the ratio of the rotor swept area of the turbine, or turbines, to the cross sectional area of the channel $A_c$. Nishino and Willden [5] confirmed that this result agrees well with computational fluid dynamics (CFD) simulations of an actuator disk in channels of various cross section. They also found that the limit could be exceeded when the effect of turbulent mixing in the near wake was considered. Turbulent mixing was found to result in momentum transfer from the faster bypass flow to the slower core flow, accelerating the core flow through the turbine, thus increasing the $C_{P\max}$.

In order to extract sufficient energy from tidal resources to make a meaningful contribution to energy demands, many devices will need to be installed in a given tidal channel. Groups of devices in rows across the channel cross section are often referred to as "tidal fences" or "tidal turbine arrays". In long channels, it may also be possible to install multiple rows along the channel to create tidal energy farms.

While LMADT suggests that turbines should be installed across a large fraction of a channel cross section to achieve high blockage, this is unlikely to be feasible due to competing uses (navigation, wildlife, etc.) and varying bathymetry. It is more likely that turbines will be installed in arrays occupying only a small fraction of a channel cross section, i.e. with small global blockage (ratio of total turbine frontal area to channel cross-sectional area). By applying the model of Garrett and Cummins [4] for the flow around each turbine also to the flow around the entire array, Nishino and Willden [6] have developed an analytical model for such a 'partial' array of turbines. One of the key findings of this analysis was the existence of optimal intra-turbine spacings. For a given water depth, the optimal spacing is the result of the competing effects of local blockage due to neighbouring turbines and the effect of array scale flow reduction as the overall thrust of the array increases. An extended version of this analytical model [7] compared well with 3D RANS actuator disk simulations, which also indicated that turbulent mixing in the array near wake was responsible for the increased power of an optimally spaced partial turbine array.

As discussed in [8], the analytical models to date have delivered important results but still represent an incomplete description of the wake mixing mechanisms. Additionally, all of the analytical models discussed assume uniform inflow and operating conditions across the array. The current work aims to investigate the effects of allowing variable operating conditions for turbines across an array. It is postulated that turbines at the centre of the array will experience a different flow than those closer to the fence edges, and therefore non-uniform operating conditions may be required to achieve better