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# An assessment of efficient tidal stream energy extraction using 3D numerical modelling techniques

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*Abstract*— **Tidal stream energy is an emerging sector of the energy generation industry. It has more potential than other renewable energy resources to provide base-load power due to the predictability of the speed and direction of tidal currents. However, the practical use of tidal stream energy requires efficient energy extraction - including an efficient device or array at a suitable location – to make it economically viable. A tidal stream array is one of the most practical extraction methods, but the design of an efficient array is a challenging and complex process. The current knowledge of the effects of tidal stream arrays on hydrodynamic processes and wake interaction between tidal turbines is still limited. Several studies have tried to investigate the optimal array configuration for maximum and economically viable power extraction. This paper investigates some key factors that affect the power extraction by a tidal array, exploring the various approaches to design an efficient tidal array layout, and validating the outcome using numerical modelling techniques. A number of numerical experiments were conducted using a model of a real tidal channel, Hoy Sound, in Orkney to evaluate tidal array performance with different layout configurations. The paper proposes a new concept of Staggered Sub-Array SSA layout which combines the benefit of packed partial-fence and the staggered grid. It allows increasing the local blockage within the sub-array, while the gaps between the sub-arrays in a row can be increased to avoid array-choking or wake interaction with the downstream sub-arrays.**

*Keywords*—**Efficient tidal arrays, Tidal array layout, Tidal energy.**

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## I. Introduction

WITH the rapid increase in global warming, renewable energy has become an important option for electricity generation, as one of the most efficient and effective measures to slow down climate change [1]. Problems with energy supply are not limited only to environmental concerns, but also extend to the availability of conventional energy resources. In contrast to renewable energy resources, fossil fuel reserves are finite and decreasing rapidly. Based on the current rates of energy consumption, the last available fossil fuel reserve will run out in 114 years [2].

Oceans and seas cover more than 70% of the Earth. Among the many available renewable energy sources, tides are favoured for their substance (up to TeraWatts globally) and due to their predictability. While skill in the prediction of wind, wave and most other sources diminishes within days, tides are largely predictable for at least 100 years [2], [3].

The total power in global ocean tides is 3TW, but only part of this is accessible to tidal stream or tidal range development. Carbon Trust has estimated that 18 TWh/yr can be generated from the tidal stream energy in UK waters, which meets 5% of the UK’s current energy demand [4], [5]. With an efficient storage system, tidal energy could provide a base-load power that can help to displace conventional energy sources such as coal. Energy extracted from the tidal stream is expected to make a significant contribution to energy supply in many countries.

In recent years, there has been a significant advancement in the design of tidal energy devices. Nevertheless, the number of commercial-scale tidal energy development is still limited. The cost of energy produced by tidal turbines is still high. In order for the industry to compete with other energy sources (conventional and renewable), and become economically viable, more work needs to be done on the efficiency of tidal energy extraction.

Tidal turbines and arrays have been designed starting from the experiences of wind energy, but considerations specific to tidal stream arrays arise from the nature of tidal sites and the interactions of tidal turbines with each other and with the confined space. Considerations partly

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relate to flow characteristics and optimising power [6], but often also depend on other uses of the shared space.

This work focuses on investigating the various factors that affect the power extraction by an array of horizontal axis tidal turbines, exploring the various approaches to design an efficient tidal array layout, and validating the outcome using numerical modelling techniques.

## II. Interactions between tidal turbine wakes

It is relatively straightforward to place a single tidal stream turbine in the best flow, though even a single turbine will alter the flow. As the number of turbines in an array increases, design of an efficient array and tuning of individual turbines becomes progressively more complicated. Broadly speaking, interactions related to the optimization problem can be subdivided into overall channel dynamics, confinement effects, and wake interactions. We start by considering the effect of a single turbine and wake on downstream turbines.

In common with wind turbines, a wake will develop downstream of a tidal turbine, but the characteristics of this wake will be considerably different to the wake generated by wind turbines, mainly due to the vertically constrained nature of the tidal flow [7]. The developed wake is strong and anisotropic, and it causes a reduction in the flow velocity within the wake region. This reduction will extend to a certain distance beyond the tidal turbine, which would have an impact on other turbines located downstream in a tidal array [8].

Various theoretical and experimental studies [7]–[11] have been conducted into the effects of turbine wakes on power extraction and the interactions between tidal turbines. Chen et al. [8] suggested that RANS models can well simulate turbulence intensity and far wake velocity, but could underestimate the turbulence intensity in the vicinity of the turbine, especially if the turbine is represented by actuator disc. Nevertheless, the outcome of the experimental studies is reasonably in agreement with the results from the theoretical studies. It suggests that the developed wake behind the tidal turbine will cause an immediate reduction in the flow velocity downstream the turbine. In the horizontal plane, the developed wake will have a symmetric profile, but that could change to asymmetric profile depends on the surroundings and the location of the turbine. The presence of the turbine structure could have an obvious impact on the wake profile [8]. The vertical profile of the wake will vary between symmetric and asymmetric depends on the position of the turbine in the water column, i.e. seabed mounted, submerged or floating turbines. However, at 4D downstream (4D signifies a separation of 4 times the turbine diameter of the centre of the turbine, here and in what follows), it will become symmetric regardless of the turbine position [10].

Stallard et al [10], [11] conducted experimental studies using three bladed rotor equivalent to a turbine with a thrust coefficient $C_t$ = 0.87 and a tip speed ratio of approximately 4.5. The experiments were conducted in a constant flow condition with a mean turbulence intensity of about 10%. They observed that mean axial velocity slowed by approximately 80% - 40% over the range 1.5D to 4D downstream the tidal turbine. The mean velocity recovers gradually, with a deficit of approximately 20% at 10D and 10%-15% at 20D downstream the tidal turbine [10], [11]. Several factors can affect the wake recovery rate, including the thrust coefficient, $C_t$, Tip Speed Ratio, TSR, ambient turbulence intensity and the blockage ratio (see next section). Using a different $C_t$, TSR=3.53 and blockage ratio of 16.4%, Chen et al [8] observed a higher recovery rate under inflow condition with an ambient turbulence intensity of 2%; 20% velocity deficit at 5.5D and 11.1% deficit at 10D downstream the turbine.

The wake shape, width and length are also influenced by the ambient turbulence intensity. In flow with a higher turbulence intensity, the wake area is larger and more diffuse than that with a lower one [8]. In their experiment, Stallard et al [10] found that the wake width will expand laterally in cone-shaped profile, from 1D to 1.5D at 2D and to 2D at 4D downstream the tidal turbine. If the lateral spacing (i.e. cross-stream spacing) between the tidal turbines in an array is 2D or less, then the wake from those turbines would be expected to interact at some point between 1D – 4D downstream the turbine. The velocity deficit mid-distance between adjacent wakes is approximately 10%, which means placing a tidal turbine there will lead to an immediate loss in the stream velocity available for the turbine by 10%. At 4D downstream, the deficit mid-distance between turbines is nearly 30% [10]. Although the wakes from adjacent turbines with lateral spacing less than 2D will merge, individual wakes will still be identifiable behind the turbine at 12D downstream, with nearly constant velocity deficit and turbulence intensity (1-2% greater than the ambient turbulence) over the width of the wakes beyond 8D [10], [11].

A lateral spacing between turbines more than 3D would have minimal impact on the velocity in between the turbines. On the other hand, lab experiments [7], [10], [11] show that immediately downstream the turbine, the bypass flow around the turbine has a greater velocity than the ambient flow. Therefore, optimal lateral spacing can increase the kinetic energy in the flow passing between the tidal turbines.

## III. Confinement and Blockage

Over the past few years, significant advances have been made on understanding the interaction between the tidal stream turbines and the flow in tidal channels. The constraints exerted on the flow by the confines of the channel and the presence of the tidal turbines impose higher power yield limits than the Lanchester-Betz limit, often termed as the “confinement” or “blockage” effect [9], [12], [13]. The yield from each tidal turbine is influenced by the finite cross-section of a channel and the fraction of that cross-section occupied by turbines (the global blockage ratio). Typically, maximum power yield is associated with a finite blockage.

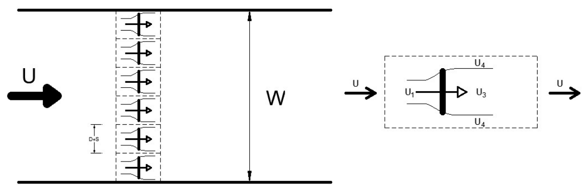


Fig. 1. Schematic diagram of the tidal fence and the flow around the turbines under the blockage effects.

U is the undisturbed flow velocity in the channel, $U_1$ is the flow speed through the turbine, $U_3$ is the flow speed downstream the turbine $U_3<U_1$, and $U_4$ is flow speed outside the wake area.

Several scientists have conducted lab experiments and numerical computations to investigate blockage effects on tidal energy extraction, starting with global blockage, but progressing to consideration of “local blockage” within arrays or sub-arrays. Firstly, Garrett & Cummins [9] showed analytically using a 1D quasi-inviscid model that the Lanchester-Betz limit is proportional to $(1 - \beta)^{-2}$, where β is the (global) blockage ratio. Consul et al [14] observed experimentally that increasing the blockage ratio leads to a substantial increase in the power coefficient Cp. Chen et al. [8] suggested that a blockage ratio over 10% can significantly improve the performance of a tidal turbine. The blockage constricts the bypass flow, which requires a greater acceleration of the flow around the tidal turbine than in unconfined flow. As a result of this confinement, the stream velocity through the turbine increases, which improves the power curve and shifts it to a higher tip speed ratio [14]. One of the most efficient methods to arrange the tidal turbines to benefits of the blockage effects is a tidal fence [9] (Fig. 1). The “fence blockage” or global blockage ratio, $\beta_G$) is defined in this case as:

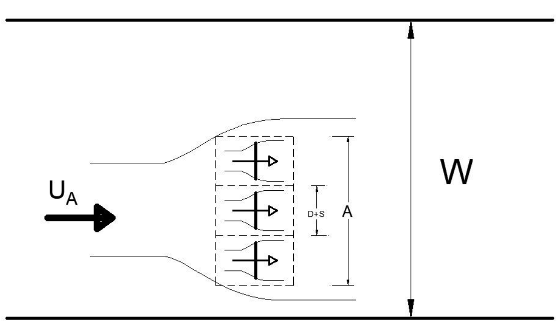


Fig. 2. Partial fence array covers a fraction of the channel width.

$U_A$ is the flow velocity immediately upstream the array, D is the rotor diameter, S is the cross-stream spacing between the turbines, and A is the partial-fence length equal to Nx(D+S), where N is the number of turbines.

$$\beta_G = \frac{total\ rotors\ area}{channel\ cross-sectional\ area} = \frac{N \times \frac{\pi D^2}{4}}{H \times W} \quad (1)$$

Where $\beta_G$ is the global blockage, D is the rotor diameter, N is the total number of the turbines, H is the channel depth, and W is the channel width.

A simple fence is often difficult to achieve or impractical for a number of reasons, such as navigation of vessels. Instead, turbines may be clustered in arrays or sub-arrays that leave one or more navigable passages. It is then useful to introduce the concept of “local blockage”, $\beta_L$ to describe the blockage within an array or sub-array. The efficiency of arrays can be improved by tuning the local blockage. A good example of this concept is the partial-fence, Fig. 2; here, the local blockage ratio can be defined as:

$$\beta_L = \frac{single\ rotor\ area}{local\ passage\ cross-sectional\ area} = \frac{\frac{\pi D^2}{4}}{H \times (D+S)} \quad (2)$$

Where $\beta_L$ is the local blockage ratio, D is the rotor diameter, H is the channel depth, and S is the cross-stream spacing between the turbines.

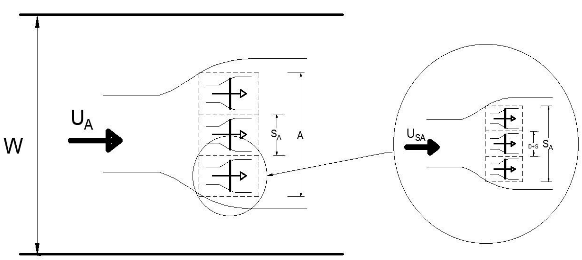


Fig. 3. Sub-array group within a tidal fence or partial-fence.

UA is the flow velocity immediately upstream the array, $U_{SA}$ is the flow speed through the sub-array, D is the rotor diameter, S is the cross-stream spacing between the turbines, $S_A$ is the sub-array length, A is the length of the fence equal to $JxS_A$; J is the number of sub-arrays.

Decreasing the lateral spacing between the turbines creates a local blockage that increases the local velocity, and consequently increases the available extractable power. However, there will be an optimal lateral spacing at which the performance of the turbine will be maximum, but any further decrease in the lateral spacing will block the flow through the array and cause array-scale choking, which will reduce the array efficiency dramatically [15]. Cooke et al. [16] have suggested that introducing a sub-array concept (Fig. 3) can increase the yield. The sub-array concept means that, in a tidal fence [9] or partial fence [15], the turbines can be re-arranged in sub-groups with high blockage ratios, while keeping wider spacing between the sub-groups to retain an "array blockage ratio", that limits choking. The sub-array blockage ratio can be defined as:

$$\beta_{SA} = \frac{sub-array\ rotors\ area}{sub-array\ cross-sectional\ area} = \frac{M \times \frac{\pi D^2}{4}}{H \times [M \times (D+S) + S_{SA}]} \tag{3}$$

Where $\beta_{SA}$ is the sub-array blockage ratio, D is the rotor diameter, M is the number of the turbines in sub-array, H is the water average depth at the sub-array location, S is the cross-stream spacing between the turbines, and $S_{SA}$ is the cross-stream spacing between the sub-arrays.

Besides the local blockage ratio, other factors such as tip speed ratio TSR and characteristics of the blade can strongly influence the blockage effects. For example, Kolekar & Banerjee [17] found that at TSR < 4 the blockage ratio has little influence on the turbine performance, while at higher TSR values, the turbine performance is improved by confinement.

While power coefficient Cp is an important indicator of the turbine/array kinetic efficiency, and a coefficient of the potential yield, the hydrodynamic efficiency η, which is the ratio of useful power available to the tidal turbines to the total power extracted from the flow, is also important, especially to limit the environmental impact. Low hydrodynamic efficiency is associated with high wake losses due to large flow speed differential between the wake and bypass flow. Thus, higher global blockage increases available power, but reduce hydrodynamic efficiency. However, a balance can be achieved between power and hydrodynamic efficiency [16]. Consul et al. [14] have observed that hydrodynamic efficiency can be greater for higher array blockage ratio, since this confinement increases stream velocity through the turbines, reducing the differential between core and bypass flow.

## IV. Efficient Tidal Array Layout

Efficient tidal stream capture is affected by a number of factors, but the key elements are efficient device design and efficient array layout. This paper focuses on the array layout configuration.

To design an optimal layout of tidal stream array, several studies have been undertaken to investigate the effects of array scale as well as configuration on the power output [15], [18]–[21]. In general, designing a tidal array layout involves two design stages: macro- and micro-design. Macro-design focuses on the location, size, general arrangement of the array and the total number of turbines. Whilst, micro-design deals with the position of each turbine within the array and the required tuning for each individual turbine [21]. One important factor is the interference of wakes with turbines, since the performance of tidal stream turbines is affected strongly by the ambient turbulence intensity. It can cause dramatic fluctuations in the turbine's performance [8].

Garrett & Cummins [9] suggested packing the width of the channel with a single row of turbines to create a tidal fence (Fig. 1), since this avoids wake effects on downstream rows, and enhances the containment effect. However, in most real-life cases, this is not possible due to the need to have clear navigational routes through the channel. Nishino & Willden [15] suggested creating a partial fence blocking part of the channel width instead of blocking the entire width (Fig. 2). The spacing between turbines can be reduced to maintain the total number of turbines and global blockage but increasing local blockage. An optimal local blockage balances containment and choking effects. Nishino & Willden [15] reported that an optimal local blockage raised the power coefficient from the Lanchester-Betz value of 16/27 (= 0.593) to 0.798. Cooke et al. [16] suggested splitting the tidal fence into sub-fences (Fig. 3) and achieved a further increase in coefficient from 0.798 to 0.865.

For example, Schluntz & Willden [22] have conducted a study using four different blockage ratios with four different rotors design (each rotor was designed for a specific blockage ratio). They observed that each rotor performed best for the blockage ratio that it was designed for. A rotor designed for a low blockage condition was improved in a high blockage condition, but could not match a rotor designed for high blockage condition. A rotor designed for a high blockage condition performed far more poorly in a low blockage condition than a rotor designed for that condition. Devices should be tuned for a specific site and specific layout design.

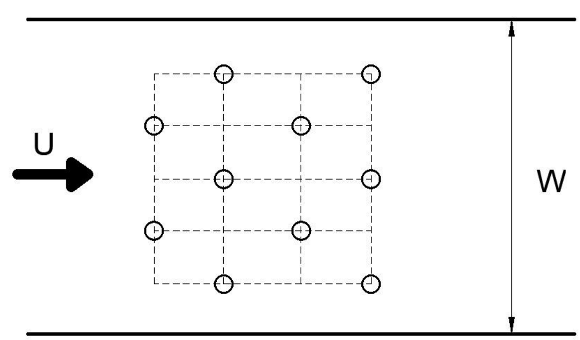


Fig. 4. Staggered array layout.

A tidal fence or partial fence does not always provide the best solution under real constraints. For example, if a narrow, but long channel area is permitted, an array with multiple rows may be suitable. That situation raises the question of downstream spacing. The wake recovery distance behind a tidal turbine is crucial [17]. In general, the flow recovers 80%-90% at 10D to 20D downstream the turbine (Section II). However, that much spacing may be impractical. Staggered grid arrays (Fig. 4) can be a partial solution. The flow through the gaps between the turbines in a row gains some acceleration due to the blockage effect. This will provide enhanced flow to the turbines in the next row [21]. On the other hand, reducing the lateral spacing to increase local blockage must be limited for a staggered array, since the wake downstream of a turbine expands conically and will interact with turbines in a downstream row if the lateral spacing in insufficient. Bai et al. [23] suggested that 2.5D lateral spacing is an appropriate value for the staggered grid layout A minimum of 4D downstream spacing should be appropriate (Section II).

Vennell et al. [21] suggested that there is a link between arranging the turbines in a packed row and a staggered grid. The staggered arrangement benefits from the enhanced flow through the gaps in the upstream row. This enhanced flow will be affected by the gap size which is optimised to increase the local blockage for the turbines in the upstream row. Considering the advantages and disadvantages of the different array layouts, we suggest arranging the turbines in a Staggered Sub-Array SSA formation (Fig. 5). The advantage of this layout that it combines the benefit of packed partial-fence and the staggered grid. The lateral spacing between the turbines in the sub-arrays can be reduced to less than 2D to increase local blockage (the optimal value for the lateral spacing varies depends on the site conditions and other factors as discussed previously), while the gaps between the sub-arrays in a row can be increased to avoid array-choking or wake interaction with the downstream sub-arrays.

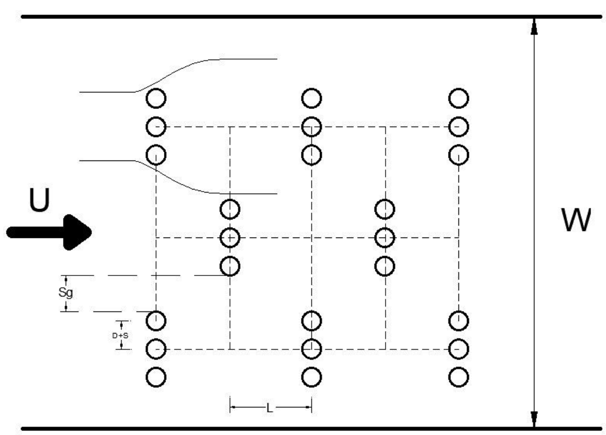


Fig. 5. Staggered Sub-Array SSA formation covers friction of the channel width.

Finally, we consider the size and position of a turbine within the water column. Kolekar & Banerjee [17] observed that the vertical position of the turbine and the proximity to the free surface add more complexity to the flow structure and affect the turbine efficiency. They have investigated the effect of boundary proximity on tidal turbines performance. Interestingly, they found that placing the turbine away from the channel bottom improves the turbine performance. This can be explained due to the restriction applied by the channel bottom on the wake expansion, which results in reducing the turbine performance. On the other hand, placing the turbine too close to the surface results in significant free surface deformation behind the turbine, which interacts with the wake and reduces the turbine performance. As a result of their study, they suggested that the optimal vertical position for the turbine should be within 1R above the channel bottom 0.5R below the sea surface (the distance is measured from the channel bottom or the sea surface to the blade tip), and the optimal depth for the deployment site should be 3.5R, where R is the rotor radius.

## V. NUMERICAL SIMULATIONS OF TIDAL ARRAYS

Various lab experiments and numerical methods such as CFD, BEM and RANS models [7], [10], [11], [14], [17], [22]–[24] have been used to study the interaction between tidal turbines and the tidal flow, and to understand the relationship between individual turbines within a tidal array and the power extraction efficiency. However, most of these studies consider idealised cases that cannot easily be translated to unsteady and non-uniform flow through a real channel [25].

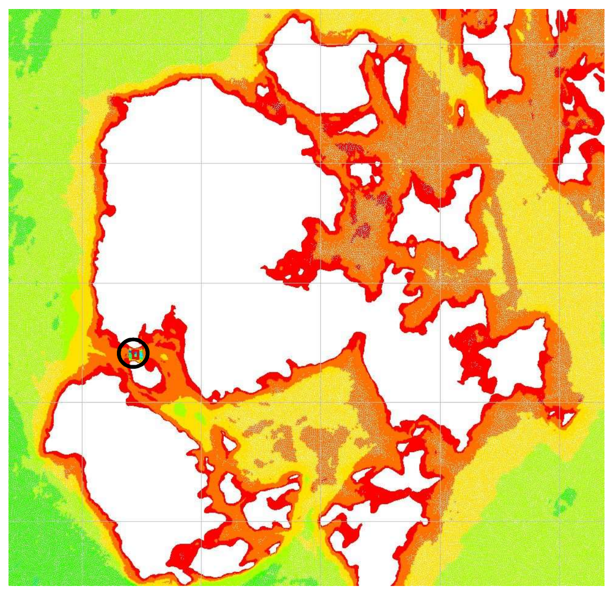

Fig. 6. Orkney Islands: Hoy Sound is marked with a black circle.

In this study, a number of layout configurations will be assessed numerically in Hoy Sound, Orkney, Scotland. The channel has a complex geometry, including the bathymetry deepening from 4m to 20m in a small fraction

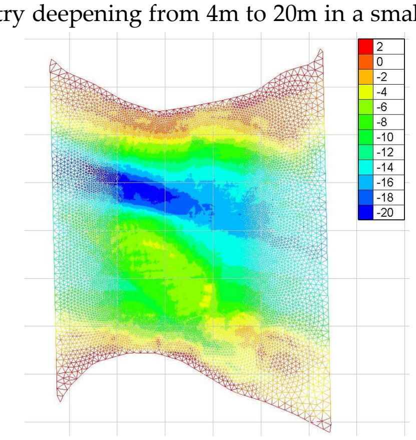


Fig. 7. Hoy Sound bathymetry.

of the width (Fig. 6 & Fig. 7). A potential tidal array development at Hoy Sound will be constrained mainly by water depth, the location of high currents and navigational routes. This makes it a good site to test the efficiency of various array layouts in realistic conditions.

### A. *3D model set-up*

To assess the energy extraction efficiency of a number of tidal array configurations, and to examine the effects of each configuration on the flow through Hoy Sound, a three-dimensional hydrodynamic model was built using TELEMAC-3D module of the TELEMAC-MASCARET modelling system. More details about TELEMAC-3D can be found in [26]. The boundary conditions were obtained from the European Shelf tidal model TPXO7.2 ES. The model domain covers a wider area around Hoy Sound to allow for a better coupling with TPXO7.2 ES (Fig. 8). To better represent the tidal flow and capture the turbines wake without increasing the computational cost, the model was constructed with four different resolution scales. The average resolution of the wider model is 150m, then the resolution is increased gradually to 30m around Hoy Sound and 5m for the middle of the channel. The resolution of the farm area was increased to 1m (Fig. 9).

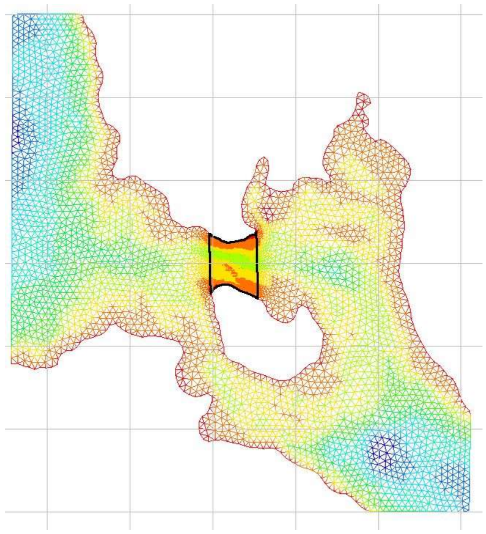

Fig. 8. Model domain.

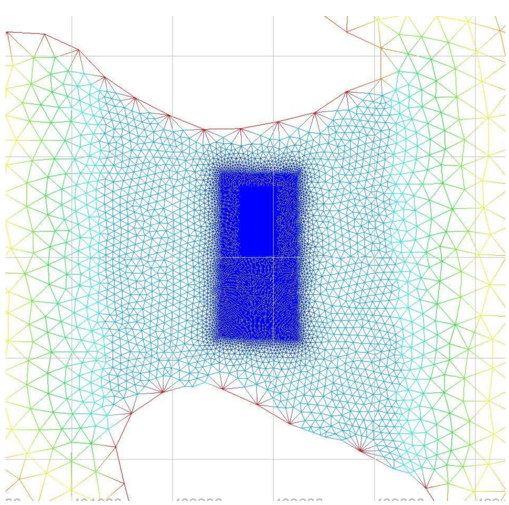

Fig. 9. Model resolution.

The farm location and size (marked in Fig. 10) were dictated by the availability of suitable depth and strong tidal flow. The farm size is 120m x 250m, and the mean water depth is 14m (min depth is 10.5m and max depth is 20m). The simulation was run for one tidal period of a semidiurnal tide which is approximately 12 hours and 25 minutes (i.e. one flood tide and one ebb tide).

Tidal turbines can be represented in the TELEMAC modelling system as a drag force. This function is implemented only in TELEMAC-2D module (details about using the drag force concept to model tidal turbines in TELEMAC-2D can be found in [27]). We developed a code to capture the effects of the drag force, which is exerted by the turbines on the flow, and apply it as a head loss in TELEMAC-3D.

To achieve the optimal vertical positioning for the turbines as suggested in Section IV, submerged turbines of 6m diameter rotor are deployed at 4.5m depth. A cut-in speed of 0.1 m/s is included, but not an upper cut-out. Also, the turbines are assumed to operate bi-directionally, which means the array will generate power from the flood tides as well as the ebb tides. A turbine power coefficient, $C_p$ = 35%, and a drag coefficient $C_d$ = 1.2 are applied (more details about $C_p$ and $C_d$ can be found in [27]).

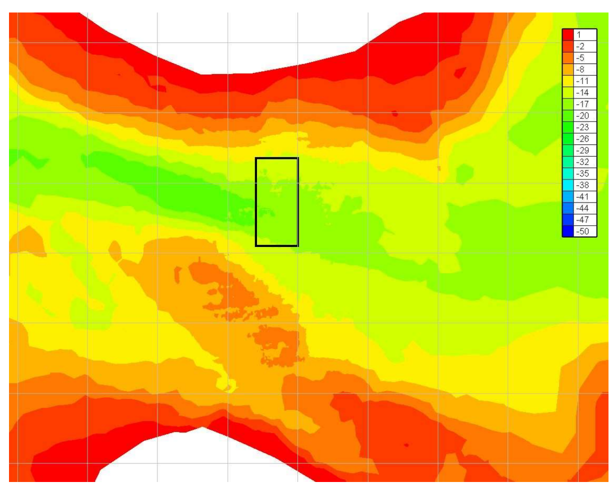


Fig. 10. Tidal farm boundaries.

### B. *Results*

Considering the site characteristics and size, an array of 26 turbines is modelled in five different layout configurations as illustrated in Fig. 11:

1) partial fence
2) sub-arrays fence
3) staggered formation
4) staggered sub-array (SSA) formation
5) funnel configuration

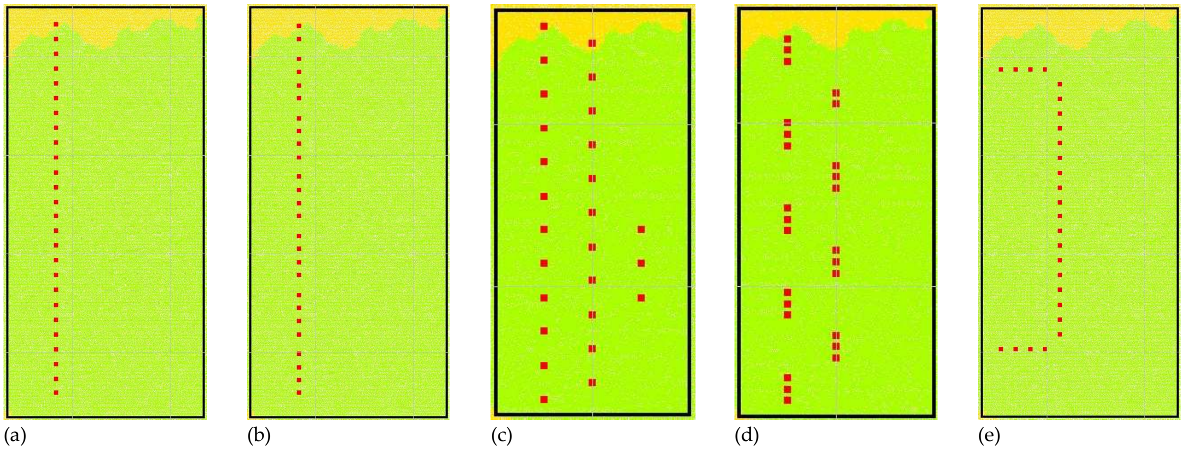


Fig. 11. Five scenarios of array layout configurations.

The size of the array is chosen base on the maximum number of turbines that can be packed, with a reasonable spacing, in a partial fence configuration occupying the entire width of the farm.

1) *Partial fence layout:*

The turbines in the partial fence were spaced at 0.5D tip-to-tip clearance, which achieves on average 12% global blockage ratio. Although this value does not reflect a high blockage ratio, the shape of the channel geometry (Fig. 7) and the spatial distribution of the flow (Fig. 12-a) amplify the effects of the blockage. On the other hand, the average local blockage in this arrangement is fairly high at 29%.

Fig. 12-b shows the impact of the array on the flow. Comparing it with the undisturbed flow Fig. 12-a, it shows how the array acts as a fence that blocks the flow and reduces the downstream velocity as a result of the power generation. The average power generated by the partial fence array is approximately 8.671MW as summarised in Table 1.

2) *Sub-arrays fence configuration:*

Rearranging the partial fence layout as suggested by Cooke et al. [16] by splitting the fence into multiple co-linear sub-fences, as shown in Fig. 11-b, will increase the local blockage ratio while maintaining the global blockage ratio. This should improve the efficiency of the array. The spacing between the turbines in each sub-fence is reduced from 0.5D to 0.33D, and the spacing between sub-fences is increased to 1D. Each sub-fence consists of 4 turbines, except the last group which consists of 2 turbines to maintain the same size of the array and approximately the same length of the fence.

The array efficiency is improved by 0.34% compared with the standard partial fence configuration (Table 1). Fig. 12-c shows how a small change in the fence arrangement can change the behaviour of the array and its impact on the flow.

3) *Staggered formation:*

Arranging the turbines in a staggered formation enables a reduction in the minimum spacing between multiple rows. The advantage of this configuration is apparent in sites where the width of the development site is relatively small compared with its length. In such scenarios, using the fence layout approach limits the size of the array comparing with the staggered formation.

In this study, the turbines were arranged as illustrated in Fig. 11-c. The lateral spacing is 2.5D, and the spacing between rows is 5D, as suggested in Section IV. In this case, the global and local blockage ratios are around 6% and 12% respectively. As expected, reducing the blockage ratio while maintaining the array size will reduce the array efficiency. The efficiency of the array dropped by approximately 10.89% relative to the partial fence layout (Table 1). It can be noticed from Fig. 12-d that the complexity of the channel geometry and the flow direction can affect the interaction between the turbines wakes. Perhaps arranging the turbines to be perpendicular to the flow direction could improve the array efficiency, but the channel geometry and the farm

TABLE 1 – POWER GENERATED BY EACH ARRAY CONFIGURATION

| | Array (avg) MW | Turbine (avg) MW | Global blockage ratio | Average local blockage ratio | Power extraction improvement |
|---|---|---|---|---|---|
| **Partial fence** | 8.671 | 0.333 | 12% | 29% | 0.00% |
| **Sub-array fence** | 8.700 | 0.335 | 12% | 32% | 0.34% |
| **Staggered** | 7.727 | 0.297 | 6% | 12% | -10.89% |
| **SSA** | 8.792 | 0.338 | 7% | 37% | 1.40% |
| **Funnel** | 7.079 | 0.272 | 8% | 29% | -18.36% |

boundaries will impose a limit on the maximum number of turbines that can be allocated in each row, which will reduce the efficiency of the array. Hence, this type of array configuration (spacings, direction, size ... etc) needs to be designed for each specific site in a way to achieve a balance between the various factors, which can result in the best power extraction efficiency for a staggered array configuration.

4) *Staggered sub-array (SSA) formation:*

A staggered sub-array configuration can combine the advantages of both the fence and staggered layout configurations. The turbines are arranged in multiple rows of multiple co-linear sub-fences, as shown in Fig. 11-d. The spacing between the turbines in each sub-fence is reduced to approximately 0.17D. To determine the optimal spacing between sub-fences, a number of values have been tested. It has been observed that the turbines wakes will interact with the downstream turbines when the spacing between sub-fences Sg (Fig. 5) is less than 1.5D. Therefore, for this study, the spacing between sub-fences is set at 1.5D. Each sub-fence consists of 3 turbines, except the last group of the first row which consists of 2 turbines to maintain the same size of the array and approximately the same length of the fence. Similar to the staggered layout, the spacing between rows is set at 5D.

In this configuration, the global blockage decreases to approximately 7%, whilst the local blockage increases to 37%. The array efficiency is improved by 1.40% relative to standard partial fence configuration (Table 1). Thus, a high array efficiency is achieved at a low global blockage. Fig. 12-e shows how the gaps between the sub-arrays create a secondary confinement, or funnel effect, that directs the enhanced flow towards the sub-fences in the next row.

5) *Funnel configuration:*

The funnel configuration is a tidal fence layout with a few turbines arranged in the same direction of the flow at both ends on the fence to create a shape of a funnel (Fig. 11-e). The purpose of having those turbines at the sides of the fence is to direct the flow towards the fence and impede escape to the sides. To do so, a higher number of turbines is required to create the same fence size. Although this could improve the efficiency of the array, it will increase the development cost due to the extra turbines. In this study, the size of the array is maintained for all the scenarios, thus a number of turbines will be removed from the fence formation and relocated to the sides of the fence to create the funnel formation. As a result, the global blockage ratio will decrease to 8%, but the local blockage will remain at 29%.

The bathymetry of Hoy Sound creates a natural funnel effect that directs the flow towards the farm location. Arranging the turbines in a funnel shape does not provide any extra benefit. In fact, it reduces the efficiency of the array by 18.36% compared with the standard fence layout. This significant reduction in the array efficiency is mainly due to two reasons: reducing the number of turbines in the fence and the poor performance of the turbines on both sides of the fence, which can be noticed clearly in Fig. 12-f. Further investigation is required to explore other methods of creating the funnel effect.

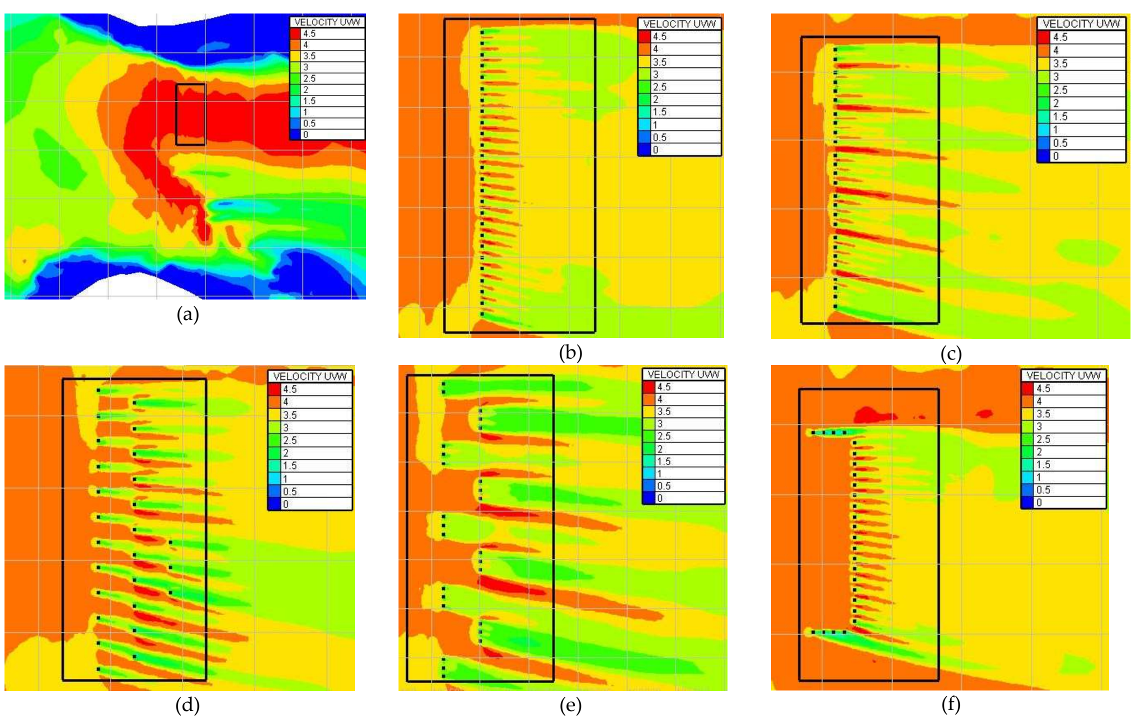


Fig. 12. Numerical simulation results.

In general, the numerical investigation agrees with the literature that local blockage is more important and has more influence on the efficiency of the turbines than the global blockage, especially when the geometry of the site creates a natural funnelling of flow. The fence and sub-array fence provide the highest maximum power generated at the peak velocity, while the SSA formation provides the best array efficiency and the highest average power generated during the simulation period.

Though the efficiency improvement by SSA is relatively small, however, the benefits of SSA formation may be more noticeable for commercial-scale tidal arrays.

### C. *Numerical optimisation*

It is relatively simple to design formations and spacings in a very simple channel with ideal flow conditions, compared to real channels. Further complexity is added when considering external constraints such as navigational routes, subsea cable routing etc. Therefore, an analytical solution is unlikely and. the optimisation problem is primarily numerical. Nevertheless, an accumulated knowledge of different formations and spacings can provide expertise for an initial layout design. Starting the search from a favourable point should reduce the computational cost. The array optimisation can proceed by a number of methods, including gradient-free and gradient-based algorithms, such as the Genetic Algorithm GA [28], the Adjoint approach [29], [30] and many others. In-depth review of those methods is outwith the topic of this paper. However, to the extent of our knowledge, all those methods deal with the problem in two-dimensional space only, and further work is required to consider all factors that influence the performance of tidal stream arrays.

## VI. CONCLUSION

This paper presents numerical investigations of the efficiency of various configurations of tidal arrays layouts. There are various factors that affect the efficiency of a tidal stream array, such as the characteristics of the site, the interaction of the turbine wakes and the blockage effect.

There is a strong relationship between the blockage ratio and the power extraction efficiency. The blockage impedes the bypass flow since it must accelerate through a constriction. As a result, the stream velocity through the turbine increases, which improves the power extraction efficiency. The efficiency improvement is described as proportional to $(1 - \beta)^{-2}$, where $\beta$ is the blockage ratio.

Increasing the global blockage is important to enhance the flow velocity through the array as a whole. However, the local blockage has a more significant influence on improving the power extraction efficiency than the global blockage. Hence, reducing the spacing between the individual turbines is crucial to achieve higher power coefficient. On the other hand, small gaps may lead to array choking. Arranging the turbines in multiple co-linear sub-fences can allow a higher local blockage, and consequently increase in the power coefficient, by reducing array choking.

Sometimes, due to various constraints, creating a tidal fence or partial fence does not provide the most efficient power extraction solution (e.g. the width of the available area for the array is relatively small, while the length of the area is sufficient for reasonably spaced multiple rows). Therefore, this study proposes a new concept of a Staggered Sub-Array SSA layout that combines the benefit of a packed partial-fence and the staggered grid. It enables high local blockage within the sub-array, while the gaps between the sub-arrays avoid array-choking or wake interaction with the downstream sub-arrays. The numerical simulation results suggest that arranging the turbines in a staggered sub-fences configuration of 3 turbines per sub-fence, with a minimum spacing of 1.5D between the sub-fences in the row, and 5D between the rows can achieve a higher power extraction efficiency than other array configurations. The spacing between the turbines in each sub-fence can be reduced to 0.15D.

Other benefits of the SSA formation includes the ability to increase the size of the array by including more rows, reducing the maintenance downtime as each sub-fence can be scheduled for maintenance separately, and the ease of navigating around each sub-array. Arranging a tidal stream array in SSA configuration fits well with a number of existing submerged or floating tidal stream devices such as PLAT-O and PLAT-I [31] (PLAT-I consists of 4 turbines forming a sub-fence), which with some tuning can achieve the maximum possible local blockage and the optimal vertical position that results in the highest possible power coefficient.

Further investigation is still required to assess the full performance of SSA layouts under various arrangements and different conditions.

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