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A Study on the Tidal Energy Yield Capability according to the Yaw Angle in Jangjuk Strait

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장죽수도에서의 요각변화에 따른 조류에너지 생산량에 관한 연구

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Abstract : *The interest of researchers and governments in exploiting tidal energy resources is increasing. Jangjuk strait is a place with high tidal energy density potential and is therefore appropriate for the constructing of a tidal turbine farm. In this study, a numerical approach is presented to evaluate the current flow and power potential in Jangjuk strait with an ADCIRC model. Then, the tidal field characteristics are utilized as input parameters for tidal resource calculation with an in-house program. The 1 MW scale tidal energy converter devices are employed and arranged in 4 layouts to investigate the annual energy yield as well as flow deficit due to the wake effect at the surveyed area. The best-performed array generates an annual energy yield up to 12.96 GWh/year (without considering the wake effect); this value is reduced by 0.16 GWh/year when accounting for the energy loss caused by the flow deficit. Moreover, by altering the turbine yaw angle during the flood and ebb tides, the impacts of this factor on the energy extraction are analyzed. This indicates that the turbine array attains the maximum tidal power when the turbine yaw angle is at 346o and 164o (clockwise, to the North) for the spring and neap tide in turns.*

Key Words : *Tidal potential, Jangjuk Strait, Tidal turbine array, Energy yield, Yaw angle*

요 약 : 최근 점점 더 많은 연구자와 정부에서 해양에너지 자원 개발에 대한 관심이 고조되고 있다. 장죽수도는 조류에너지 밀도가 높아 조류 발전소를 건설하기에 적합한 잠재적 후보지 중 하나이다. 따라서 본 연구에서는 ADCIRC 모델을 이용하여 장죽수도의 조류자원의 잠재량을 평가하기 위한 수치적 접근방식을 제시하고, 내부 코드를 이용하여 조석 특성을 입력 매개변수로 활용하여 1 MW급 규모의 조류에너지 변환장치를 대상으로 4개의 레이아웃으로 배열하고 후류 효과로 인한 연간 에너지 생산량에 관한 수치해석을 수행하였다. 그 결과 효율이 가장 좋은 배치는 연간 최대 12.96 GWh/year의 에너지를 생성할 수 있으며, 이 값은 후류 효과로 인한 에너지 손실을 고려하면 연간 0.16 GWh씩 감소될 수 있음을 보였다. 또한, 창낙조 때 터빈 요 각도를 변경함으로써 이 요소가 에너지 추출에 미치는 영향을 분석하였으며, 터빈 배열은 터빈 요 각도가 346°와 164°(북쪽에서 시계 방향으로)일 때 대조기와 소조기에서 차례로 최대 조류 에너지를 얻을 수 있었다.

핵심용어 : 조류 잠재량, 장죽수도, 조류터빈 배치, 연간 생산량, 요각

1. Introduction

In our modern world, the demand for energy consumption has increasingly grown year by year, making a big challenge for energy sources since fossil fuel is becoming exhausted. A series of global issues such as climate change, global warming, and lacking energy impulse the attempt to reduce the use of fossil fuel and to invest more effort in new sources of renewable energy. Ocean-related sources including tidal energy, wave energy, and thermal energy provided a massive and perennial amount of power can be the feasible solutions for the thorny energy problem. Although there are still some weaknesses related to sediment

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accumulation and ecological change, it is undeniable that the advantages of the tidal energy are overwhelming the drawbacks. It is not only highly predictable relative to wind energy with higher rate of power absorbability (Esteban and Leary, 2012), more environmentally friendly due to fewer construction requirements for large-scale tidal turbines farmer but also less sensitive to the natural habitat of marine creatures.

The energy consumption of Korea is ranked the 8th largest amount in the world with 282 million tons of oil equivalent in 2016 (Korea Energy Agency, 2018). These statistics combined with the fact that Korea is a peninsula surround by sea by three sides and possess huge resources of tidal energy make them spend more progress on harvesting this potentially renewable source. To utilize the tidal resource, two important missions needed to be executed are to investigate the tidal current characteristics as well as the potentiality of tidal power at interested regions and to select the optimal configuration for tidal energy converters array which can maximize the power output of the energy projects. In recent years, several research applied different methods have been carried out to accomplish these above essential tasks. By using the experimental method, Byun (Byun et al., 2013) observed measured data at 264 stations to estimate the prospective tidal current energy resource of the south and west coast of Korea and categorized locations into six groups according to their annual power density. A study on the characteristics of tidal elevation and current in the Chusu Bay based on numerical modeling experiment was conducted (Jung et al., 2013). They found that in Chunsu Bay the size of the tidal residual currents was 1-7 cm/s in the northern part and 10-30 cm/s in the south with the highly complex distribution which largely depends on the geographic factors such as bathymetry and coastline. The numerical approach using tidal-related simulation software has also proved to be an alternative solution for tidal energy estimation. Ribal (Ribal et al., 2017) employed ADCIRC (Advanced Circulation) model and Green's function to perform an assessment of tidal energy around Buton Island, Indonesia. Meanwhile, Martin investigated the flow characteristic of the tidal energy converters farm with the three-dimensional OpenFOAM model (Martin and Tao, 2018). Nguyen optimized the tidal farm around Jangjuk-sudo by testing 3 layouts of 28 tidal turbines with different longitudinal and lateral spacings. The energy yield, as well as wake pattern for each layout, was well predicted by the numerical modeling method (Nguyen et al., 2016).

Jangjuk strait was famous for its relatively high depth (25-45 m), medium current speed and was estimated to possess an annual energy density from 6.9 to 8.8 MWh/m^2 (Byun et al., 2013; Ko et al., 2018). The interested area in our research is located between Jangjuk island and Jindo island which is remarked within the dark dot rectangular in Fig. 1. The tidal simulations are carried out in a region with the longitude between 126°04'00"E and 126°10'30"E and the latitude between 34°19'10"N to 34°22'30"N. In this paper, we present a numerical approach to analyze the tidal current flow at Jangjuk strait and then investigate the effect of tidal turbine arrangements and the turbine yaw angles on the energy yield capability. The former target is performed with a hydrodynamics model - ADCIRC which has been tested and intensively employed for tidal flow simulations in decade (Bacopoulos, 2006; Blain et al., 2002). While the influence of array layout and yaw angles are analyzed with the aid of a program relying on indispensable inputs including flow field data (tidal current's direction and magnitude, ambient turbulence intensity), turbines' characteristic, devices installation constraints, and model specifications. The annual energy yield of a tidal turbine array, as well as visualization of the wake effect due to devices mutual interactions, will be predicted. The flow speed during flood and ebb-tides obtained by the computational method will be compared with the gauged data at the real site provided by KHOA (Korea Hydrographic and Oceanographic Administration, 2010). After that, the energy yield and power loss are considered as key factors to determine the effects of turbines' arrangement and yaw angles on the extracted power of the tidal turbine farm.

Fig. 1. Region of interest in Jangjuk strait.

2. Methodology of numerical approach

2.1 Tidal flow field simulation with ADCIRC

2.1.1 ADCIRC model

In this study, the tidal elevation and the currents speed are simulated with a two-dimensional, depth-integrated, barotropic time-dependent longwave, hydrodynamic circulation model - ADCIRC. This model can be applied to computational domains encompassing the ocean, continental shelves, coastal seas, and small-scale estuarine systems. The model's formulation is in the form of the Generalized Wave Continuity Equation based on the shallow water equations, hence solves the continuity and the momentum equations (with advection, Coriolis, eddy viscosity, and surface stress terms included). ADCIRC utilizes the finite element method in either 2D or 3D depth-integrated form on a triangular unstructured grid with Cartesian or spherical coordinates.

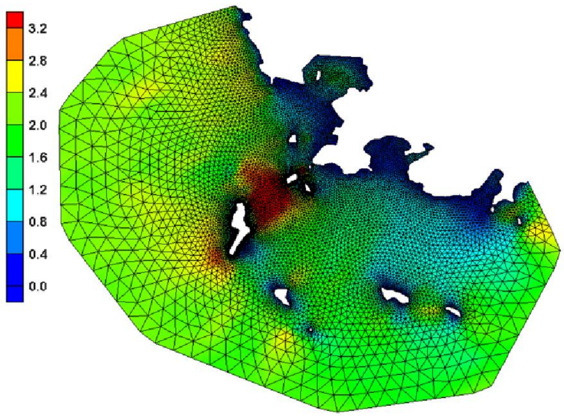


Fig. 2. Mesh formation for the region of interest.

2.1.2 Model set up

To prepare for simulations in ADCIRC, the data of coastlines, islands, and bathymetry must be imported to the model. When the geometrical data are available, the finite element grid can be generated with specific setting factors that are appropriate to domain size and computational accuracy. Fig. 2 displays the unstructured grid of the simulated area with depth integration. The mesh formation consists of 19,657 elements and 10,303 nodes in a calculation domain area of 85.8 km^2. The size of the minimum and the maximum grids are 20 m (for islands) and 500 m (for the open ocean), respectively. Meanwhile, the coastline nodes' spacing is about 50 m. In terms of boundary conditions for the ocean, Table 1 contains set up parameters employed in the model. Eight major tidal constituents are applied to Jangjuk strait based on the suggestions that they are fulfill the demand for calculating the tidal elevation and current speeds. The eight major tidal constituents are divided into two groups, the first one includes K_1, O_1, P_1, Q_1 for diurnal tides which are one cycle per day, the second group are K_2, M_2, N_2, S_2 for semidiurnal tides which are two cycles per day. Eight principal constituents and their periods are formed by the gravitational attraction between the earth and the moon and sun. The detail of the tidal constituents can be found in the study done by Militello (Militello and Zundel, 1999). The model runs in a period of 30 days from the 1st to 31st July 2019 with 1 day ram time and a time step of 5 seconds and the calculated results are obtained every 30 minutes.

Table 1. Set up parameters in ADCIRC

Parameters	Value
Model type	2D Depth-integrated
Lateral viscosity	4 L^2/T
Friction coefficient	0.002
Ramping time	1 day
Run time	30 days
Time step	5 seconds
Constituents	K_1, O_1, P_1, Q_1, K_2, M_2, N_2, S_2

2.2 Tidal potential energy assessment

2.2.1 Calculation process

An in-house software is employed to provide the comprehensive and detailed assessment of the potential energy captured by tidal arrays. This software allows us to design a tidal array to achieve the maximum energy production within the geometric and environmental constraints of the site. It uses mathematical models to predict the flow throughout and around a tidal turbine array. Fig. 3 describes the required inputs to calculate the energy yield for a tidal turbine array, classified into 3 main components, namely: flow field data, tidal energy converter (TEC) features, and selected specifications in model setup. The data of the flow field including tidal current's direction and intensity over the surveyed location can be attained with the hydrodynamics output of the ADCIRC model. Whereas the design parameters, as well as performance characteristics of the tidal turbines, are the results of the specific researches involved in tidal turbine's blade design and behavior testing (Hoang and Yang, 2014).

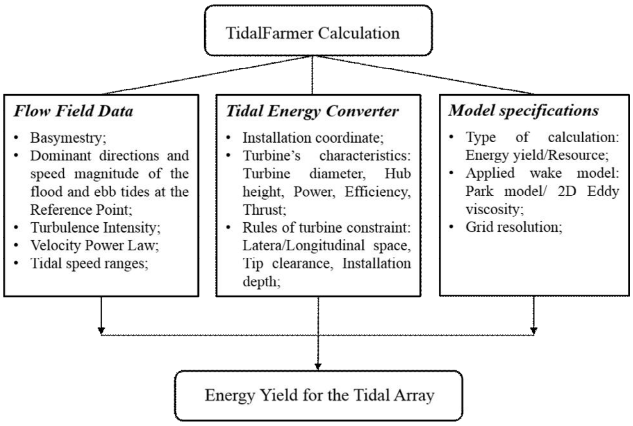


Fig. 3. Annual energy calculation for the tidal array.

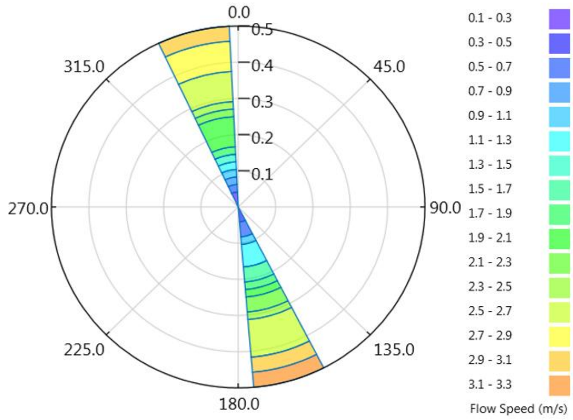


Fig. 4. Tidal dominant directions at the reference point.

Along with the provided information on the flow and tidal turbines, the program utilizes a proper wake model to determine the downstream wake deficit which considerably affects the energy absorbability of the downstream devices. Energy yield value, which is calculated by Equation 1, is a key output of the model, enabling the effect of wake losses and array efficiency to be evaluated for different array layouts.

$$E_{Array} = \sum_{k=1}^{N_{Dir}} \sum_{j=1}^{N_v} \sum_{i=1}^{N_t} P_{jk}^{i} \cdot f_{jk} \tag{1}$$

where E_{Array} is the gross energy output for the array, concerning the wake effect on the incident flow, P_{jk} and f_{jk} is the power output and the frequency of occurrence, N_t is the total number of devices in the array and i is the device index, N_v is the number of flow speeds (bin) for each flow direction and j is the flow speed index related to the speed bin, N_{Dir} is the total number of flow speed directions and k is the index for flow direction.

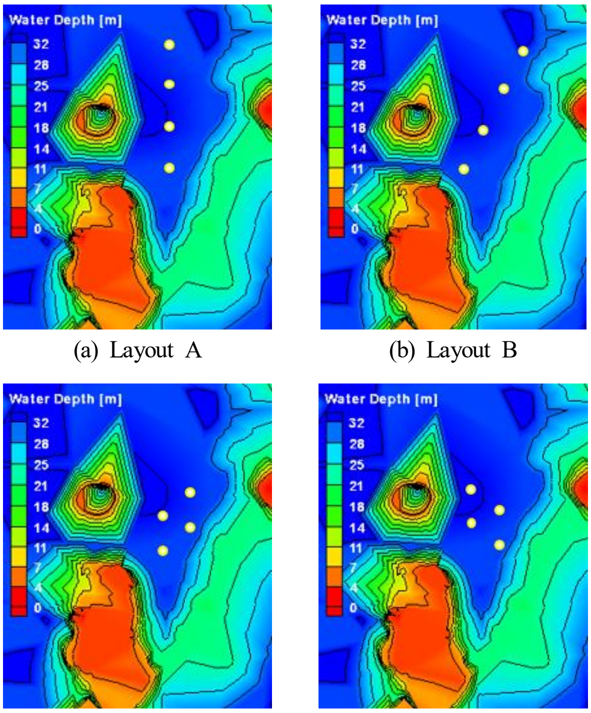
2.2.2 Initial inputs and set up parameters

In order to specify the flow resource in the hydrodynamic data and investigate the local potential energy yield, a series of initial conditions should be inputted, including the coordinate and depth of simulated area, long-term resource at a certain point, power law, and turbulence intensity profiles. The long-term resource is typically based on a harmonic model of the flow currents which is displayed in Fig. 4. It presents the principal directions and magnitude of the flood and ebb-tides at the long-term reference point (a point at the feasible turbines installation place). At the researched site, the dominant directions during the flood and ebb tides are 346° and 164° to the North in turn while the bin speeds range from 0.2 m/s to 3.2 m/s.

Besides, the parameters of turbines' characteristics and constraints for device installation also play essential rules in the energy yield evaluation. In this study, a model of 1 MW power scale tidal stream turbine is employed. The tidal turbines with a rotor diameter of 22 m, rated velocity of 2.33 m/s are deployed near Jangjuk strait, obeyed the regulations in Table 2. The constraints should be defined with the purpose to make sure that the deployment of turbines at any location is feasible. Otherwise, the violated turbine will be switched off, unable to be considered in calculating the total energy yield of an array. Fig. 5 shows the depth information of the expected installing area and 4 layouts of turbines' arrangement, namely layout A, B, C, and D. With the installation depth of around 30 m, four tidal turbines are arranged in 4 array configurations to investigate their extracted output power. Hence, it is able to analyze the impact of the wake deficit and turbines' position to find out the best layout should be applied to the surveyed region.

Table 2. Tidal turbine's set up parameters

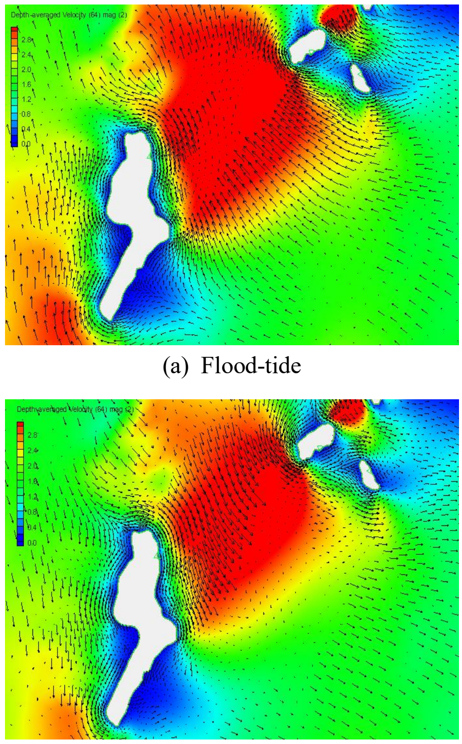
Parameters		Value	Unit
Turbine Characteristics	Rated power	1000	kW
	Rotor diameter	22	m
	Hub height	16	m
	Rated velocity	2.33	m/s
Installation Constraints	Minimum depth	20	m
	Maximum depth	40	m
	Tip clearance	5	m
	Slope	30	deg
	Lateral spacing	3	dia
	Longitudinal spacing	10	dia



(a) Layout A (b) Layout B

(c) Layout C (d) Layout D

Fig. 5. Sea depth and layouts for turbine installation.



(a) Flood-tide

(b) Ebb-tide

Fig. 6. Tidal currents distribution.

3. Results and Discussion

3.1 Demonstration of the tidal flow field

Fig. 6 illustrates the tidal current distribution around Jangjuk island during the flood and ebb-tides. As can be seen, due to a narrow channel between two islands the flow is accelerated in both tides, accounting for a maximum depth-averaged velocity of 3.2 m/s. Besides, the geographic features at this site make the flow considerably change its direction compared to the surrounding area as mentioned in Fig. 4. The high current speed gives rise to a high potential energy density and consequently a higher extracted power. It induces this place to become a feasible location for the construction of a tidal turbine farm.

The ADCIRC model's calculation is validated by a comparison between simulation results and measured data provided by KHOA at an observed point. The tidal gauge station is located at the coordinate 34°21'18"N, 126°4'44"E while the tidal simulations have been conducted for 1 month from 1st to 30th June 2019 as can be seen in Fig. 7. For each source of data, the results are recorded every 30 minutes. The maximum flow velocity of the observation data from KHOA is slightly higher than that of computed data with the ADCIRC model. Nevertheless, two lines show a good agreement in both speed magnitude as well as the tidal phase. This reveals the accuracy of the numerical model and ADCIRC outputs can be used as the initial conditions for energy yield calculation.

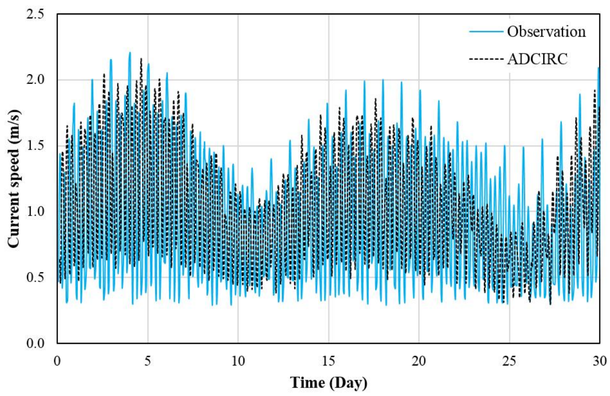
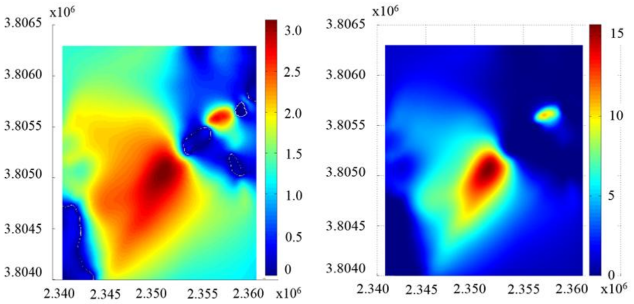


Fig. 7. Comparison of the current speed between numerical and measured data at the observation point.

3.2 Tidal turbine arrangement analysis



(a) RMC speed (m/s) (b) Energy density (kWh/m^2)

Fig. 8. Tidal resource at investigated area.

In the next step, the flow field information obtained from the ADCIRC model is used for resource calculation to investigate the available power across the site. The root-mean-cube flow speed and the energy density, which are two essential factors indicating the potential power, are depicted in Fig. 8. The root mean cube speed (V_{rmc}) is defined by Equation 2 while the energy density over a certain period time is estimated by Equation 3:

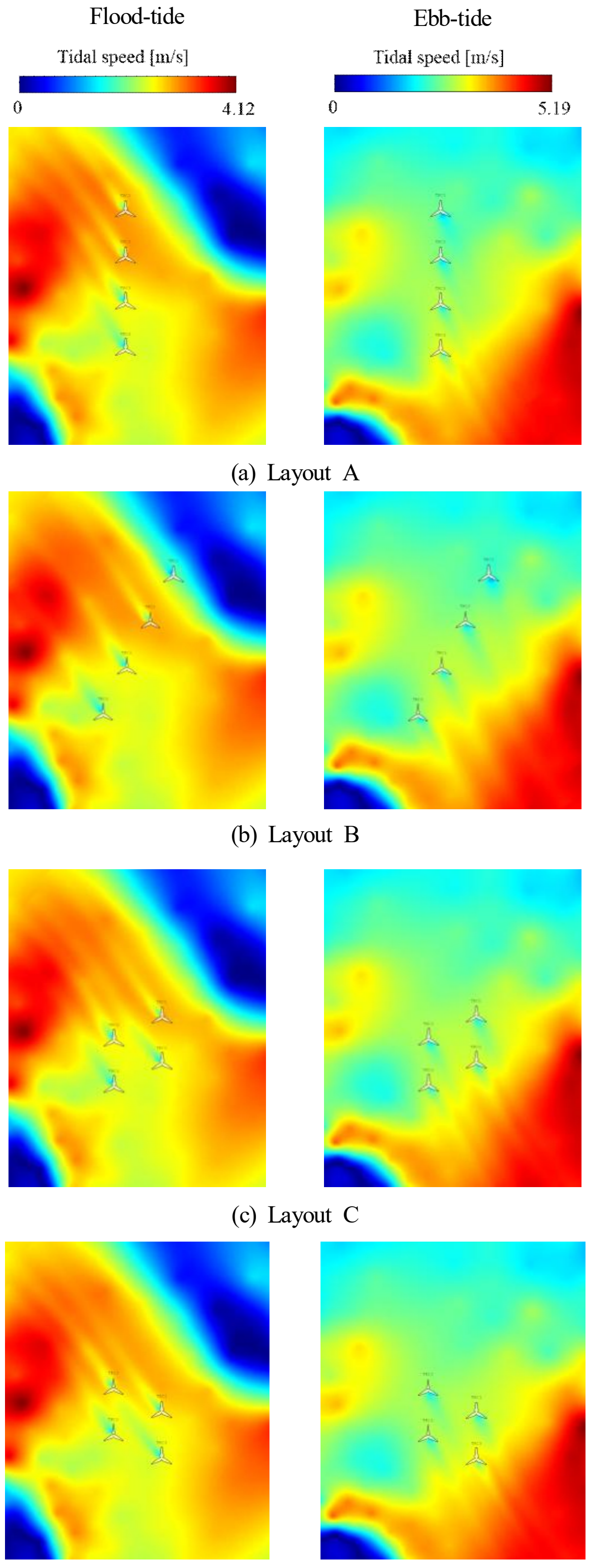
$$Vrmc = \sqrt[3]{\overline{V^3}} \tag{2}$$

$$E_d = \frac{1}{2}\int_0^T \rho V^3 dt \tag{3}$$

where V_{rmc} is the root mean cube speed (m/s); V is the flow velocity (m/s); T is the time of surveyed period (hour); E_d is the energy density (Wh/m^2).

Table 3. Energy loss due to wake effect

	Energy Loss [GWh/year]			
	Layout A	*Layout B*	*Layout C*	*Layout D*
TEC 1	0.0743	8.10^{-6}	0.0304	0.0178
TEC 2	0.1990	0.0011	0.0679	0.1091
TEC 3	0.1241	0.0000	0.0276	0.0198
TEC 4	0.0147	0.0000	0.0273	0.0554
Total loss	0.4120	0.0011	0.1532	0.2022
% loss	3.40	0.01	1.18	1.57



(a) Layout A

(b) Layout B

(c) Layout C

(d) Layout D

Fig. 9. Wake pattern illustration during flood and ebb-tides in 4 cases of turbines' arrangements.

A close relationship between Vrmc and Energy density is obvious in Fig. 8 since the higher RMC speed is, the higher energy density is observed. The maximum energy density at the narrow channel is around 15 kWh/m^2, being relatively good for tidal energy exploitation. In general, the numerical visualization of the tidal flow speed and tidal energyresource provides a quick effective method to evaluate the potential energy at the interested region. These useful functions facilitate the process of looking for the best location with high energy density for the construction of tidal turbine array, thus shorten the required time and progress compared to real site measurement.

Moreover, by conducting the energy yield calculation for different configurations of the turbine array, it is able to appreciate the impacts of wake effect on the captured energy each turbine. Fig. 9 illustrates the wake flow visualization of 4-turbine arrays arranged in 4 layouts in two directions of flood and ebb-tides. Theoretically, placing turbines at high flow velocity places results in more output power. Nevertheless, in reality, the turbines must be positioned in a manner that satisfies the installation constraints including maximum slope, minimum depth, minimum tip clearance, and lateral and longitudinal spacing. Fig. 10 shows the energy yield with and without the wake effect. The most significant feature is that layout C and layout D experience better performance than two others, both for gross energy and net energy. It may be caused by the fact that there are more turbines installed at higher power density region in layout C and layout D. As for the gross energy, layout C extracts the maximum value of 12.96 GWh/year while the minimum number belongs to layout B with 1.1 GWh/year less.

Nonetheless, due to a great loss brought about the wake effect of 3.4 % (presented in Table 3), the net energy captured by layout A is the smallest, comprising only 11.69 GWh/year. It reveals that turbines in layout A are the most impacted by the wake, especially device No. 2 with a remarkable loss of 0.199 GWh/year. In contrast, layout B is almost uninfluenced by the wake as the rate of loss is only 0.01 %. Concerning the power loss among turbines in an array, device No. 4 witnesses the least amount of energy deficit while device No. 2 suffers from the highest loss which means it is most vulnerable to the flow attenuation caused by other turbines in the array.

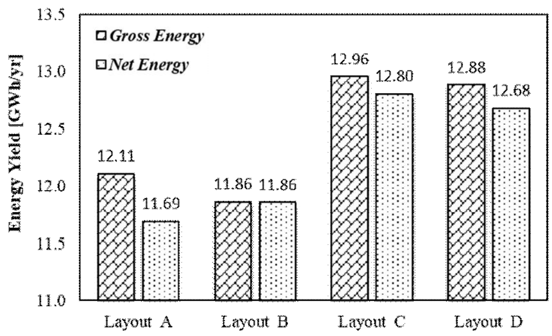


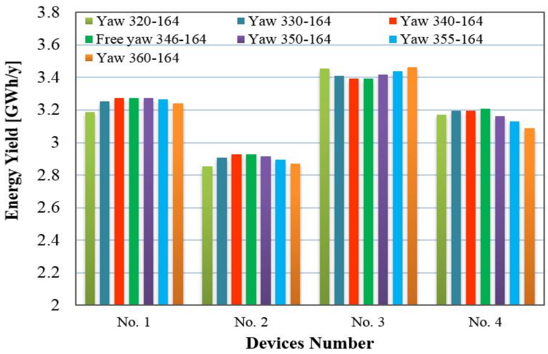
Fig. 10. Gross & Net energy yield for different layouts.

3.3 Impact of the yaw angle on the tidal energy absorbability

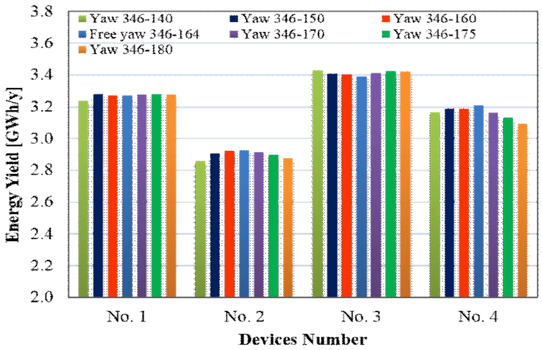
The angle between the turbine plane and the flow direction plays an important role in determining the volume of extracted power by dint of its effect on the incident angle to the blade. Therefore, the influence of the turbine yaw angle (defined as the angle between the North and turbine hub, clockwise) will be analyzed by evaluating the net energy yield at various yaw angles. Based on the results in section 3.2, layout C is selected to perform the investigation. For each case, the angle of turbine is changed either in flood-tide or ebb-tide. Fig. 11a and Fig. 11b express the energy yield each device when altering the yaw angle during flood and ebb-tides, respectively. A feature observed from the chart is that each turbine experiences individual trends and intensity of variation in output power. Device No. 4 seems most effected by yaw angle change whereas the impact on device No. 1 is negligible. In Fig. 12, the yaw angle of 346°-164° (flood-ebb) is the position at which the tidal array generates the highest power. At these angles, the turbines' plane is perpendicular to the current direction. It is obvious that the net yield energy is in inverse proportion to the energy loss. For instance, turbine arrays with yaw angle 320° and 360° (spring-tide) possess the biggest losses of 1.67 % and 1.6 % in turn, hence they produce the lowest power production of 12.66 GWh/year. A similar point occurs to the array when varying the yaw angle during the neap-tide. The obtained energy peaks at the angle of 164° and gradually decreases even if the angle goes up or down.

4. Conclusion

In this paper, the tidal current conditions at Jangjuk strait was simulated to analyze its flow field behavior as well as the potential tidal energy resource. The efficiency of the tidal turbine



(a) Yaw angles during flood-tide



(b) Yaw angles during ebb-tide

Fig. 11. Energy yield absorbed by individual TEC.

(a) Yaw angles during flood-tide

(b) Yaw angles during ebb-tide

Fig. 12. Array annual energy yield at various yaw angles.

arrangement and the influence of the yaw angle on energy yield are investigated to obtain some following points:

The area of interest possesses a number of favorable conditions including averaged-depth current speed of 3.2 m/s, sea depth around 30 m, showing high potential to build a small scale tidal turbine farm for harvesting tidal current energy.

The flow deficit and energy loss caused by the wake effect are visualized and presented. Among 4 layouts of turbine array, the stagger layout C performs the best with the net annual energy yield of 12.8 GWh/year while layout A generates the lowest output power.

The turbine yaw angle is one of the factors impacting on the amount of extracted energy. The energy production reaches the highest value at the yaw angle of 346° and 164° during flood-tide and ebb-tide where the turbine plane is perpendicular to the current.

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