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Flow characteristics of unit artificial reefs in 3-D placement models

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ABSTRACT

To quantitatively evaluate flow characteristics (wake and upwelling regions) of unit artificial reefs (ARs), three 3-D models such as Hexa, Rect, and Ryra were investigated. The element-based finite volume method was used for numerical flow analyses, by facilitating ANSYS-CFX software. From the analyses results, the following conclusions were made. First, each placement model has a different wake volume up to 58% variation, showing that Hexa is the most advantageous due to its size of 140m^3 while Rect has the largest volume of 1970m^3 in terms of upwelling volume. Second, considering the wake and upwelling distributions, Pyra has a unique characteristic showing that 77.04% of the wake volume concentrates on a sub-region, which is beneficial to demersal fish.

1. INTRODUCTION

Wake and upwelling regions around an artificial reef (AR) are believed to be important to marine lives because these regions contain a variety of organic, dead plankton, nutrient salt and accordingly attract more marine species such as fish (Oh *et al.* 2011). For example, fish (predators) have a strong chance to get preys which stay the wake and upwelling regions. Although the attraction and production debate has not been solved yet, there are scientific clues supporting the production, attraction, or both, which are depend on various parameters such as the age, size, gender, and other ecological factors of fish (Bortone 2011, Grossman *et al*. 1997, Pickering and Whitmarsh 1997, Pitcher and Seaman 2000). Thus, many marine ecologists support the fact that the primary producers around ARs are dominant in the wake and upwelling regions and accordingly the food chain is formed in the areas (Oh 2004). In a sense, wake and upwelling regions are the critical factors in estimating the fishing grounds, which are often facilitated by ARs.

A small sized AR unit (or module) is usually installed as a unit (or set), the so-called a unit artificial reef, as shown in Fig. 1. In other words, a unit artificial reef (unit-

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AR) consists of several artificial reefs to maximize their functions. Then, these units can be combined together and called an artificial reef group (AR-group), as also shown in Fig. 1, for making easy management and maximizing the function of ARs. The size of each unit or group is highly regional dependent. For example, in South Korea, ARs are installed as a unit artificial reef of 800m^3. Obviously, the shape of each unit or group is also dependent on a special use of ARs. Hence, there exist several placement models.

In South Korea, some studies proposed eight different placement models. Among them, a concentrated type is only three-dimensional placement model. However, the model is a conceptual model and the detailed quantification is not exactly possible because the ARs for the model are installed in a target area using free fall (downward movement under the gravitational force only). Accordingly, the units established by the free fall have all different three-dimensional shapes and quantifying their fishing grounds is not easy. An interesting fact is that the fishing ground can be regarded as an engineering parameter (or standard). However, it is not easy to quantitatively define the physical meaning of the fishing ground. No one proposes a measure for the ground.

The preliminary studies about ARs in South Korea can be classified into: upwelling effect of an AR (Jeon *et al*. 2007), upwelling phenomenon caused by an artificial seamount (Kim *et al*. 2009b), upwelling due to a super AR (Kim and Pyun 2005), fish school abundance around ARs (Hwang *et al*. 2004), material exchange rate and hydraulic characteristics of an AR (Oh 2004), These studies are all concentrated on an artificial reef unit. Regarding unit-AR, Kim *et al*. (2009a) proposed a facility volume concept, which is useful to estimate the effectiveness of a unit-AR. They suggested the formula for the facility volume k (indicating the efficient usable volume ratio, which is 0.753) and correlation between the coefficient k and year (Yr) of deployment (k = 0.0023Yr + 0.725). However, research on the shape and flow characteristic of unit-AR is insufficient.

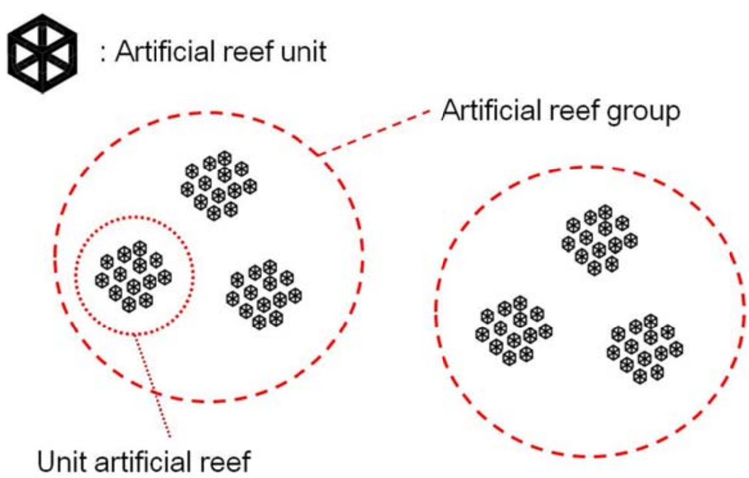

Fig. 1 Configuration of unit artificial reefs and artificial reef groups

In the study, the flow characteristics (wake region and upwelling region) of three-dimensional placements of unit ARs relevant to the minimum size 800m^3 are quantitatively evaluated. For the purpose, the shapes of the unit-ARs were classified into three types - hexahedron, rectangular, and pyramid. The hexahedron placement model is distribution of ARs from the bottom layer to the upper layer with a uniform shape. The rectangular placement model is similar to the hexahedron but it is a long-form like a mountain chain. The pyramid placement model is distribution of ARs by maximizing the number of ARs at the bottom layer and minimizing the number at the upper layer. Second, numerical flow analyses were carried out using the element-based finite volume method (FVM) to obtain flow characteristics around the units. Third, the flow characteristics were quantified through the finite volume of a particular flow component. Finally, the wake and upwelling flow volumes were estimated to construct the wake and upwelling regions. It should be noted here that the target AR unit is a cube type because it is one of popular ARs used in South Korea.

2. MATERIALS AND METHODS

There are 72 general ARs in Korea. The number has been increased; the number will increase in the near future through the approval by the central artificial reef committee. Among these, a cube type reef (hereafter AR1), as shown in Fig. 2, has been popular because of its simpler shape, better workability, and inexpensive cost. AR1 is made from concrete and reinforcing bars with its dimension of 2 × 2 × 2m^3. Hence, its apparent volume is 8m^3 and weight is 3.4-ton. The total installed amount of AR1 was estimated 139,413ha (69% of all ARs), from 1971 to 2013, in South Korea. AR1 has been installed on the Korea's coast to enhance fish spawning, growth, and feeding. When installing a unit-AR, AR1 is suitable for fisheries and protection of migratory fish because it has a high porosity.

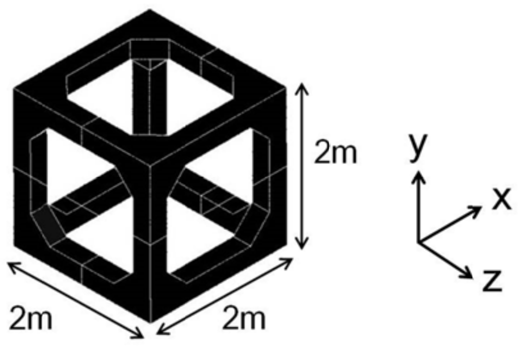

Fig. 2 AR1 (cube type AR) used in the study

A unit-AR should be installed with usable volume of 800m^3 and more (Kim *et al.* 2009a). As noted, AR1 has the apparent volume of 8m^3, and accordingly at least 100 of AR1 should be installed as a unit-AR. Keep the size and number, this study proposes three placement models, as shown in Fig. 3. They are hexahedron (Hexa), rectangular

(Rect) and pyramid (Pyra), respectively. Fig. 3a shows the hexahedron placement model, which is arranged by 5 × 5 × 4. Fig. 3b shows the rectangular placement model having the arrangement of 10 × 2 × 5. Fig. 3c shows the pyramid placement model, arranged by 7 × 7, 5 × 5, 4 × 4, 3 × 3, and 1 × 1 on each layer.

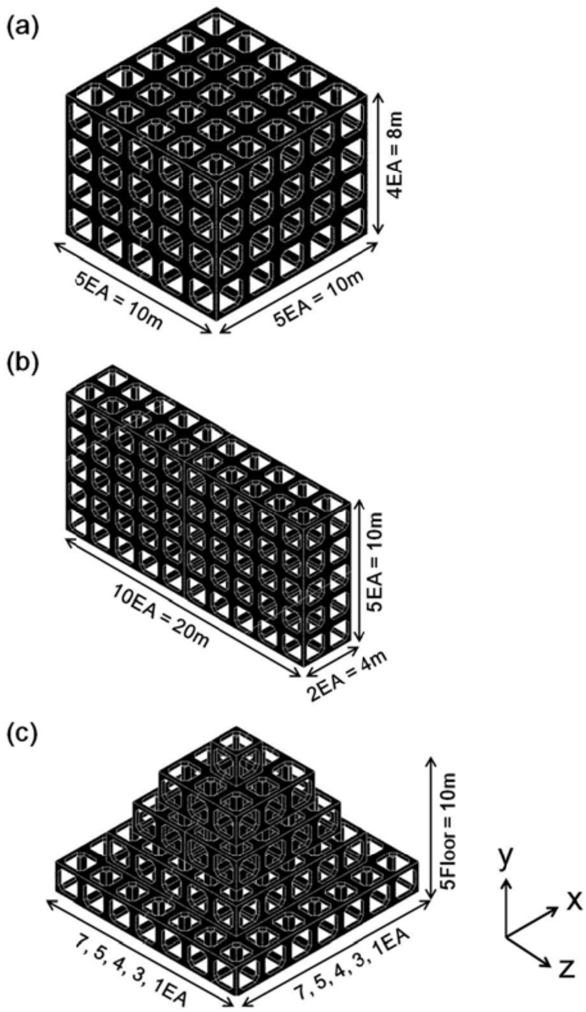

Fig. 3 Three-dimensional placement of unit-ARs (a) Hexa (hexahedron), (b) Rect (rectangular), and (c) Pyra (pyramid)

Momentum, heat and material transfer can be formulated with the Navier-Stokes equation. The equation cannot be analytically solved. Thus, computational fluid dynamics (CFD) should be used to get an approximate solution. In the study, ANSYS-CFX was used to facilitate the element-based finite volume method (FVM). This numerical scheme has been efficient in various engineering applications such as airplanes, automobiles, subsea pipelines, and artificial reefs (Kim *et al*. 2014a, Kim *et al.* 2014b, Woo and Na 2014, Woo *et al*. 2015). This method represents partial differential equations as algebraic equations; hence, values are evaluated at discrete places on a meshed geometry, similar to the finite difference method or finite element method. Here, 'finite volume' refers to the small control volume surrounding each nodal point on a mesh.

ANSYS-CFX utilizes the element-based finite volume method, which divides the region of interest into sub-regions and discretizes the governing equations to solve them iteratively over each sub-region. Thus, the value of each variable at nodal points over the domain is approximately achieved. The fundamental concepts and detailed software descriptions can be found in the literatures (ANSYS Inc. 2009).

In general, flow analysis, using CFD or its software package, is carried out by constructing a flow domain (Woo *et al*. 2014). The shape and size of the domain are problem-dependent. However, in general, a parallepiped is used for the domain, as shown in Fig. 4. In the figure, the size is characterized by the width *B*, length *L*, and height *H*. Also, the target AR located at the center of the bottom face. In the study, the dimensions were selected as Table 1, by considering the size of AR1 and each unit.

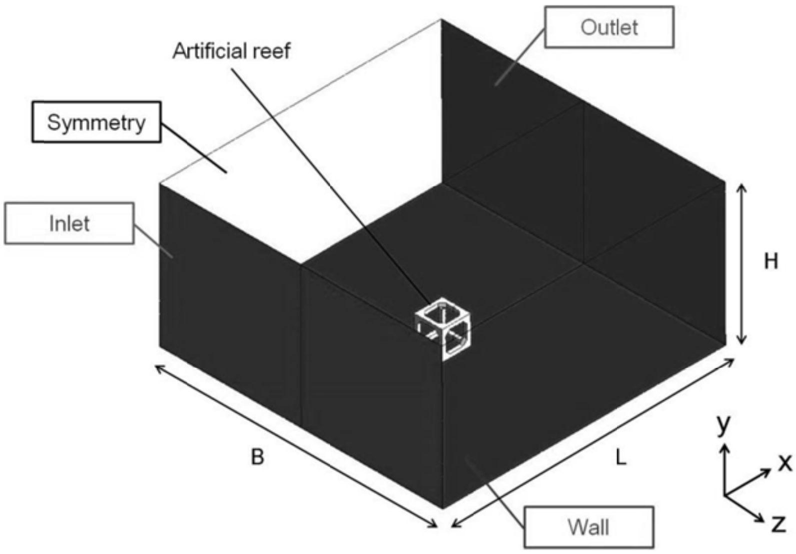

Fig. 4 Boundary conditions of flow field

Table 1 Dimensions of each flow field

	B (m)	L (m)	H (m)
AR1	20	20	10
Hexa unit-AR	40	60	15
Rect unit-AR	40	50	15
Pyra unit-AR	40	50	15

As shown in Fig. 4, the inlet boundary provides a flow to the domain, and the outlet boundary absorbs the flow from the domain by assigning zero pressure. In addition, the bottom boundary condition is a no-slip wall, which means that the velocity is ‘0’ at the wall. However, depending on the way to calculate the velocity at the wall, the velocity at the bottom cannot be vanished. In the other hand, the conservative method uses the corresponding control volume including a node at the bottom, and it extracts the average velocity; hence, no-slip wall boundary condition may not assign zero velocity. In this study, the conservative method was used to investigate the bottom velocity profiles. In addition, in the modeling process, only half of each placement model was modelled to construct fine meshes and save a computational time. Through the numerical analyses, the following hypotheses were made. First, the water is incompressible, viscous, and Newtonian. Second, the water temperature is 25℃. Third, the turbulence model is k-ε model. Fourth, the design water velocity is 2m/s. Finally, the finite volume has the shape of cube with 8 nodes, and the maximum size of a grid is controlled by limiting the length of each side, up to 0.2m.

3. RESULTS

It is found that the wake volume of AR1 is 2.91m^3 (V_w). The average velocity of the wake volume is about –0.33m s^{-1}. Here, the negative sign indicates the opposite (recirculating) direction with respect to the main flow direction. The wake volume of AR1 is shown in Fig. 5. Consider the unit-ARs, the wake volumes of Hexa, Rect, and Pyra are 140.0, 119.7, and 88.4m^3, respectively, as shown in Figs. 6, 7, and 8. These are 48.1 (Hexa), 41.1 (Rect), and 30.4 (Pyra) times the corresponding AR volume (V_w). Thus, Hexa is a better choice in terms of the wake volume size. The average recirculating flow velocity is –0.21 (Hexa), –0.41 (Rect), or –0.23m s^{-1} (Pyra). Table 2 shows the mean flow velocities and wake volumes of AR1 and each unit-AR.

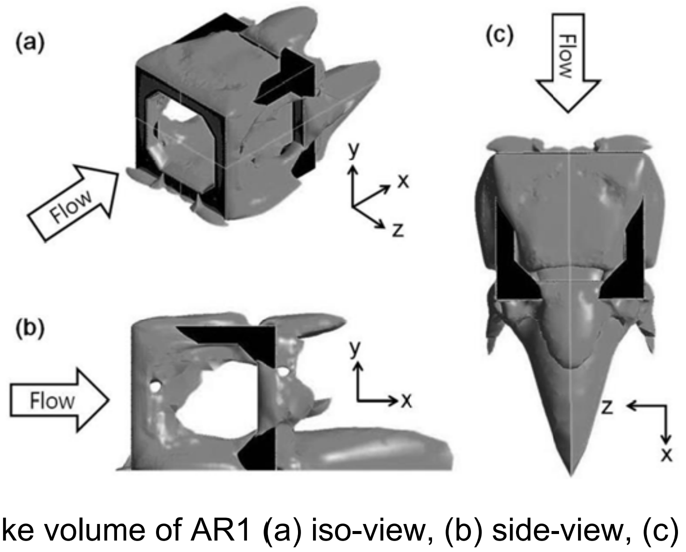

Fig. 5 Wake volume of AR1 (a) iso-view, (b) side-view, (c) plan-view

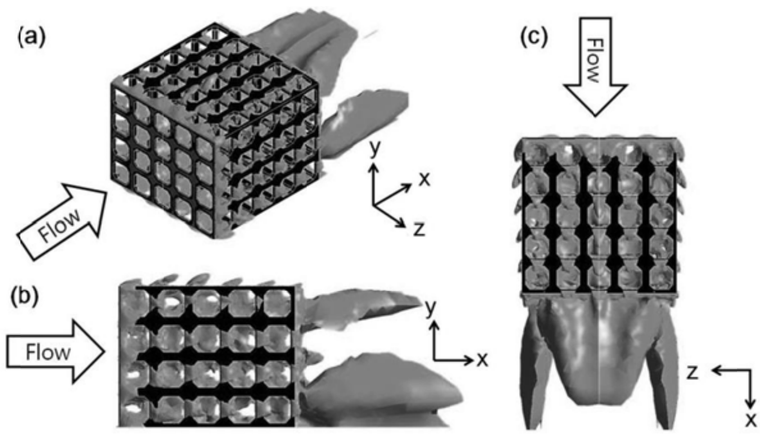

Fig. 6 Wake volume of Hexa unit-AR (a) iso-view, (b) side-view, (c) plan-view

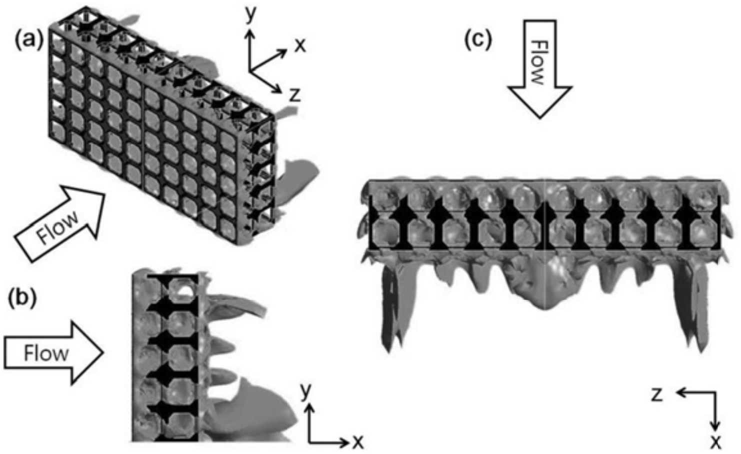

Fig. 7 Wake volume of Rect unit-AR (a) iso-view, (b) side-view, (c) plan-view

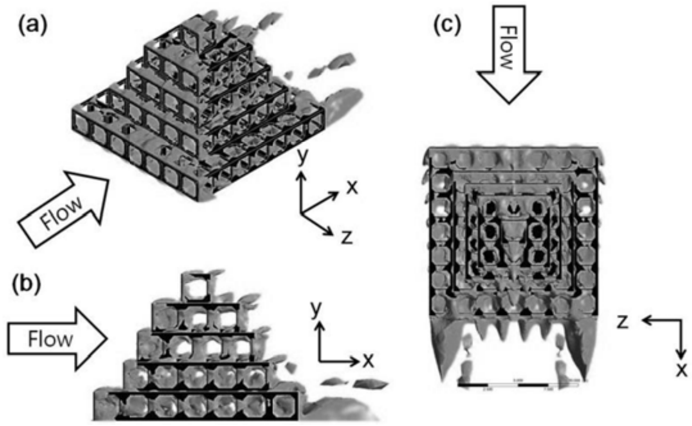

Fig. 8 Wake volume of Pyra unit-AR (a) iso-view, (b) side-view, (c) plan-view

Table 2 Wake regions of AR1 and unit-ARs

		AR1	Hexa unit-AR	Rect unit-AR	Pyra unit-AR
Wake region	Volume (m^3)	2.9 (V_w)	140 (48.1V_w)	119.7 (41.1V_w)	88.4 (30.4V_w)
	Ave. velocity (m/s)	-0.33	-0.21	-0.41	-0.23

Table 3 Upwelling region of AR1 and unit-ARs

		AR1	Hexa unit-AR	Rect unit-AR	Pyra unit-AR
Upwelling region	Volume (m^3)	24.9 (V_u)	1276.7 (60.3V_u)	1969.5 (93.0V_u)	1574.6 (74.4V_u)
	Ave. velocity (m/s)	0.22	0.25	0.29	0.24

In addition, the wake regions of the placement models were characterized by their horizontal profiles to investigate the planar distributions. The results show that Pyra has a unique characteristic showing that 77.04% of the wake volume concentrates on a sub-region near the seabed, which is beneficial to demersal fish.

Similarly, it is found that the upwelling volume in AR1 was 24.9m^3 (V_u, the upwelling volume of AR1) and the average velocity was 0.22m/s. In addition, it is found that the upwelling volumes of Hexa, Rect, and Pyra unit-ARs were 1276.7, 1969.5, 1574.6m^3, respectively. Each upwelling volume is 60.3, 93.0, or 74.4 times the corresponding the upwelling volume of AR1 i.e., V_u. The average upwelling velocity is 0.25 (Hexa), 0.29 (Rect), or 0.24m/s (Pyra). The results are shown in Table 3.

4. CONCLUSIONS

In this study, in order to quantitatively evaluate flow characteristics (wake region and upwelling region) of unit ARs, three 3-D placement models (Hexa, Rect, and Pyra) were investigated. The element-based finite volume method was used for numerical flow analyses, by facilitating ANSYS-CFX, a general purpose CFD software package. From the flow analyses, the following conclusions were found.

First, the AR1 has the wake region quantified by the wake volume (V_w) of 2.9m^3. In addition, the units have the wake volumes of 140 (Hexa), 119.7 (Rect), and 88.4m^3 (Pyra), which are 48.1, 41.1, and 30.4 times the reference wake volume (V_w). This result shows that Hexa has the most desirable in terms of the size of wake volume, followed by Rect. In terms of the average recirculating flow velocity, it is found the sequence: Rect (0.41m/s), Pyra (0.23m/s), and Hexa (0.21m/s). Thus, considering the quality of recirculating zone or wake region (a so-called tranquility), Hexa has a better quality. However, it should be noted here that the average counter velocity (0.41m/s, the highest average among three placement models) of Rect is about 20% of the inlet velocity (2m/s); hence, the tranquility of the corresponding wake region is likely secured. From the observations above, it is shown that each placement model has different wake volume up to 58%. In overall, Hexa unit-AR is the most advantageous based on wake volume. In addition, the wake regions of the placement models were characterized by their horizontal profiles to investigate the planar distributions. The results show that Pyra has a unique characteristic showing that 77.04% of the wake volume concentrates on a sub-region near the seabed, which is beneficial to demersal fish.

Second, the AR1 has the upwelling region quantified by the upwelling volume (V_u) of 24.9m^3. In addition, the units have the upwelling volumes of 1969.5 (Rect), 1574.6 (Pyra), and 1276.7m^3 (Hexa), which are 93.0, 74.4, and 60.3 times the reference upwelling volume (V_u). This result shows that Rect has the most desirable in terms of the size of upwelling volume, followed by Hexa. In terms of the average upwelling flow velocity, it is found the sequence: Rect (0.29m/s), Hexa (0.25m/s), and Pyra (0.24m/s). Thus, considering the quality of upwelling zone (a so-called tranquility), there is no considerable difference. It should be noted here that the upwelling region is defined by 5% of and more than the inlet velocity (2m/s). Thus, the average velocities are between 5% and 14.5% of the reference velocity. From the observations above, it is shown that each placement model has different upwelling volume up to 54%. In overall, Rect unit-AR is the most advantageous based on upwelling volume.

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