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Experimental Study on Artificial Upwelling Device Combined V-shaped Structure with Flexible Underwater Curtain

Tetsuo Nagamatsu[1]* and Naofumi Shima[2]

Key words： upwelling, artificial structure, model experiments, flow visualization

Abstract

An artificial upwelling device is widely recognized to be effective for fertilization of the coastal sea. Many kinds of structures installed on the sea bottom to induce upwelling have been proposed so far. A V-shaped structure, which looks like the letter ‘V’as viewed from the top, is one of the most effective devices to induce upwelling. In order to further improve upwelling, the authors tried to develop a new device combining the V-shaped structure with a vertical flexible underwater curtain hung on floating buoys. These vertical flexible underwater curtains are such things as fishing nets, or silt fences which are used for prevention of water pollution at undersea works. In order to examine whether there is an improvement of upwelling using the new device, flow visualization tests were carried out in a circulating water channel by using a 1/500th scale model. As a result, it was confirmed that the new device is more effective than the conventional device composed of the V-shaped structure only.

Nowadays, major fishery is almost limited in coastal areas and natural upwelling regions in the world. In enclosed sea such as inner sea and bay, aquaculture is conducted prosperously, but issues of worse environmental change due to crowded nursery are worried. The natural upwelling is a current ascending from sea bottom and brings deep sea water up to euphotic zone which is well known as rich fishing ground. Although such natural upwelling areas are only 0.1% of the sea surface in the world, the quantity of fishes produced there occupies more than half of all products of fishes in the world. Thus, the upwelling area is well known to be very desirable and effective for increasing the productivity of fishes. Therefore, many studies on artificial upwelling devices, which yield less environmental change, are made for fertilization of the sea so far.

There are two ways for artificially ascending the deep sea water. One is the way using a pump and another is to install a special underwater structure on the sea bottom for occurrence of upwelling. Recently, an interesting device of the former type is under development in Japan.[1, 2] However, comparing the former, the latter is advantageous in the view point of no power supply and less maintenance of the upwelling devices. Several underwater structures are proposed such as fence,[3] V-shaped structure[4] and mount.[5-7] When an effectiveness of upwelling is defined by the ratio of attainable height of ascending current to the height of structure, it is found from our experiments that

1 鹿児島大学水産学部環境情報科学講座（Department of Environmental and Information Science, Faculty of Fisheries, Kagoshima University, 4-50-20 Shimoarata, Kagoshima 890-0056, Japan）
2 財団法人鹿児島県環境技術協会（The Foundation of Kagoshima Environmental Research and Service, 1-1-10 Nanatsujima, Kagoshima 891-0132, Japan）
* Corresponding author, E-mail: nagamatu@fish.kagoshima-u.ac.jp

V-shaped structure is most effective.

The V-shaped structure is very simple shape and was firstly proposed by Asaeda.[8] The model used in the present experimental study is shown in Fig. 1-A. The V-shaped structure consists of two long flat plates which are connected with each other at 90° of a dihedral angle. The V-shaped structure is placed against to the horizontal bottom current, facing the vertex toward the downstream. When the current gets over the V-shaped structure, a pair of vortices with counter-ward rotation issue[9] and shed in the wake of the structure as shown in Fig. 1-B. Asaeda[8] illustrated the flow pattern behind the V-shaped structure as shown in Fig. 2. A separation zone is formed just behind the V-shaped structure and vortices are generated so frequently in the separation zone. Some of vortices coalesce with others in short time and horse-shoe shaped vortices are formed in the downstream. The pair of vortices are observed in the transverse vertical plane across the horseshoe vortices as shown in Fig. 3.[10, 11] They rise up by interaction between them and accordingly lift up the head of horse-shoe vortices. Then, the deep sea water including a plenty of nutritive salts rises up together with these vortices.

In the present study, a new device combined V-shaped structure and a vertical flexible underwater curtain hanged on floating buoys is proposed in order to improve more an effectiveness of upwelling. The vertical flexible underwater curtain is supposed such as fishing nets or silt fences used for prevention of water pollution at undersea works. The schematic of the new device is shown in Fig. 4. The vertical flexible underwater curtain, abbreviated by 'underwater curtain' thereafter, is located in the upstream site of the V-shaped structure. The underwater curtain is tied to the buoys which are moored to several anchor chains. The underwater curtain works to disturb the flow over the V-shaped structure. As a result, upwelling induced by V-shaped structure rises up higher and more effectively.

In order to investigate the effectiveness of the new device, flow visualization tests were carried out by use of 1/500 scale model in a circulating water channel.

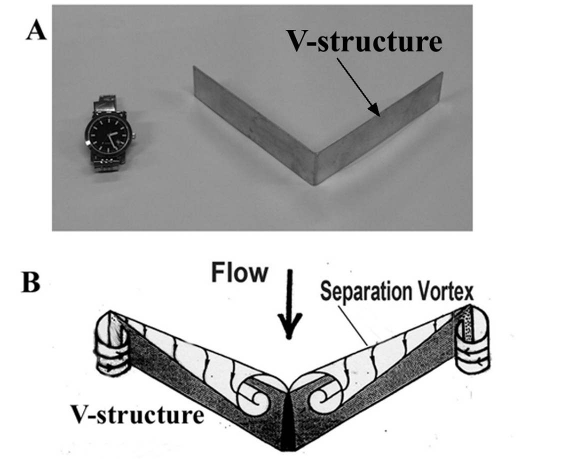

Fig. 1. A: V-shaped upwelling structure model used in the present study. B: Illustration of separation vortices issued from top edge of the V-shaped structure when bottom flow gets over the V-shaped structure installed on the sea bottom.

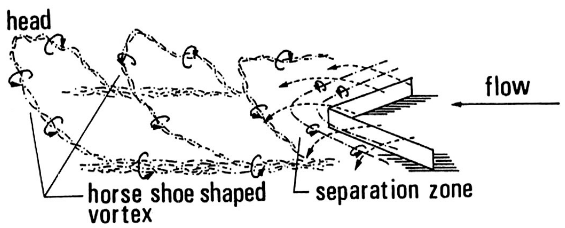

Fig. 2. Illustration of flow pattern behind a V-shaped structure cited from Asaeda (1989).

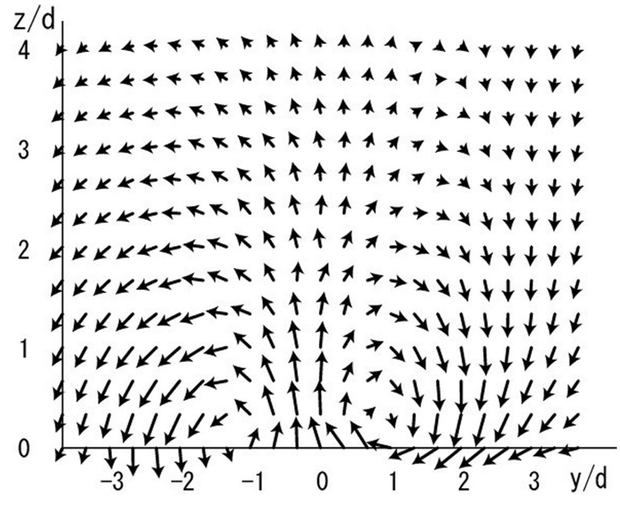

Fig. 3. Velocity vectors measured at a vertical section behind a V-shaped structure cited from Nagamatsu *et al*. (2003), which shows a pair of vortices with counter-ward rotation.

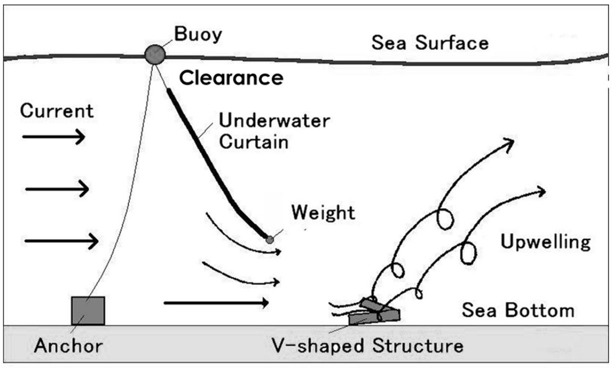

Fig. 4. Schematic of new artificial upwelling device , which is a combined V-shaped structure with vertical flexible underwater curtain hung from floating buoys.

Materials and Methods

The circulating water channel used in the present study belongs to the Faculty of Fisheries, Kagoshima University. The schematic is shown in Fig. 5. The water flow in the channel is generated by an impeller driven by an electric motor. The walls and bottom of the observation channel are made by acrylic glass and the dimensions of the channel are 1.3 m long, 0.3 m wide and 0.2 m deep. The uniformity of the velocity at the observation channel is kept within velocity fluctuations of 3% by using guide vane and honeycomb. The flow velocity is controlled from 0.05 m/s to 0.7 m/s. The schematic of test arrangement is illustrated in Fig. 6, which shows the view of the channel from the downstream site. A model of V-shaped structure was set on the channel bottom at middle part of the observation channel. A model of underwater curtain was hanged on a bar across the top of the channel walls by two strings.

By the way, when model experiments are carried out, we have to consider the similarity law to simulate the flow phenomena around the full scale structure. In general, the flow phenomena dependent on Reynolds number are difficult to satisfy the hydrodynamic similarity law. Discrepancy between the full scale and its model experiments caused from this difficulty is usually called by scale effect. There are few studies on

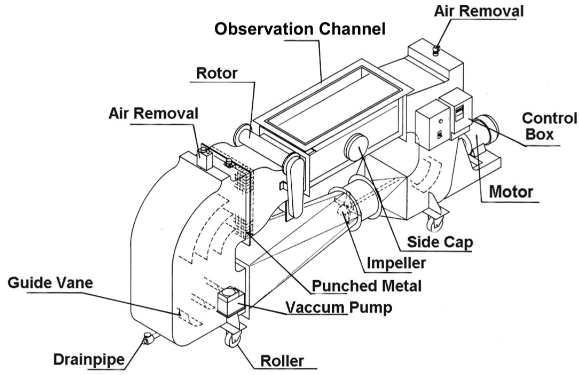

Fig. 5. Schematic of the circulating water channel used in the present study. An observation section is 1.3 m long, 0.3 m wide and 0.2 m deep.

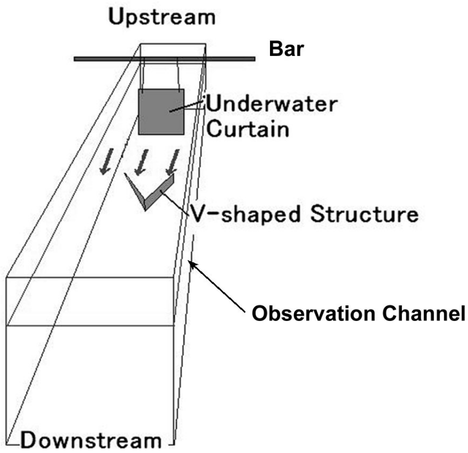

Fig. 6. Schematic of test arrangement in the circulating water channel, showing positions of V-shaped structure model and underwater curtain in the channel, and water flow from upstream to downstream.

scale effect for vortex flow separated from sharp edge structure.[12] Nagamatsu *et al.*[11] have investigated on the scale effect on vortex flow produced by V-shaped structure. Based on both theoretical consideration and experiments, they concluded that scale effect on the vortex motion induced by V-shaped structure exists somewhat and it is nearly proportional to Reynolds number to one tenth. This means that the effectiveness of upwelling of full-scale device is greater than the effectiveness deduced from model experiments. In the present study, scale effect on the vortex flow induced by V-shaped structure is not considered, because the present model experiments discuss relative effectiveness of upwelling induced by the new device to the

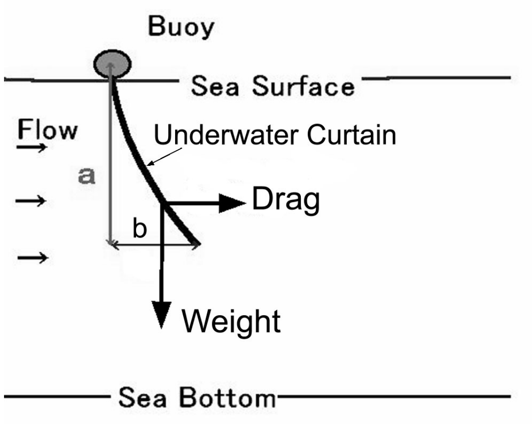

Fig. 7. Definition of curtain inclination, which is dependent on the ratio of hydrodynamic drag of underwater curtain to the curtain weight.

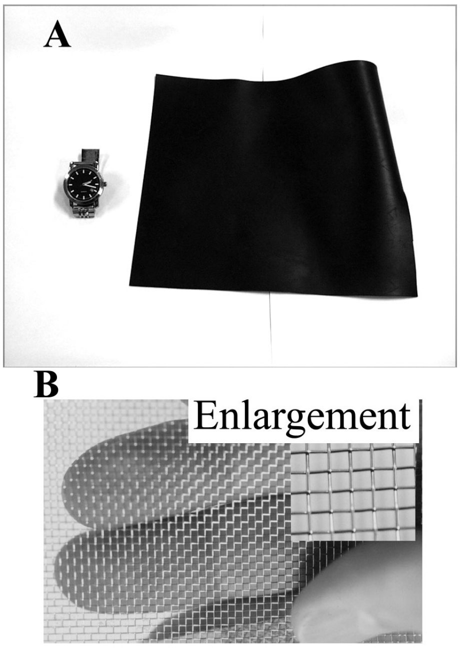

Fig. 8. Photographs of underwater curtain used in the present study. A, rubber curtain; B, net curtain.

conventional device of the V-shaped structure. On the other hand, flow fields behind the underwater curtain are strongly affected by inclination of the curtain, which is mainly determined by ratio of the curtain weight to its hydrodynamic drag as shown in Fig. 7. Therefore, similarity of the flow field behind the underwater curtain is approximately realized under the same inclination of the curtain for both the full scale and model experiments. In the present study, therefore, flow visualization tests were carried out to investigate the effect of curtain inclination on upwelling. In order to change the curtain inclination, the flow velocity was set to be a constant of v=0.084 m/s, and the weight of the curtain was adjusted by an additional weight as shown in Fig. 4. The curtain inclination θ is defined by b/a, where a and b are shown in Fig. 7.

Now we assume an actual sea depth of 100 m. Since the depth of circulating water channel is 0.20 m, scale ratio becomes to be 1/500. The model of V-shaped structure is 3.0 cm high and two branches are 15.0 cm long. Two kinds of the curtain model were used in the flow visualization tests. One is rubber sheet as shown in Fig. 8-A and another is polyester net as shown in Fig. 8-B. The dimensions of the rubber sheets and polyester nets are 15.0 cm in vertical length and 20.0 cm in transverse length. A mesh size of the polyester net is 1.0 mm square. The curtain models were put on the position of 20.0 cm in front of the V-shaped structure.

Flow visualization tests were carried out on various combinations of underwater curtains and V-shaped structure. Reynolds number based on the inflow velocity and the height of V-shaped structure model was about 2500. Flow was visualized by using a diluted solution of black ink with ratio of 1:9. Before flow visualization tests of upwelling, the tracer was injected from a slender pipe into uniform flow to examine its specific gravity. The results shown in Fig. 9-A indicate that the specific gravity of the tracer is a little bit heavier than that of fresh water and the tracer diffuses some extent in the downstream. The tracer was also confirmed to diffuse less in case of bottom flow without any obstacles as shown in Fig. 9-B. From these figures, this tracer is considered to be available in the flow visualization tests of upwelling, which compare the upwelling induced by the new artificial device with that induced by the conventional device as the first step of the study.

Flows around V-shaped structure models were

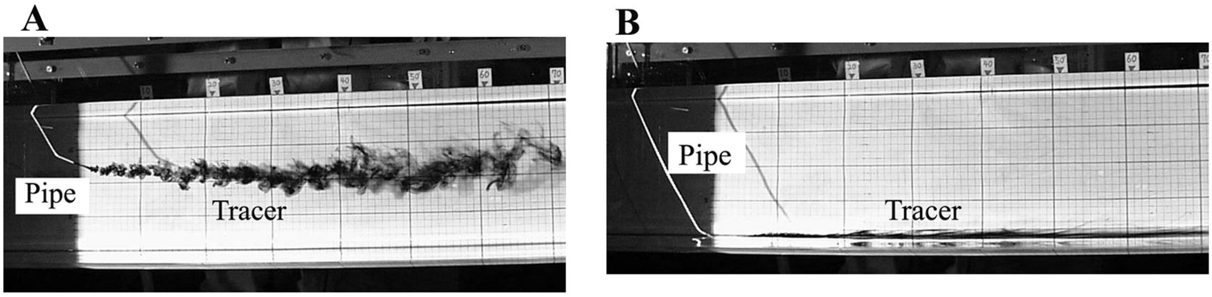

Fig. 9. A: Behavior of the tracer in uniform flow, showing that the specific density of the tracer is nearly equal to that of fresh water. B: Tracer's behavior near channel bottom without any obstacles, showing no ascending flow.

visualized by injecting the tracer in front of the structure models set on the bottom of the channel. A scale grid was pasted on the side wall of the channel to measure the height of ascending current visualized by the tracer. The behavior of the tracer was recorded by a digital video camera from another acrylic glass wall of the channel.

Results and Discussion

Examples of the visualization tests are shown in Figs. 10-A to 10-D. Fig. 10-A shows the results of the conventional device, i.e. only V-shaped structure. The water flows from left to right. It is found that black tracer, i.e. deep sea water ascends gradually and expands in the downstream area of the V-shaped structure. The upper edge of black tracer reaches finally to the height of about 7 times of the V-shaped structure.

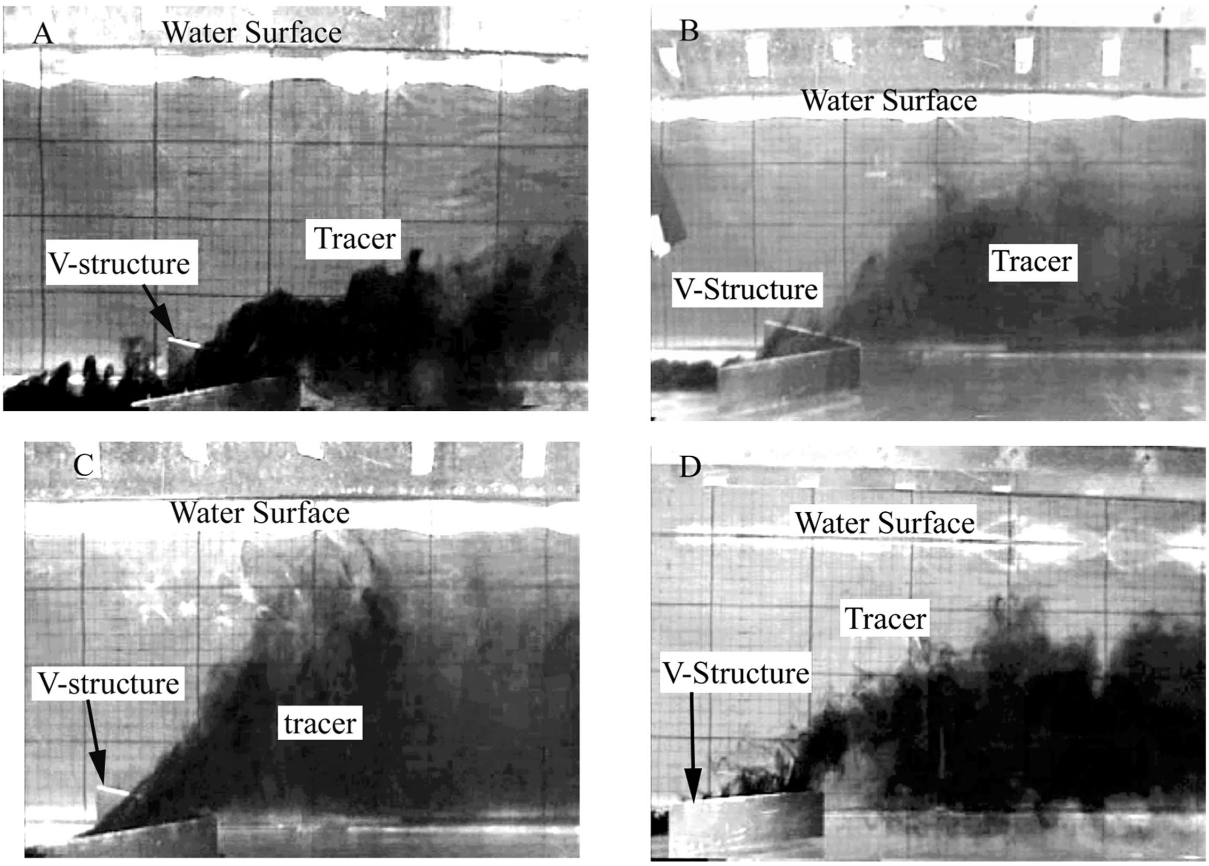

Fig. 10. Flow visualization test results for artificial upwelling device. A, V-shaped structure only; B, rubber curtain model with larger curtain inclination and V-shaped structure; C, rubber curtain model with smaller curtain inclination and V-shaped structure; D, net curtain model and V-shaped structure.

As illustrated in Fig. 4, the underwater curtain of the new device is hanged from buoys with a certain clearance between the curtain and buoy for small ship navigation. The present experiments were carried out for various clearances including the case of zero clearance. Figures 10-B to 10-D are results of visualization tests for zero clearance as representative examples. Both Fig. 10-B and Fig. 10-C are results for rubber curtains, and their curtain inclinations are 1.08 and 0.89, respectively. It is observed the tracer goes up sharply from V-shaped structure as compared with the results of only V-shaped structure shown in Fig. 10-A. The smaller curtain inclination shown in Fig. 10-C is more effective than the larger one shown in Fig. 10-B. From these figures, the rubber curtain is found to be very effective for occurrence of upwelling attainable to the euphotic zone. Fig. 10-D shows the results for net curtain which is pervious to water. It is found that effectiveness of net curtain on ascending deep sea water is greater than that of only the V-shaped structure, but less than that of the rubber curtain.

Here, the effectiveness of upwelling device is defined by upwelling slope H/X, where H and X are denoted in Fig.11-A. H is the height from the sea bottom to the euphotic zone, which is assumed to be 10 m below the sea surface. X is horizontal distance from V-shaped structure in the downstream direction. A comparison of H/X versus curtain inclination is shown in Fig. 11-B. The device with both rubber and net curtains are clearly found to be more effective than the conventional device of only the V-shaped structure shown by broken line. The effect of inclination of rubber curtain is significant. On the other hand, the inclination of net curtain is small due to relatively smaller hydrodynamic drag of net curtain. H/X of the net curtain is comparable to that of the rubber curtain with the largest inclination among the present experiments. The flow pattern behind rubber

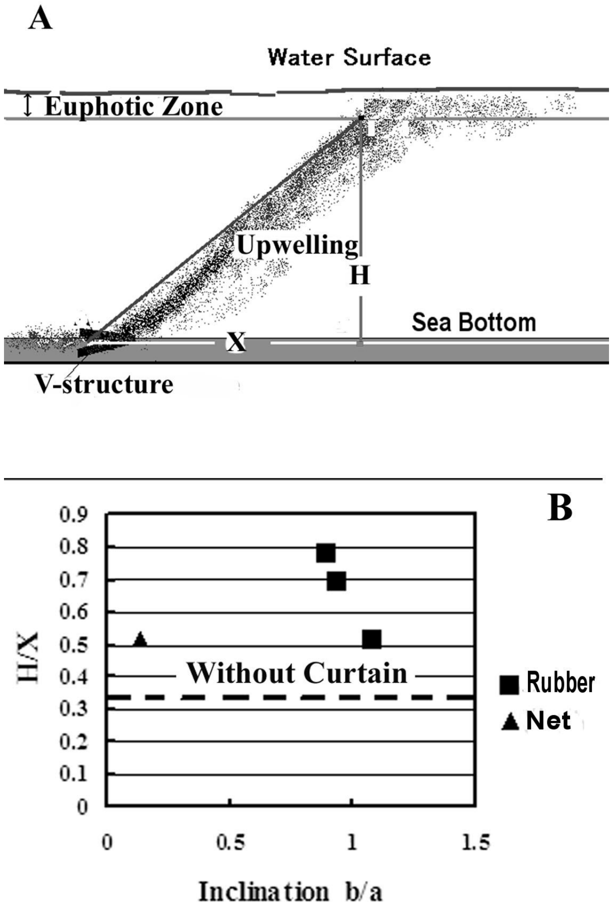

Fig. 11. A: Definition of effectiveness of artificial upwelling device by H/X. Larger H/X indicates steeper ascendance of upwelling. B: Diagram of H/X versus curtain inclination b/a for rubber and net curtains.

curtains is illustrated in Fig. 12-A. A large separation zone exists just in the rear of the rubber curtain and a counter-clockwise rotating flow has occurred just above the V-shaped structure. Furthermore, inflow velocity to the V-shaped structure is magnified due to narrow passage under the curtain. Consequently, stronger separation vortices are issued from V-shaped structure and go up steeply along the rotating flow. These phenomena are magnified for the smaller inclination of the curtain because the flow passage under the curtain becomes narrower. In the case of net curtain illustrated in Fig. 12-B, magnitude of horizontal velocities of water passed through the net curtain is reduced considerably and many small rotating flows are formed as crowded small vortices. As a result, the upwelling issued from

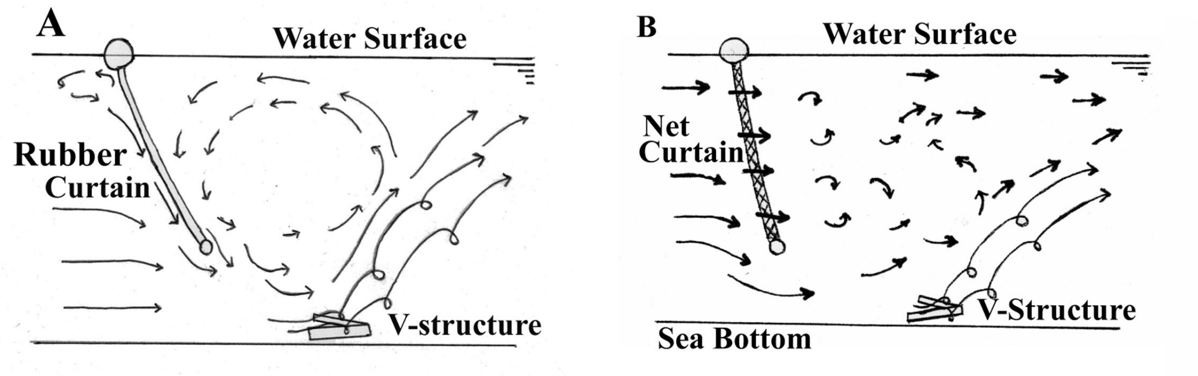

Fig. 12. A: Schematic of flow pattern behind rubber curtain showing existence of large separation zone, which results in steeper upwelling. B: Schematic of flow pattern behind net curtain showing velocity reduction due to passage through net mesh.

the V-shaped structure goes up higher in the weakened horizontal flows.

An effect of clearance between curtain and buoy on the effectiveness of upwelling device H/X is shown in Fig. 13. The abscissa is a ratio of the curtain-buoy clearance and water depth. In the case of rubber curtain, H/X decreases gradually with the curtain-buoy clearance. On the other hand, H/X increases very slightly with the curtain-buoy clearance in the case of net curtain. Fig. 14-A shows the flow pattern behind the rubber curtain with the curtain-buoy clearance. As compared with Fig. 12-A, separation zone becomes small and the horizontal flow velocities near the water surface maintain almost unchanged from the flow velocity in front of the curtain because the water passes through the curtain-buoy clearance easily. From these reasons, the upwelling is interrupted to attain the euphotic zone sharply. In the case of net curtain shown in Fig. 14-B, the flow velocities below the water surface affect less on flow field behind the net curtain, because difference between the flow velocity below the water surface and that

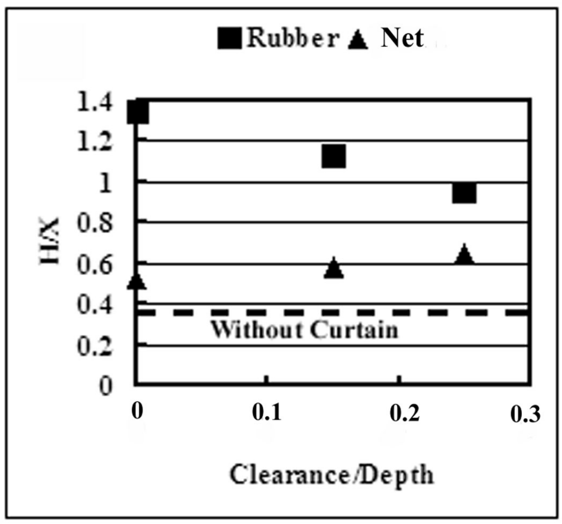

Fig. 13. Diagram of H/X versus curtain-buoy clearance, showing that H/X decreases with clearance by using a rubber curtain, while H/X increases very slightly with clearance by using a net curtain.

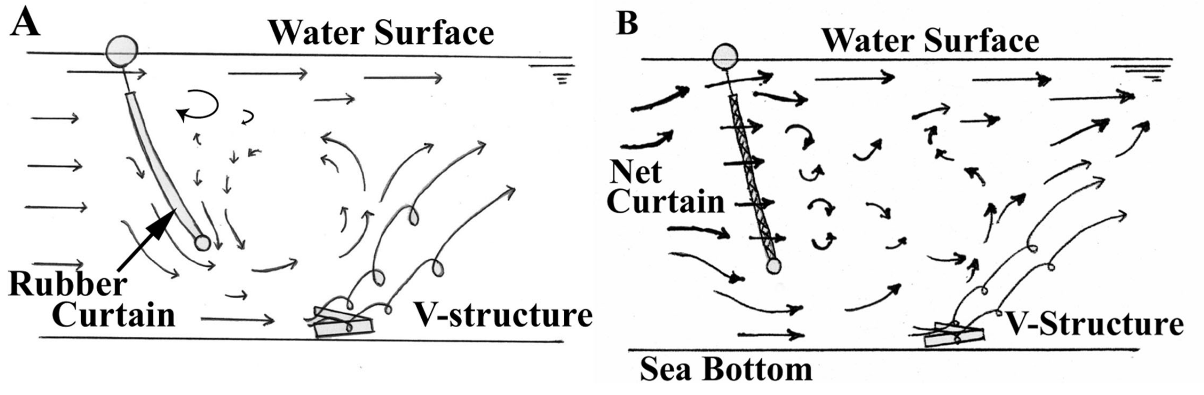

Fig. 14. A: Schematic of flow pattern behind rubber curtain with curtain-buoy clearance, showing separation zone reduced as compared with Figure 12-A. B: Schematic of flow pattern behind net curtain with curtain-buoy clearance.

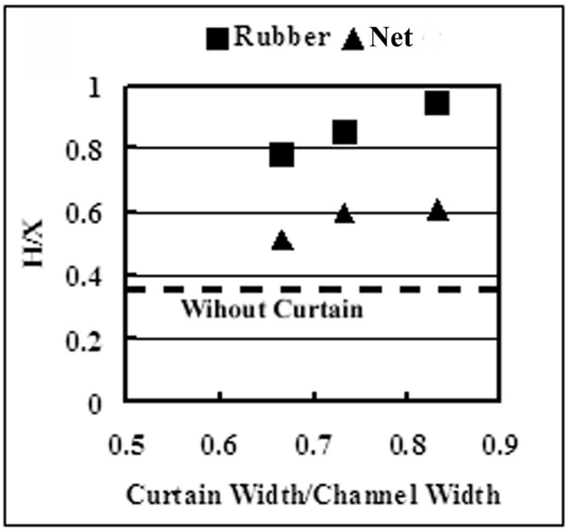

Fig. 15. Diagram of H/X versus ratio of curtain width to channel width, showing channel wall effect on the experimental results.

behind the net curtain is not so large. The slight increase of H/X with the clearance of net curtain shown in Fig. 13 is considered to be insignificant.

Lastly, so called wall effect on H/X is shown in Fig. 15. When the model experiments are carried out in the circulating water channel, water flow is constrained by the channel wall in general. As a result, the flow around the model in the channel is different from that around the full scale structure in open water. The abscissa of Fig. 15 indicates wall ratio defined by the ratio of the curtain width to the channel width, and then smaller values of the wall ratio indicate to be close to the open water condition. It is recognized that H/X increases apparently with the wall ratio. Therefore, only experimental results obtained under the experimental condition of the smallest wall ratio, which indicates less wall effect, are described in the present paper.

As described above, the new artificial upwelling device proposed in the present paper can be said to be more effective than the conventional devices for artificial upwelling. To realize the present new device, the usual technologies are applicable to the underwater curtain, buoy mooring and anchoring. With respect to the underwater curtain, silt fence is one of impervious materials. Since the size of full scale curtain is considered to be several hundreds meters in transverse length and several tens meters in vertical length, there may exist some problems such as manufacture, field works for construction and mooring. On the other hand, the fixed shore net is considered to be applicable to the pervious underwater curtain even now. The mesh size of the full scale fixed shore net is a few tens cm, while that of net model used in the present experiments corresponds to 50 cm in full scale. Therefore, it is expected that upwelling induced by the full scale device ascends more sharply and higher than those induced by the present model experiments. Idea of the present underwater curtain is considered to be applicable to other conventional structure for artificial upwelling, such as mount type upwelling device.[7] In order to realize this new device, further investigations on the curtain material, estimation of hydrodynamic drag of the curtain, procedure of the construction and so on are necessary, in addition to the study on the effect of pycnocline on the artificial upwelling.

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