

Reviews of power supply and environmental energy conversions for artificial upwelling

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ABSTRACT

Wave energy is being increasingly regarded as a major and promising resource since the artificial upwelling was invented. There are many different ways to convert wave energy to electricity and some other energy such as the power supply for artificial upwelling in this paper. An overview of wave energy converters in artificial upwelling application as well as the power systems and environmental energy conversions for the artificial upwelling all over the world is given in this article. Some basic principles are present, assessment and advices are shown for each category. Some suggestions of the outlook of power systems and wave energy converters in air-lift artificial upwelling application are also given.

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1. Introduction

Nearly all natural upwelling areas are significant fishing grounds. This is because of the nutritious deep seawater rich in inorganic nutrient salts, such as nitrate, phosphate and silicate [1,2]. These nutrient salts are essential for the growth of plants. Upwelled water from depths below 300 m is cold, clean and rich in nutrients. While

upwelling regions account for only 0.1% of the ocean surface, they yield over 40% of the world's fish catch [3–6]. If nutrient-rich deep ocean water could be distributed in the surface waters, it would open a potentially vast new source of food by dramatically increasing fish and other marine organism populations [7].

Therefore, techniques for artificial upwelling are being researched, and many new devices and equipments are invented and developed. Air-lift artificial upwelling devices are the most widely used equipments in modern times [8–11]. Air-lift artificial upwelling devices are quite well developed and widely applied in practice. However, there are still some key techniques needed improving, such as deployment, control and power supply. Among

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these techniques, power supply is especially important and crucial. Power supply does affect air-lift artificial upwelling devices' working duration and mission completion. These years, institutions and scientists have dedicated great efforts to the research of power systems and new energy sources for the air-lift artificial upwelling. A great progress has been made, and the techniques that address such an issue include:

- 1) Perpetual salt fountain. There is a possibility of a permanent upwelling of deep seawater with no additional external energy source.
- 2) Air-lift pump and air-bubble screen method. The air-lift pump principle is simple. Air is compressed into a vertical pipe, dipped in water. Bubbles ascend and the water level in the pipe rises due to the density decrease in the air-water mixture. Air-bubble screen is an air-lift pump without a pipe. It is an alternative air-lift pump technique.
- 3) Ocean Thermal Energy Conversion (OTEC) method. The main power is supplied by an OTEC unit.
- 4) Ocean energy conversion. Wave energy is used to invert the density structure of the ocean and pump deep, nutrient-rich water into the sunlit surface layers.
- 5) Distributed generation method. Distributed generation such as photovoltaics array, wind turbines, wave energy converter array and conventional diesel generator are deployed as power supply for the air-lift artificial upwelling.

Besides, there are several other methods in consideration, for example, battery method application, which is feasible in theory, but unsatisfactory in practice as there are continuation and environmental concerns which make them inconvenient and inaccessible to most groups. This paper, we will present the researches of power supply for air-lift artificial upwelling applications.

2. Perpetual salt fountain

Stommel et al. in 1956 proposed a concept for a perpetual salt fountain and suggested the possibility of upwelling deep seawater without an energy source [12]. In ocean deserts where very little phytoplankton is produced, such as the middle latitudes of the Northern Pacific Ocean and some areas of the tropics and subtropics, the salinity of surface seawater is higher than that of deep seawater. As a result, seawater is overall stably stratified, and little convective motion occurs in the vertical direction [13]. When a pipe is inserted to connect deep seawater and surface seawater, and the pipe is filled with the low-salinity deep seawater, the salinity of the water inside the pipe is lower than that outside and the pump is primed by moving some water upward inside the pipe [14,15]. The upwelled deep ocean water becomes almost the same temperature as the surrounding water, hence a buoyant force occurs in the pipe. The upwelling continues as long as differences in temperature and salinity exist [16,17].

Laputa project (Fig. 1) was proposed by Maruyama et al. in 2004, proposing to cultivate phytoplankton based on the principle of perpetual salt fountain [13]. The nutrient-rich deep sea water is drawn up by the perpetual salt fountain to the photic region and cultivate phytoplankton using a large number of vertical floating pipes. The drawn up deep seawater is heated during its flow up through the pipe and then remains on the surface. An independent ecosystem of ocean farm shown in Fig. 1, consisting of fisheries and sea plant fields, is constructed in the area.

This perpetual salt fountain was tried in the Mariana area in the tropical Pacific Ocean in 2005, where the experimental apparatus is schematically shown in Fig. 2 [17]. The apparatus consisted of a

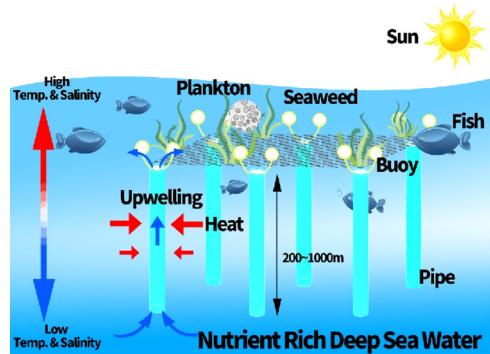


Fig. 1. Diagram of the Laputa project.

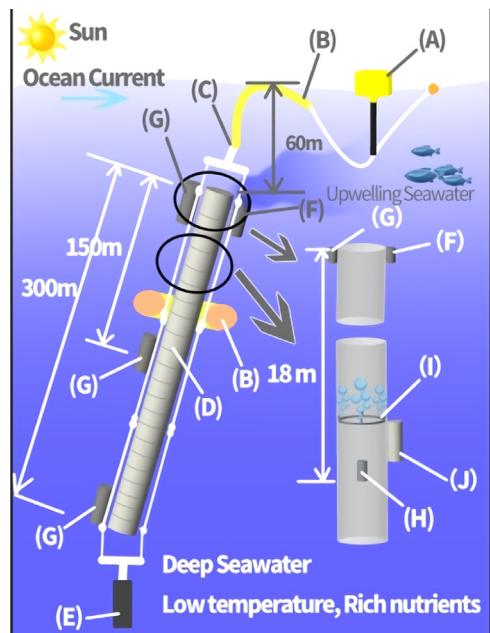


Fig. 2. Schematic diagram of experimental apparatus equipped with air-lift pump: (A) primary buoy with GPS, (B) adjusting buoys, (C) rope, (D) pipe, (E) weight, (F) portable chlorophyll sensor, (G) bathythermograph, (H) conductivity-temperature sensor, (I) air-lift pump and (J) gas bomb for air lift [7].

pipe, buoys, measurement systems, and an air-lift pump. The pipe with the dimension of 300 m long and 0.3 m in diameter was floated with spherical buoys, which were attached to decrease the tension of the ropes due to the pipe weight. The buoys and ropes were adjusted so that the pipe exit was approximately 60 m below sea level, in order to provide nutrient of upwelling seawater with surface layer. This depth, plus the pipe length of 300 m, equals the bottom depth of 360 m, which coincides with the salinity minimum layer depth, resulting in the maximum upwelling velocity. The air-lift pump used for initial filling of the pipe with deep seawater was installed inside the pipe at 10 m below the outlet for the initial draw-up of the deep seawater. The air-lift pump drew water up by the buoyancy of gas bubbles, which was used only on the first day of the experiment.

Fig. 3 shows the experimental apparatus deployed in the ocean [18]. The pipe was made of a fiber-reinforced PVC sheet, 0.5 mm in thickness. Steel coil rings were attached at every 0.25 m to maintain a circular cross section. The flow rate with a single pipe was estimated as only approximately 45 m³/day [18,19]. The results indicate that upwelling deep seawater by the perpetual salt fountain can creative the possibility to enhance the primary production of the ocean if the pipes are deployed in a large scale [20,21].



Fig. 3. Photograph of experimental apparatus deployed in the ocean.

Perpetual salt fountain is considered to be an effective mechanism to draw up the deep seawater. It is driven by the difference in salinity and temperature between deep seawater and the epipelagic layer, and needs no other energy supply. Another advantage of adopting perpetual salt fountain is that, a complicated structure is unnecessary for realization of upwelling based on this principle. More importantly, the possibility of a permanent upwelling of deep seawater with no additional external energy source has been confirmed by numerical simulations and in ocean experiments. However, the perpetual salt fountain technologies is strongly limited in the middle latitudes of the Northern Pacific Ocean and some areas of the tropics and subtropics, where the salinity of surface seawater is higher than that of deep seawater and the seawater is overall stably stratified, and little convective motion occurs in the vertical direction [22,23].

3. Air-lift pump and air-bubble screen method

The air-lift pump has been well-known since the end of the 18th century. It can be used to pump hydrocarbons, dirty water, dangerous fluids and transport solid materials [24–27]. Compared with other hydraulic transport processes, the air-lift process is very simple, insensitive and needs little maintenance. The principle of air-lift pump is very simple. Air is compressed and injected in the lower part of a pipe that transports the water. As a result, bubbles ascend and the water level in the pipe rises due to the density decrease in the air–water mixture. Once the water level reaches the top of the pipe and the water flows out, the water flows continuously from the lower end.

Air-lift pumps for artificial upwelling of ocean water are finding increasing use for marine primary productivity, which could be enhanced by pumping nutrient-rich deep water to the surface to feed phytoplankton. A conceptual air-lift pump as a device for upwelling deep ocean water was proposed, by means of compressed air introduced into the upper end of the vertical pipe, which was totally submerged in the seawater. It was estimated that the seawater flow rate ratio could be hundred times higher when compared to the air flow rate [28–32].

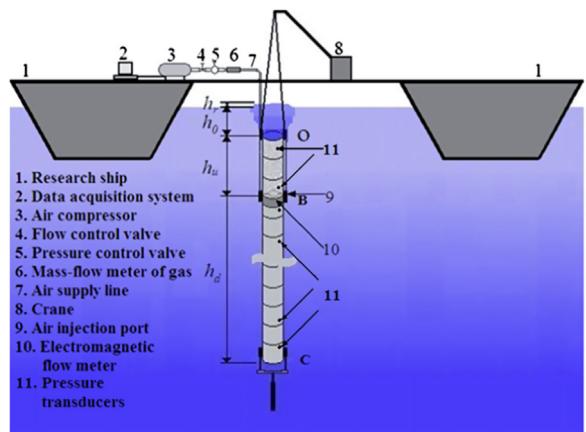


Fig. 4. Schematic diagram of the air-lift pump for artificial upwelling of deep water.

Fig. 4 shows the schematic diagram of the experimental set-up with air-lift pumping system developed by Zhejiang University in 2011 [10]. The field experiments were run in the Xinanjiang Experiment Station located in the Thousand Island Lake, Chun'an County, Zhejiang Province, China. The test area is a hundred meter squared area with an average depth of 50 m, which provides pier side mooring, storage and a ship based crane for loading the air-lift pumping system. Unlike the conventional air-lift pumps which are devices for lifting water through a vertical pipe partially submerged in the water, the air-lift pump for artificial upwelling of deep water is operated in a totally submerged mode. As illustrated in **Fig. 4**, a vertical pipe was totally submerged vertically in water with the submerged depth of pipe outlet $h_0=2.1$ m. The upwelling pipe was composed of a water suction pipe ($h_d=20$ m) with only water flowing and a gas injection section pipe ($h_u=8$ m) occupied by the two-phase water-air flow. An air compressor was used to transport the compressed air through a 15 mm diameter pipe line to an on/off valve, then to a pressure control valve, where the pressure was reduced to the working pressure (1.2–3.2 bar). Finally, the compressed air was delivered at point B through an external pipe.

Fig. 5 shows the experimental apparatus deployed in the lake. The upwelling pipe is 28.3 m length and 0.4 m internal diameter, made of nylon-reinforced PVC sheet. The experimental results show that the air-lift pump for air-lift artificial upwelling is feasible and effective for upwelling deep, nutrient-rich waters into the euphotic zone to feed phytoplankton and mimicking natural upwelling which sustains the most productive ocean fishing grounds in the world. The efficiency of the air-lift artificial upwelling was shown to be strongly dependent on the geometrical parameters of the upwelling pipe, type of air injection nozzle and air volume flow rate [10,11]. Moreover, as a new and primitive ocean fertilization method, air-lift pumps for artificial upwelling still needs further improvement and perfection.

An alternative air-lift pump technique is the air-bubble screen, which is an air-lift pump without a pipe. An upwelled flow is induced by the air-bubble screen from an orifice or orifice series. **Fig. 6** shows a bubble curtain used in the inner part of Arnafjord to lift deeper, nutrient-rich seawater to the upper layer [33,34]. Three 100 m long parallel, perforated air pipes with individual horizontal separations of 1.25 m (**Fig. 2**) were placed at 40 m depth in the inner arm of the Arnafjord. A horizontal separation of the pipes distributed the buoyancy flux to the extent that the virtual source of the plume was a few meters deeper. A 390 kW compressor was used to press 44 m³ of air at normal pressure through 300, 2.5 mm diameter holes each minute to produce the buoyancy flux [35].

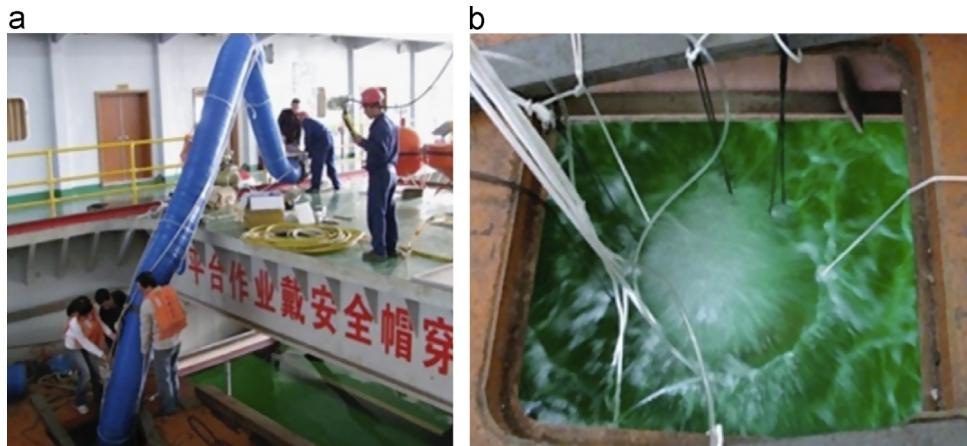


Fig. 5. Photos of the experimental apparatus deployed in the lake.

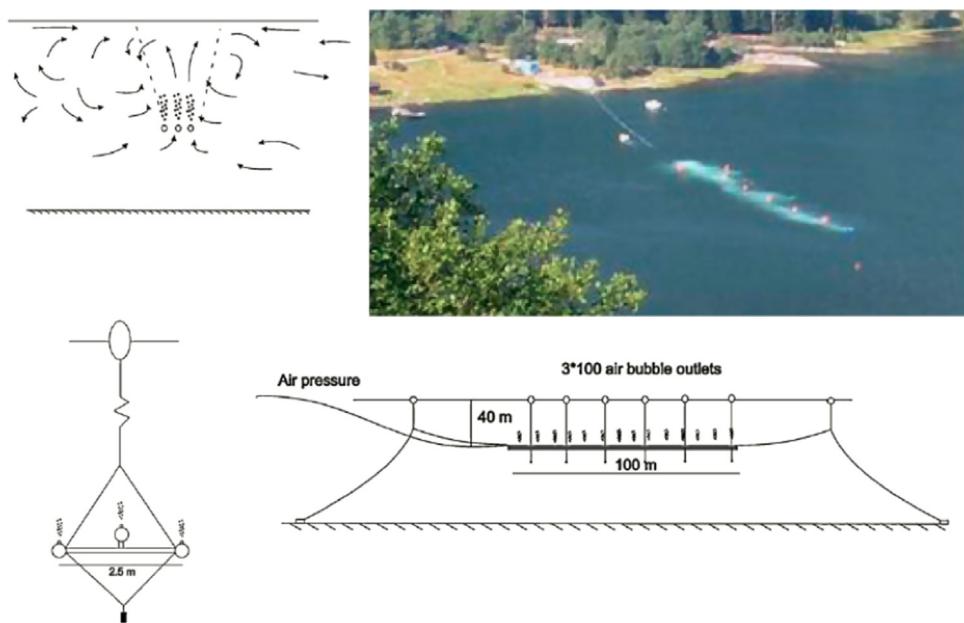


Fig. 6. The bubble curtain in Arnefjord. Upper left: cross-section of the induced circulation. Upper right: view from the mountain side. Lower left: cross-section of the construction. Lower right: suspension scheme.

As shown in the lower right of Fig. 6, the lines between the floats and the raft were adjusted to secure a constant 40 m depth along the entire curtain [35,36]. The central upper pipe was used for flotation and ballast. An air hose was attached to one end, while an opening for water inlet/outlet was on the far end. The system was deployed and retrieved by air pressure manipulation. Violent mixing with the upper water in the bubble curtain gave a density of the mixed water close to that of the ambient water at 10 m depth. This was the nominal intrusion depth of the spreading, nutrient-enhanced water. The diffuser created an upwelling zone that constituted less than 0.2% of the surface area of the inner fjord, and was run for an experimental period of 21 days.

The experiment demonstrated that a submerged bubble curtain can transport nutrient-rich deep water up to 4–17 m depth and generate a local reduction in stratification close to the upwelling zone. In addition, vertical diffusion of nutrients from the deeper intruding core can reach the upper 10 m of the euphotic layer. The observed rise in phytoplankton biomass is considered to be a result of the total increased nutrient supply to this layer created by the artificial upwelling.

As a simple method of power supply for artificial upwelling, the performance of an air-lift pump as a device for upwelling deep

ocean water through a vertical pipe totally submerged in the seawater has been confirmed by experiments. Especially when the compressed air supplied by the air-lift pump is introduced into the pipe near the upper end, it can be expected that the seawater flow rate can be a hundred times higher when compared to the air flow rate, which is highly effective and very inexpensive. However, the device is easy to fail as the flexible pipe is prone to twist when the large number of bubbles climb along the pipe. According to experimental results, the artificial upwelling induced by air-bubble screen seems more promising compared to air-lift pump, where pipe is not involved. However, either air-lift pump or air-bubble screen, the power source for the air-lift pump itself in the open sea can be a serious problem.

4. OTEC method

One of the most important technical subjects for artificial upwelling is to minimize sinking and diffusion of deep ocean water (DOW) after discharge into the euphotic zone. In order to solve this problem, a density current generator was proposed and adopted in the Marino-Forum 21 project, aiming to create new

fishing ground by enhancement of marine primary production using artificial upwelling.

Fig. 7 illustrates a concept of ocean nutrient enhancer adopted in a stratified water areas, which is an applied density current generator for artificial upwelling [37,38]. The ocean nutrient enhancer (ONE) consists of a spar-type floating structure equipped with a double impeller, a riser pipe for pumping up DOW, and a single point mooring system. It can intake both high-density nutrient-rich DOW and low-density warm surface seawater, and discharge the medium-density mixed water into the euphotic zone as a density current.

As shown in **Fig. 8**, the first Japanese ONE device, TAKUMI, was constructed and deployed in 2003, the height and breadth of the floating structure are 32.0 m and 16.8 m, respectively. The main power will be supplied by a Ocean Thermal Energy Conversion (OTEC) unit. TAKUMI has a riser pipe 1 m in diameter and about 200 m in length, and the deep seawater flow rate is only about $1.2 \text{ m}^3/\text{s}$.

However, OTEC as power system of artificial upwelling is mostly limited in tropical and subtropical sea areas, where the temperature difference is more than 20°C (36°F) between surface and water in depth of 1000 m as a result of heating effect of solar radiation [39]. Generally speaking, development of OTEC is still at

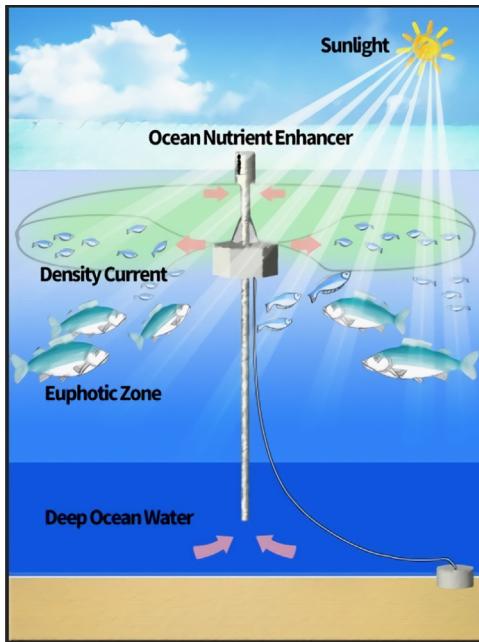


Fig. 7. A concept of ocean nutrient enhancer.



Fig. 8. Photo of TAKUMI in operation.

the stage of study. Although considerable progress has been achieved in aspects of the thermodynamic cycle, high efficiency compact heat exchanger and marine engineering, other aspects such as technology of low efficiency in pumping cold water from deep ocean, high costs in construction are still immature. Therefore the main challenge for development of OTEC as power supply for artificial upwelling is economy and reliability for long time operating.

5. Ocean energy conversion

5.1. Wave energy conversion

In 1976, John D. Isaacs proposed to use wave energy to invert the density structure of the ocean and pump deep nutrient-rich water into the sunlit surface layers, by means of the wave pump [40]. A wave-driven artificial upwelling device consisting of a buoy and a vertical long pipe with a flow controlling valve is shown in **Fig. 9** [41]. The valve is closed when the wave crest approaches; at this time, the water column inside the pipe is accelerated upward with the device. As the wave descends, the device is subjected to a larger inertial force than the water column, which causes the valve to open. The deep ocean water then flows out of the device from the top of its tail pipe. It is reported that operating in regular Hawaiian waves, a wave-driven artificial upwelling device that consists of a buoy 4.0 m in diameter, a flow-controlling valve and a long tail pipe 1.2 m in diameter and 300 m in length can bring up more than $0.5 \text{ m}^3/\text{s}$ of deep ocean water to the surface.

A wave-driven artificial upwelling device was designed and constructed by University of Hawaii at Manoa, and two ocean field experiments were conducted in 1990s, about 1 mile off the southern coast of Oahu, Hawaii. As shown in **Fig. 10**, a 4-in. diameter PVC tail pipe protrudes from the bottom of the buoy [42,43]. The pipe is connected by a bolted flange to the lower plywood sheet. The flow-controlling valve is a rising stem type and is constructed of lightweight materials to allow the valve to open and shut with a minimum of force.

The experimental data showed that the upwelling flow is about 0.14 cubic feet per second, and it is noted that 1:10 model scale was used in this experiment. Mathematical and hydraulic modeling analysis indicate that a wave-driven artificial upwelling device consisting of a buoy with a water chamber of 4.0 m in diameter and a tail pipe 300 m in length and 1.2 m in diameter with flowing controlling valves can produce an upwelling flow of up to $0.95 \text{ m}^3/\text{s}$ in typical ocean waves off the Hawaiian Islands [44].

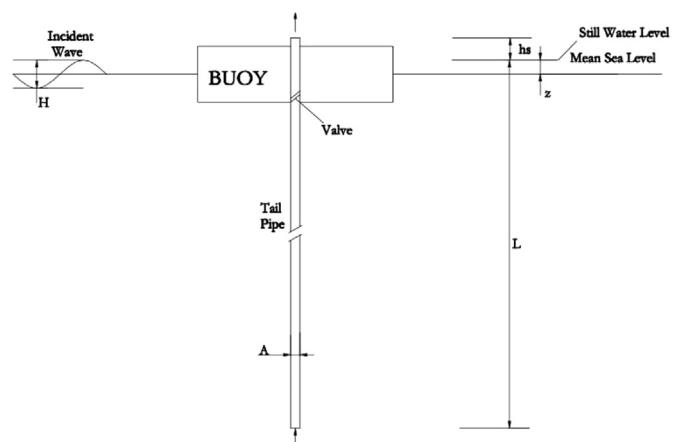


Fig. 9. Schematic diagram of a wave-driven artificial upwelling device.



Fig. 10. Ocean field experiments and Schematic diagram of the wave-driven artificial upwelling device designed by University of Hawaii at Manoa.

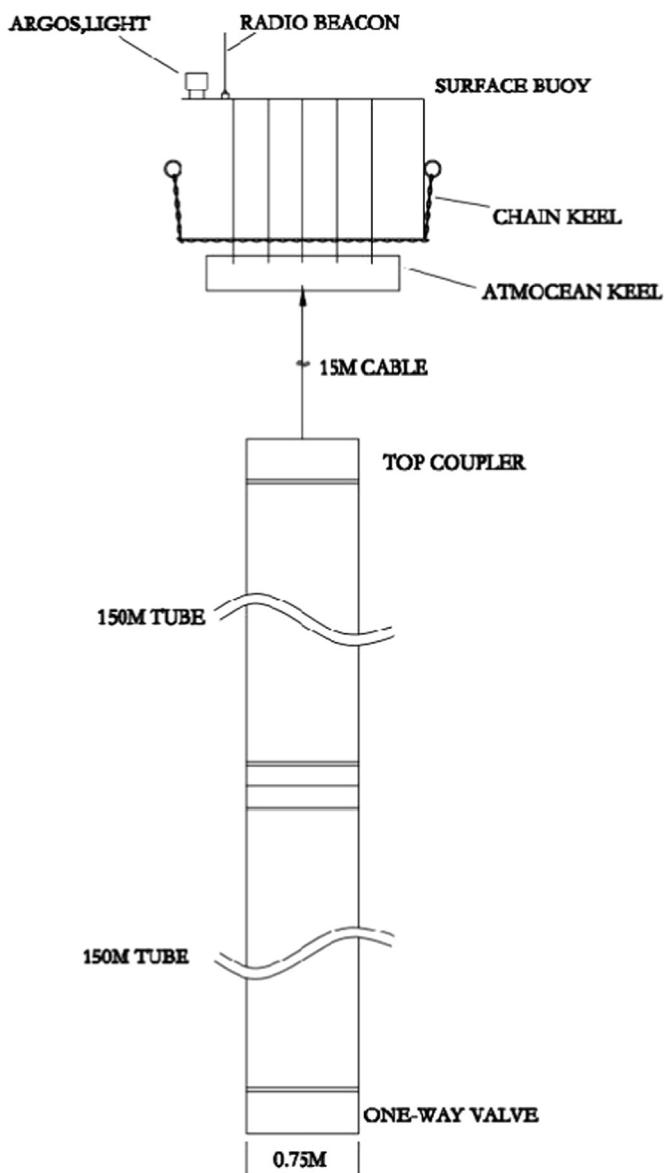


Fig. 11. Schematic diagram of the wave pumps deployed in northern Oahu, Hawaii.

A modern version of this concept is depicted in Fig. 11. It consists of a vertical The Isaacs wave pump consisted of a vertical long pipe attached to a surface buoy at the top and a one-way valve at

the bottom can be extended below the euphotic zone to act as a conduit for deep water. The vertical motion of the ocean forces the attached valve to open on the downslope of a wave and close on the upslope, thus generating upward movement of deep water to the surface ocean. The advantage is that the Isaacs wave pump device requires no power supply, only the natural current and wave forces were used to power the device. Upwelling velocities and total volumetric inputs generated by these pumps are a function of the amplitude and frequency of waves as well as the dimensions and efficiency of the individual pump [44].

As shown in Fig. 11, each pump kit consisted of a cylindrical ionomer foam surface float with an eye bolt on each end, two 0.75 m diameter, 150 m length sections of polyethylene "tubing" surrounding a 150 m length of 3/8 in. vinyl coated cable; a coupler to connect the two lengths; a set of five nylon ratchet straps; and associated hardware, including keel to affix the tube assembly to the surface float and the valve at the base.

Fig. 12 shows the deployment of the single pump [45]. The buoy was deployed firstly, and then the main masses of the pumps were deployed with the bottom valve of the pump system secured on deck. The forward motion of the ship causes the tube to slowly unwind to achieve full length. After it was fully opened, the valve and recovery line were deployed. The ocean productivity perturbation experiment failed to generate a measurable biological response, due to the materials failure. By all measures, the tube material, the welds, and the keel were structurally insufficient to survive the forces encountered in an open ocean deployment. Nevertheless, it is also shown that the underlying principal of the wave pump technology is sound. Wave pumps can transport deep, nutrient-rich water to the surface ocean.

Wave energy as power supply for artificial upwelling has been developed rapidly in the world. But in general, wave energy technology is immature. The existing wave energy devices for artificial upwelling are still deficient in many aspects, such as high cost, low efficiency, poor reliability, poor stability and small scale. The technology of wave energy as power supply for artificial upwelling could be widely used after it was matured and the price dropped notably. Besides reducing the price, the stability of power supply should be improved and independent power supply system should be developed so that wave energy can be directly used for artificial upwelling. According to current technical level, development of wave energy as power supply for artificial upwelling can be introduced into demonstration operation stage and cannot be commercialized in the near future.

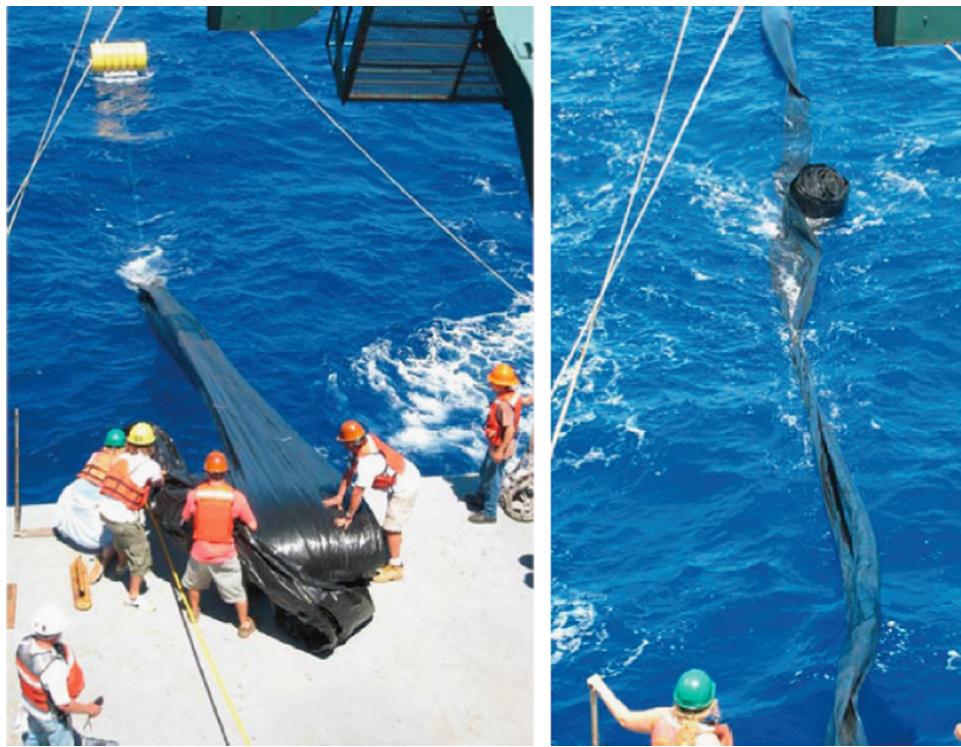


Fig. 12. The deployment of single pump.

5.2. Ocean current energy conversion

In 1978, a theory about a submerged apparatus consisting of a buoy, several horizontal contraction and expansion tubes was proposed by Liang [46]. By means of the dynamic of ocean current, the sub-surface sea-water containing abundant nutrients can be pumped to surface layer. As a result, the dynamic of ocean current can be expected as the power supply to the artificial upwelling. As shown in Fig. 13, a contraction and expansion tube and a long pipe are moored by a submerged buoy system [46]. Due to the Bernoulli effect, a low pressure is generated at the middle of the tube and the nutrient-rich sea-water will be sucked through the pipe and flow out of the tube. Because the apparatus is 50–100 m below the sea surface, the possibility of being destroyed by the seaway is hence very low.

Fig. 14 shows a schematic description of a preliminary laboratory experiment, both main body and tank are fixed to the towing vehicle, and the pipe connects the main body and the tank [46]. The water level in the tank is the same as that outside of the tank as the experiment begins, and as the speed of the vehicle is constant, then the valve will be opened and the water level begins to sink. From this curve the negative pressure head, which must be equal to the density difference head, and the corresponding velocity in the pipe can be obtained. Results from the laboratory experiment show that the capacity of pumping the nutrient-rich sea water by the dynamic of ocean current is worth to build a pilot prototype model, which is comparable to the natural upwelling.

Instead of contraction and expansion tube, a tube-pair, which consists of two contraction and expansion tubes, one inner tube and one outer, is designed and the field experiment is executed in 1978 at Nan Wan, southern tip of Taiwan, as shown in Fig. 15 [47]. The flexible upwelling pipe is of 40 cm in diameter and composed of iron-made ring, strong nylon cloth, protecting steel wires and small buoys. The experiment result shows that the pumping speed in field is much better than that in the laboratory. This may be due to scale effects and the big turbulence of ocean current.

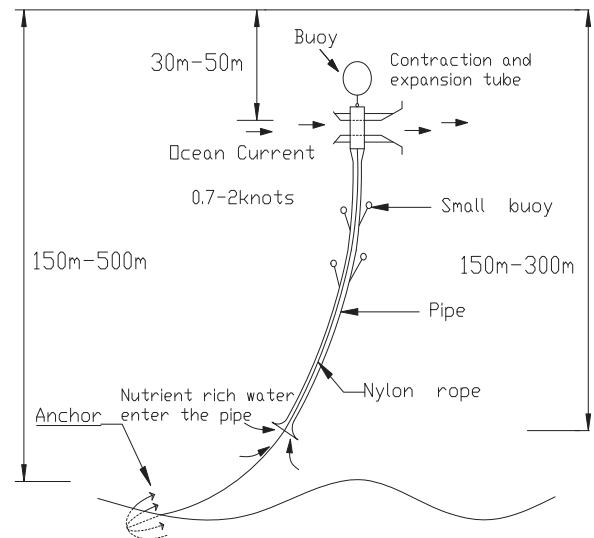


Fig. 13. A schematic description of artificial upwelling induced by ocean current.

Although the principle of ocean current energy as power supply for artificial upwelling is simple, there are lots of difficulties to be solved to achieve large scale and industrialization. Some experts hold that ocean current energy as power supply for artificial upwelling is difficult to be practically applied and commercialized, as the ocean current energy exploitation involves the environment of relatively strong ocean flow mainly in strait or water channel, where the environment impact both on the artificial upwelling and the flexible upwelling pipe can not be ignored. Therefore, few researchers in the world does further research on it after doing some theoretical and experimental researches and putting forward on some other environmental energy conversion as power supply for artificial upwelling.

6. Distributed generation method

The proposed distributed generation (DG) system used for air-lift artificial upwelling consists of DG units of a wind turbine, a

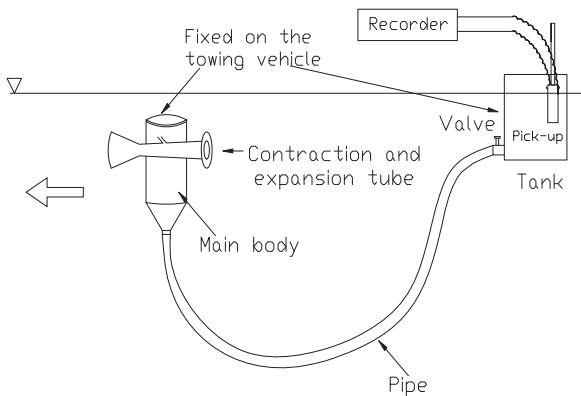


Fig. 14. A schematic description of the preliminary laboratory experiment.

wave energy converter (WEC) array, a PV array, a diesel generator and an air compressor, as shown in Fig. 16. The wind turbine generation system is modeled with an induction generator driven by a wind turbine controlled by a wind governor via a pitch angle of the turbine blades. Mechanical energy from the wind turbine drives the induction generator to generate AC electric power, which is converted into DC power to form the common dc link. PV array generates DC power by a DC-DC converter with a maximum power point tracking (MPPT) module to boost DC voltages, thus the PV array voltage can be raised to the equivalent common DC voltage level. The grid-side inverter changes DC power from wind turbine and PV array into AC power, of which voltage and frequency is required for being supplied into the air compressor. Moreover, a diesel generator is essential, which can be used to supplement the power to drive the air compressor especially when the wind turbine and PV array could not supply enough power. A typical WEC system consists of WEC array converting wave energy to compressed air generated by the pneumatic transmission system [48,49]. The output compressed air both from air compressor and WEC array is supplied to air-lift artificial upwelling. The

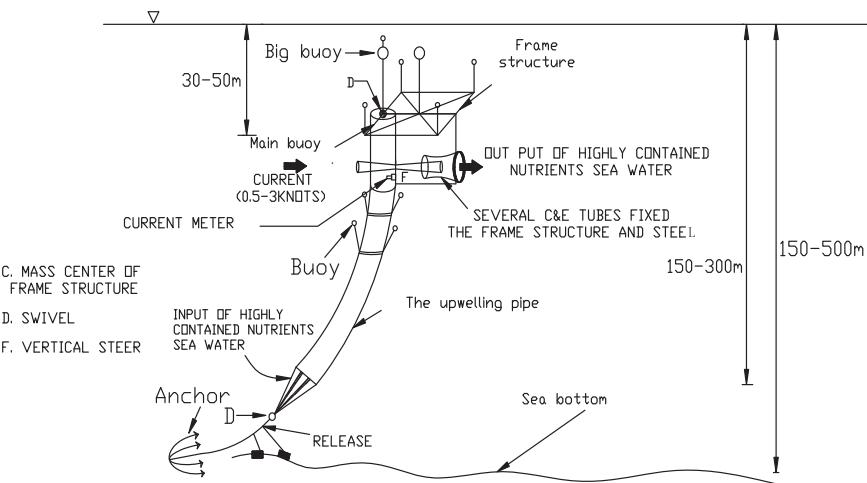


Fig. 15. A schematic description of the preliminary laboratory experiment.

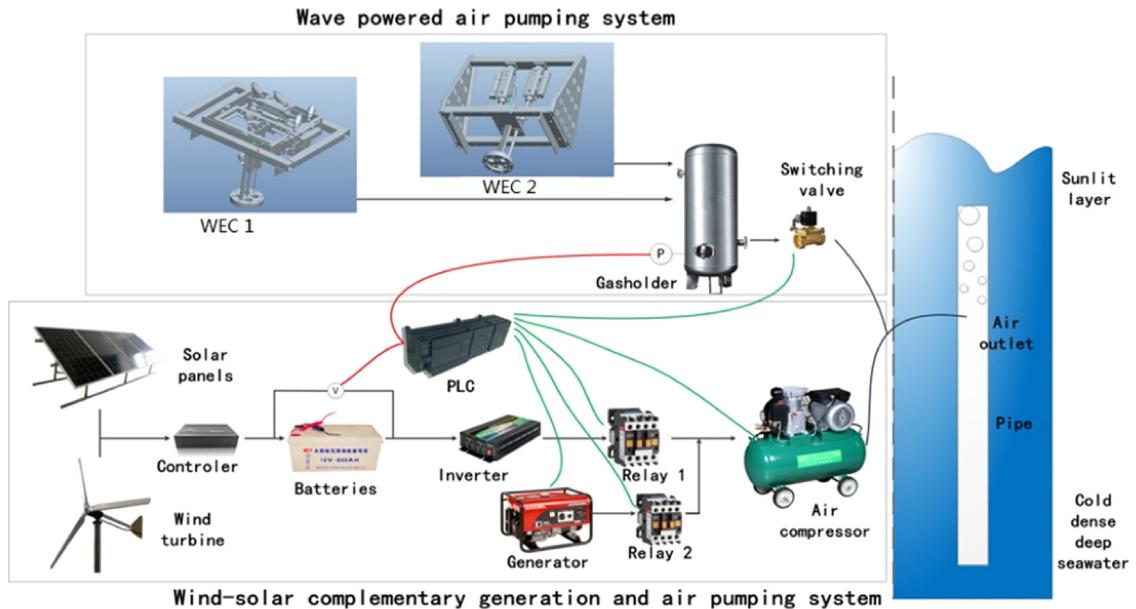


Fig. 16. Schematic diagram of the DG system.

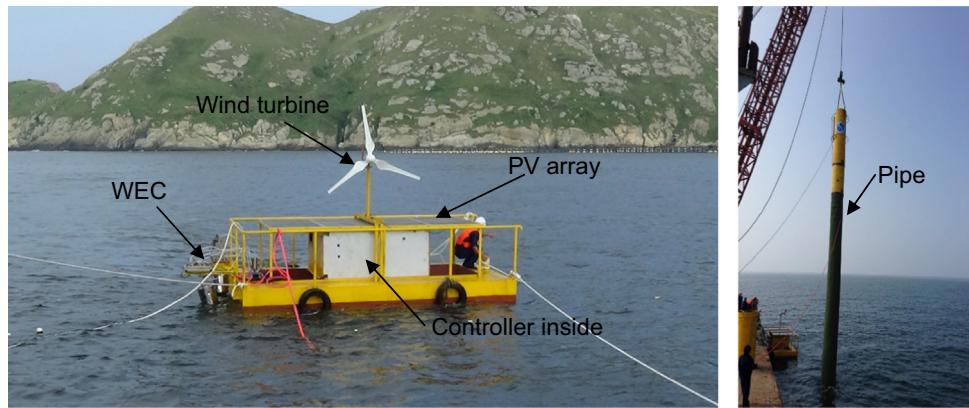


Fig. 17. The deployment of the DG system in sea trial.

deployment of the DG system developed by Zhejiang University in sea trial is shown in Fig. 17.

Energy storage is not discussed in this study. If there is excess local generation, the surplus electricity produced from DG units can be fed into the battery bank. If there is not enough local generation or there is excess local demand, the battery bank is assumed to be able to supply electricity to the air compressor and other loads. This system is assumed that the DG unit can operate independently by the on/off position of the breakers in the circuit.

The technology development of DG system used as power system for artificial upwelling is going to maturity now [50–52]. Some DG systems are in the stages of preparing works before demonstration at present. With solution of the key problems of power flow calculation, power quality, voltage control, fault diagnosis and stability, technological breakthrough is expected in near future [53–56]. The next stage, the research on DG energy as power supply for artificial upwelling should be concentrated on building of 100 kW level demonstration plants bases integrated with variety kinds of ocean energy in the long run.

7. Discussion and conclusions

In general, the techniques about power supply for air-lift artificial upwelling are appropriate and suitable for certain applications. They own unique advantages and drawbacks.

Perpetual salt fountain can provide unlimited operation time without consideration of power limitation. However, the perpetual salt fountain technology is strongly limited in the middle latitudes of the Northern Pacific Ocean and some areas of the tropics and subtropics, where the salinity of surface seawater is higher than that of deep seawater and the seawater is overall stably stratified, and little convective motion occurs in the vertical direction. Besides, only if the pipes are deployed in a large scale, upwelling deep seawater by the perpetual salt fountain could have the possibility to enhance the primary production of the ocean.

Air-lift pump and air-bubble screen method is probably the most efficient and matured way as power supply for air-lift artificial upwelling. It is very simple, insensitive and needs little maintenance. However, there are also some drawbacks: (1) air-lift pump method is shown to be strongly dependent on the geometrical parameters of the upwelling pipe, type of air injection nozzle and air volume flow rate; (2) the working range of air-bubble screen method is limited by the topography; (3) high-power air compressor is needed as the power system, and the power supply for high-power air compressor is a big problem in the ocean; and (4) long tube may be twisted or broken.

Ocean thermal energy conversion (OTEC) is quite a novel way to power artificial upwelling. It is reliably and predictably available at all hours. It can be harvested while underway. However, the limitation is that the temperature gradient is not available globally. It can only be satisfied in tropic and semi-tropic areas. That is because the temperature difference it needs must be greater than 10 °C between surface and depth. Therefore, the vehicle powered by thermal energy can only be used between 35° south latitude and 35° north latitude. Moreover, it is not cost-effective in practice as it cost too much.

Wave energy conversion is quite feasible for air-lift artificial upwelling' power supply. However, harvesting wave energy is quite a difficult process, because it is dispersive and random. Besides, the conversion efficiency is quite low due to energy loss during energy conversion stages. It is necessary to simplify the conversion process and minimize the energy loss to improve the reliability and efficiency.

Distributed generation method is huge, clean and renewable, and the potential to keep the artificial upwelling working a long duration, even an unmanned station keeping mission. It is much better than OTEC and wave energy conversion. It is not restricted by time or places. It can provide energy source for artificial upwelling at any time and any place in theory. However, there are still some limitations. For example, the conversion of solar energy into electrical energy is restricted by time, and it can only be completed in daylight. Wind turbine and WEC array are restricted by wind energy and wave energy, respectively.

As discussed, environmental energy conversion is the most promising choice as power supply for artificial upwelling. It is giant, clean and regenerative, and has a brighter future and more applications. As is known to us, the electrical power of artificial upwelling is traditional, carried from shores or generated by a diesel. The electrical power imported from shores by cables is costly and complicated, and the electrical power generated by the diesel is also restricted in its capacity. Instead of that, the electrical power can be obtained by the environmental energy conversion, such as wave energy, wind energy, solar energy and thermal energy.

The artificial upwelling technologies especially the technologies of power supply for air-lift artificial upwelling have significantly advanced in recent years. The present situation all over the world shows that the development of the wide variety of power supply systems in artificial upwelling application, from concept to full-scale sea trial stage, is a difficult, slow and expensive process. They are possessed with some advantages and limitations, and applied in different situations and their feasibility, survivability and reliability should be demonstrated.

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