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Enhancing fish stocks with wave-powered artificial upwelling

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Abstract

Ocean fisheries are declining worldwide due to overexploitation. Productivity could be enhanced and the problem alleviated by pumping nutrient-rich deep ocean water (DOW) to the surface to feed phytoplankton, the bottom end of a marine food chain, mimicking natural upwelling which sustains the most productive ocean fishing grounds in the world. Various pump types and power sources have been proposed for this purpose. The present article proposes a simple wave-powered pump to demonstrate the concept cost-effectively at prototype scale. Possible solutions to the problems of dilution and plunging of dense, nutrient-rich DOW are discussed. Two further possible benefits of this proposal are discussed: by extracting wave energy, relatively calm fishing grounds may be created close to markets, and by pumping up very large quantities of cold DOW, the surface temperature could be lowered enough to reduce coral bleaching on parts of the Great Barrier Reef.

1. Introduction

It has recently been estimated [1] that 75% of the world's commercial fish stocks are being fished at or above mean sustainable levels. This situation is likely to get worse as the world's population grows, unless one of two things happens: either consumption must be regulated—a difficult if not impossible task—or productivity

Abbreviations: DOW, Deep ocean water; FRP, Fibre reinforced plastic—general term for fibreglass carbon fibre and similar materials in which high strength fibres are embedded in a plastic matrix; OTEC, Ocean Thermal Energy Conversion—a process in which the temperature difference between cold deep ocean water and warm tropical surface water is used to drive a heat engine; OWC, Oscillating Water Column—a technique for harnessing wave energy.

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must be increased. The change from hunting and gathering to cultivation and husbandry on land has supported a huge increase in the earth's population over the last few thousand years, but the same has not happened to a significant extent in the oceans. Some agricultural techniques have had adverse effects on the land, but others have proven sustainable. These successful techniques generally emulate natural processes, such as the annual floods which replenish soil moisture and nutrients on some flood plains, or the nutrient pump action of deep-rooted plants. For example Yeomans [2] has shown how chisel ploughing and irrigation can increase the depth of biologically active soil, and Groocock [3] has demonstrated how productivity can be enhanced by mixing nutrient-rich clay subsoil with poor sandy topsoil. Ocean fisheries are still at the hunter-gatherer stage, and rather than developing ever more effective ways to further overexploit the existing finite resource, it is time to find ways to increase the resource by developing techniques which enhance productivity in a sustainable way.

Most marine animals and plants live in the top 40 m of the water column [4]. When they die, there remains sink. In shallow coastal waters the nutrients can be recycled and these areas can be highly productive. But if the water is deeper than about 40–100 m, they sink below the euphotic zone, enriching the deep ocean water (DOW) but becoming unavailable to phytoplankton, which form the lowest trophic level of the marine food chain and require light to grow. The nutrients can then re-enter the food chain only where this nutrient-rich DOW is brought to the surface. This does not generally happen in warm and temperate regions of the oceans due to the density difference between the warm surface water and the cold DOW. As a result most tropical and temperate oceans have low productivity [4]. But in cold waters at high latitudes and in regions where currents bring cold polar water from the high latitudes, the ocean surface temperature drops to about 4°C and its density is similar to that at the bottom. The nutrient-rich DOW is then easily brought to the surface by turbulent mixing. Upwelling of DOW also occurs near some coasts, especially the west coasts of Southern Africa and South America due to ocean circulation. These regions of natural upwelling correspond to some of the most productive ocean fishing grounds of the world, contributing 90% of global ocean natural production [5].

2. Emulating natural upwelling

There is now growing interest in the prospect of emulating this natural upwelling process and increasing ocean fish production in areas where there is no natural upwelling, by pumping large quantities of nutrient-rich DOW from depths of some hundreds of metres up to the euphotic zone. The density difference between the surface and deep water is only about 2–3 kg/m^3, and although this is enough to prevent nutrients reaching the surface by natural mixing, the mechanical energy required to overcome it is relatively small, as will be shown below. Large amounts of nutrient-rich deep ocean water could therefore be pumped up with a relatively small amount of power. If a low cost, low maintenance technology for pumping the water up and maintaining it within the photic zone without excessive dilution can be found, locations close to markets could be chosen for artificial upwelling, thereby reducing harvesting costs. The use of wave energy for pumping would reduce the energy in the waves in the area, thereby creating a relatively calm and comfortable environment for fishing. This would be beneficial in an area such as the mid-west coast of Western Australia, where "strong southerly winds that persist throughout most of the year…result in many lost fishing days" and "quite large scale seas (>2 m)…can make fishing and research operations difficult" [6]. It may also be possible to reduce coastal erosion by careful selection of sites for wave energy extraction.

Besides the potential for enhanced fish production, it has been suggested [7] that artificial upwelling on a very large scale in areas of the ocean where typhoons form could cool the surface just enough to prevent them, or at least reduce their severity. While this visionary proposal may at first sight seem like a dangerous interference with natural processes, it would be easily reversible, unlike other effects of human intervention such as deforestation, desertification and global warming. Upwelling could be trialled on a gradually increasing scale and discontinued or reduced in scale if any unexpected harmful effects were to occur.

A further possible benefit of pumping up large quantities of cold water to the surface would be to reduce the water temperature on areas of the Great Barrier Reef where coral bleaching is occurring. As with typhoons or cyclones, only a very small temperature change can make a critical difference, but unlike typhoon mitigation, reduction of coral bleaching could be trialled at moderate cost on a small area, and if successful it could be expanded.

3. Barriers to implementation of artificial upwelling

The newness of the concept and the lack of prototype operating experience on which to base designs is a barrier to the implementation of artificial upwelling. Governments tend to be cautious about committing resources to unproven technologies and private investors are unlikely to commit very large sums of venture capital until the following questions are answered:

- Would the cold, dense, deep ocean water released near the surface just sink again to a level below the euphotic zone where the nutrients it contains would not be available to phytoplankton?
- Would the nutrients be diluted by mixing to the point where their concentration is too low to make a significant impact on productivity?
- What flow rate would be needed to prove the concept?
- How much would it cost to construct, deploy, tether and power very large pumps capable of lifting the required amount of water from the required depth, in the open ocean where they would be subject to storms and would get little maintenance?
- Who would have rights to fish in the productive areas created: who would pay and who would benefit?

However the potential benefits are so enormous that it seems well worthwhile to seek to overcome these barriers and investigate possible conceptual designs for prototype development. Models have demonstrated that water can be pumped using a simple wave-powered device, but these models were far too small to measurably increase fish stocks. They are still a long way from the proposed ambitious large-scale projects powered by ocean thermal energy conversion (OTEC). What is needed now is a low cost, high flow system to demonstrate that fish stocks can indeed be increased economically by artificial upwelling. This article addresses some of the above concerns and proposes design modifications to the wave-powered inertia pump concept, which the author believes would provide an economically feasible next stage in the development of this technology beyond the small models hitherto tested.

4. Plunging and dilution

Cold, dense, nutrient-rich water could be simply pumped to the surface and released, but it would then tend to ‘‘plunge,’’ or sink back to its neutral buoyancy level at the thermocline where the cold, dense deep water meets the warm surface water. According to Tait and Dipper [8], the thermocline is typically at a depth of 100–500 m in low latitudes. The euphotic zone, where photosynthesis can occur, extends to 40–50 m in middle latitudes during summer months and to 100 m or more in low latitudes if the water is fairly clear. Below 200 m is aphotic, i.e. no photosynthesis can occur. Therefore water plunging to the thermocline in most situations would soon become unavailable to phytoplankton again and little would be achieved.

The cold nutrient-rich water discharged into the warm surface water tends to become diluted by mixing, which reduces the density difference and hence its tendency to plunge, but also dilutes the nutrients. If there is too much dilution the increase in nutrient concentration may be too diffuse to produce an obvious measurable effect and the benefits, if any, would be difficult to quantify.

Much has been written on mixing of ‘‘plumes’’ and ‘‘fountains’’ of fluid entering a surrounding fluid of different density (see for example [9,10]). The degree of mixing depends on a number of factors, some of which may be controlled, such as discharge velocity, position and orientation of discharge ports. Liu [11] has given some consideration to the issues of plunging and dilution in the context of artificial upwelling. Liu’s modelling for a discharge of $0.95\,m^3/s$ at various depths predicts an initial dilution ranging from 47:1 for surface discharge, dropping to about 10:1 for 50 m deep discharge, and an equilibrium depth ranging from 50 m for surface discharge to 75 m for 50 m deep discharge. The degree of mixing is greater near the surface due to wave action. From figures in [8] quoted above, the diluted nutrient-rich deep ocean water sinking to these equilibrium depths would remain within the euphotic zone in low latitudes but not in middle latitudes. To assess whether DOW diluted to this degree would provide enough nutrient concentration to be useful, it is necessary to know nutrient concentrations at depth and the concentrations necessary to enhance productivity. Some data from Gauthier [5] and McKinley and Takahashi [12] are shown in Table 1, while Table 2 shows predicted nutrient concentrations near the surface where DOW is pumped to the euphotic zone and diluted by mixing as predicted by Liu [11].

Although the comparisons in Tables 1 and 2 are based on very limited data, they suggest that dilution could well cancel out the benefits of DOW pumping and should therefore be minimised, at least in the early stages of proof of concept. To overcome this problem, Gauthier [5] has suggested that nutrient-rich water could be pumped into an atoll lagoon where it would not be able to disperse and become diluted as much as it would in the open ocean. This would ensure that even a limited amount of nutrient-rich water would have a significant and readily measurable effect.

Where deep water exists close to nutrient-poor shallow coastal waters, it may be feasible to improve productivity by pumping DOW into the shallow coastal water. The more dense DOW would still tend to form a gravity current along the bottom and flow back into the depths, but it would not be lost as rapidly as it would in the open ocean where it can plunge vertically. In the absence of any natural confining bottom features, a large membrane could be suspended below the surface by means of floats, and the DOW could be pumped onto it. However this would substantially increase the cost, and Gauthier's atoll proposal seems the best option for initial proof of concept.

Table 1
Measured nutrient concentrations and productivity in deep ocean water and surface water, after Gauthier [5] and Mc Kinley and Takahashi [12]

Location	Water	NO_3 (mmol/m^3)	PO_4 (mmol/m^3)	Productivity (gC/m^2/yr)
Coastal upwelling	Natural upwelling, surface	20	?	High: 250–2000
Open ocean	Surface	<1	?	Low: 50
NELHA	Surface	0.24	0.15	?
Papeete	Surface	0.1–1	0.4–0.5	?
NELHA	600 m depth	39	2.89	Low (below photic zone)
Papeete	700 m depth	12–18	0.7–2.5	Low (below photic zone)

Table 2
Diluted nutrient concentrations in deep ocean water pumped to the euphotic zone and mixed with surface water as predicted by Liu[11]

Location	Water	NO_3 (mmol/m^3)	PO_4 (mmol/m^3)	Productivity (gC/m^2/yr)
NELHA	From 600 m depth, diluted 10:1	3.9	0.29	?
Papeete	From 700 m depth, diluted 10:1	1.2–1.8	0.07–0.25	?
NELHA	From 600 m depth, diluted 40:1	1	0.07	?
Papeete	From 700 m depth, diluted 40:1	0.3–0.45	0.018–0.06	?

5. How much flow is required, and from what depth?

To deliver useful quantities of nutrients, a large flow is needed from a considerable depth. There is no clear-cut minimum depth or flow rate. Matsuda et al [13] proposed using a 10 MW OTEC plant to pump $50\,m^3/s$ from a depth of 5–600 m. They have estimated that this amount of deep ocean water would produce $3.3 million revenue in fish per year and would be economically viable. This seems a reasonable starting point.

Gauthier [5] states that atoll lagoons range in size from a few sq km to thousands of sq km, with depths of a few tens of m. If we take for example a small lagoon 10 sq km and 40 m deep on average, the volume of water is $4 \times 10^8\,m^3$. Pumping at $50\,m^3/s = 4.32 \times 10^6\,m^3/day$ would take about 100 days to completely replace the water. There will presumably be some exchange between the lagoon and the ocean and therefore some dilution, but these figures suggest that $50\,m^3/s$ is a reasonable flow rate for proof of concept. If a very small lagoon is available for trials, a lower flow rate could be adequate.

Some authors suggest that nutrient-rich water is available at depths of around 100–300 m, considerably less than those used in Matsuda et al. [13]. This would reduce the energy required for pumping. For example Hanson [14] shows plots of nitrate and phosphate increasing steadily from the surface, reaching about half their maximum deep ocean concentrations at depths of around 300 m. Tait and Dipper [8] states

"Although this upwelling water probably does not rise from depths greater than some 100–200 m, this is deep enough to supply nutrients to the Canaries Current, Benguela Current, Peru Current, California Current and West Australian Current, and these are all areas of high fertility."

However these natural systems bring up huge quantities of DOW with little or no dilution, and for artificial upwellings a trade-off must be made between depth and concentration to achieve necessary concentrations after dilution. Thus a depth of 5–600 m seems a reasonable starting point for exploratory calculations.

6. Pumps and energy sources

Although the concept of artificial upwelling is simple, little has been published to date on practical design aspects of pumping systems large enough to make a significant impact. Various forms of pumps have been proposed, including oscillating inertia spar tube pumps [11,15], airlift pumps [16] and bellows pumps [17]. Proposed energy sources include wind power, solar power, ocean currents [17], wave power [11,15,17] and OTEC [7,13].

The more ambitious proposals are generally based on OTEC, and upwelling is often treated as a by-product of OTEC and a further justification for its development, rather than as an end in itself. As an energy source, OTEC has the advantage of constant power supply, unlike most ambient energy sources. This would be an important consideration if nutrients are continually being lost by sinking with the dense water below the photic zone, necessitating a constant flow of DOW. However constant power may not be a great advantage in a system pumping into a shallow atoll lagoon where nutrients would accumulate in the euphotic zone and could be utilised by phytoplankton at times of low energy availability, i.e. in calm weather in the case of wave energy.

OTEC is a much more sophisticated method of extracting energy than the simple inertia pump demonstrated by Liu [11] and Vershinsky et al. [15]. OTEC involves heat exchangers, which tend to have corrosion and fouling problems in a marine environment, and a low temperature heat engine which requires a volatile working fluid such as freon or ammonia, which tends to leak out unless seals are kept in good condition. It is therefore suited more to large scale, large budget projects which justify the presence of skilled technical maintenance personnel, than to modest "proof of concept" projects.

Dunn et al. [7] proposed several hundred OTEC-powered energy pods, each of 1000 MW output, each pumping 1.7 billion m^3/day (about 200,000 m^3/s) to prevent typhoons. While this scheme may be technically possible, it would seem prudent to gain experience in the design, construction, installation, operation and environmental impacts of upwelling devices by progressing gradually from simple technologies and modest sizes to large and more sophisticated installations. If evidence of cost-effective enhanced fish productivity without adverse environmental impacts can be demonstrated with a modest sized unit, this will strengthen the case for larger, more ambitious projects, possibly powered by OTEC if that appears to be the most cost-effective option.

7. Wave-powered inertia pumps

Detailed designs for practical artificial upwelling systems are scarce. Liang [16] cites an upwelling project in 1968 described in Roels et al. [18] but gives no details of how the water was pumped. Only two accounts of actual working pumps designed to demonstrate artificial upwelling have been found in the literature: those of Liu [11] and Vershinsky et al. [15]. These were both small models, orders of magnitude smaller than those that would be needed at full scale, and there is a need to assess whether this system is practicable at full scale.

In 1983, Vershinsky [15] demonstrated an elegantly simple upwelling device comprising a vertical tube with a float at its top end containing a non-return valve. In this device, shown schematically in Fig. 1, the whole assembly moves vertically up and down with the swell. Because the density of the DOW is only about 0.2% greater than that of the surface water, its gravitational acceleration is much reduced and the inertia of the DOW in the tube keeps it moving upwards as the tube moves down.

Vershinsky et al's device had a cross-sectional area of 0.071 sq m (0.3 m diameter), and pumped 10 l/s from a depth of 30 m in a 0.35 m swell with a 4 s period. Liu [11] describes model tests using a 0.1 m diameter "spar buoy" operating on the same principle as Vershinsky et al's model, in a 3 ft (0.9 m) swell with a period of 4 s. He

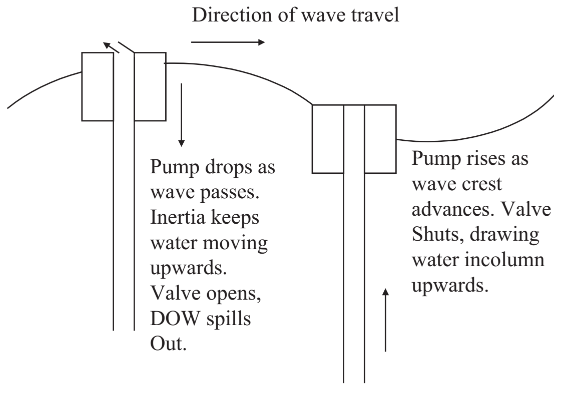

Fig. 1. Inertia pump action.

gives the following equation for ideal discharge Q from an inertia pump:

$$Q = \pi AH/T, \quad (1)$$

where A is the tube area, H the wave height from trough to crest and T is the wave period.

This is based on $Q = v_{\max}\ A = \omega r\ A = (2\pi/T)(H/2)A = \pi AH/T$, where $v_{\max}$ is the maximum upward velocity of pump, assumed equal to the maximum upward velocity of the water surface $=\omega r$ (assuming simple harmonic motion) $= (2\pi/T)(H/2) = \pi H/T$.

This equation gives the upper limit to the discharge, ignoring the following factors:

1. The retarding effect of gravity on the rising water column inside the tube. The water column will rise at a maximum velocity $v_{\max}$ equal to the maximum upward velocity of the float as it rises on a wave. But as the wave passes, the non-return valve no longer exerts a force on the water column and its upward velocity v is retarded by gravity. For Liu's model mentioned above, it is shown in Appendix A that this factor would result in only about a 3% reduction in discharge. But for a prototype, assuming $T=12$ s, $H=1.9$ m and $\Delta\rho=2\ \text{kg/m}^3$, there would be a 23% reduction.
2. The reduced stroke due to increased submergence of the float as it lifts the water column. This is shown in Appendix A to result in a 12% reduction in the stroke for a steel tube pumping $50\ \text{m}^3/\text{s}$.
3. Truncation of the stroke if the waterline area of the float is large in relation to the wavelength of the waves. This would not be a significant problem for a moderate sized pump in long wavelength waves, but would place an upper limit on the size of a float, and hence a pump, in relation to the wavelength.

Eq. (1) predicts an ideal discharge of 5.6 l/s for Liu's model. By measuring the time for dye to rise in the tube he calculated a discharge of 3.8 l/s. By measuring the time to fill a bag, presumably a more accurate method, the flow rate was calculated at about 2.1 l/s. He then used these data to predict a flow of $0.45\ \text{m}^3/\text{s}$ from a depth of

300 m using a tube 1.2 m in diameter in regular waves of 1.9 m height, and 0.95 m^3/s in irregular waves. 0.45 m^3/s is the value given by the ideal discharge equation for regular 1.9 m waves, but seems optimistic in view of his experimental results.

The 50 m^3/s flow rate proposed by Matsuda et al. [13] is 3–4 orders of magnitude larger than that achieved by Vershinsky's model and 2 orders greater than that for Liu's proposed prototype. This is a very large increase in size and would necessitate a very large tube if the whole 50 m^3/s is to be pumped by a single unit. Using Liu's equation $Q = \pi AH/T$ with $H = 1.9$ m and $T = 12$ s and assuming the actual pump achieves 50% of the ideal discharge, $A = 201\ m^2$, i.e. the tube must be 16 m in diameter. Its length must be in the order of 300–600 m, depending on the depth at which nutrient-rich water is available.

The whole structure would have to be robust enough to withstand storms and would have to be tethered to prevent it from drifting with the winds and currents. Assuming a density difference of 2 kg/m^3 between the deep water and the surface water, and a water column 16 m in diameter and a thermocline 300 m deep, a force of about 1.2 MN (120 tonnes) would be needed to lift the water column.

Calculations set out in Appendix B show that such a device would be very heavy and expensive if constructed of conventional carbon steel or reinforced concrete. It would also require a float about 30–40 m in diameter. Other more exotic materials such as stainless steel or FRP (fibre reinforced plastic or fibreglass) would be much more expensive. Another possibility is the use of a tensioned membrane structure in which a rigid frame keeps a light, relatively inexpensive flexible fabric in shape by tension. A tensioned cable net structure of circular cross section 180 m high with a maximum diameter of 140 m has been used as a cooling tower in Germany [19]. This demonstrates that such structures of the size required for upwelling are feasible.

8. Improved inertia pump design

Four design improvements to the inertia pump are proposed. The first is to locate the non-return valve at the *bottom* of the tube instead of the top, so the pressure inside the tube is greater than that outside and the tube need not be rigid to maintain its shape. The second improvement is to provide three tubes in a tripod formation, with the bottom of each tube attached via an elastic cable to an anchor. This would have three benefits: (i) it would prevent the whole assembly from drifting with ocean currents and winds, (ii) it would ensure that the bottom of the tube containing the non-return valve sinks as the float enters a trough, and (iii) it would convert some of the horizontal component of the wave's energy, compared with the conventional inertia pump which utilises only the vertical component.

The third improvement, made possible by the first, is to construct the tube of light, low cost, flexible fabric similar to that now in use in Australia for draft tubes for circulating water in reservoirs [20,21]. Assuming surface water at an average temperature of 20°C above a thermocline at a depth of 500 m, and DOW at 5°C, the density difference is about 2 kg/m^3. The maximum static pressure difference between the inside and outside of the tube is then about 10 kPa or 1 m of water, a very low pressure by normal pumping standards. If necessary the material could be reinforced longitudinally by stainless steel or carbon fibre tendons. The use of a non-rigid tube would greatly reduce the capital cost and the cost of deployment. For example $650\,g/m^2$ (gram per square metre) PVC fabric is about 0.5 mm thick, costs about AUD $10/m^2$ (US$$6/m^2$) and it has a tensile strength of about 90 MPa. This would be adequate for a pressure of up to 10 kPa in a 4 m diameter tube, so a 500 m long tube 4 m in diameter would cost about US$36,000 supply only and perhaps twice that figure fabricated. For larger diameters stronger or thicker fabric would be required, but at shallower depths lighter fabric could be used. For transportation the tube could be laid flat and folded or rolled up like a fire hose.

The fourth proposed improvement is to use an efficient wave energy conversion device instead of a simple float as a source of power, as described below. This would have several advantages.

Although the spar buoy inertia pump used by Vershinsky et al is simple and appears suitable for small sizes, it is not necessarily the most appropriate and cost-effective pumping device available. According to Liang [17], a spar buoy converts only 6% of the incident wave energy, although it is not clear how he arrived at that figure. The figures quoted in Liu [11] and Vershinsky et al. [15] suggest even lower efficiencies. The efficiency of energy conversion is not necessarily important if the energy source is limitless and the cost of conversion is low. However it has been shown above that the size of a single unit and material costs are considerable. Thus a more efficient wave energy converter is desirable.

Efficient wave energy converters have been proposed. For example a class of wave energy converters known as "terminators" has been described [22]. These are generally wide structures aligned perpendicular to the incident wave direction, moving in a damped motion in response to the waves. The damping force can in principle be converted to mechanical and hence electrical power.

Probably the best known form of terminator is the Salter "Duck" [23], which was shown in laboratory tests to extract 80% of the incident wave energy. Evans [24] showed theoretically that up to 50% of the wave energy could be extracted by a floating or submerged cylinder moving either laterally or vertically if correctly tuned to the incident wave, and up to 100% by a cylinder moving in orbital motion, thereby creating calm water in its wake. Davis [25] further developed the concept, calling it the "Bristol Cylinder," and proposed energy extraction by pairs of cables at 45° to the vertical (Fig. 2). As the cylinder moves in a circular orbit, the tethering cables are alternately pulled and released, moving in approximately simple harmonic motion.

One drawback of wide terminators aligned perpendicular to the wave direction is that the waves do not always come from the same direction. To overcome this problem, Davis has suggested a sphere with three tethering cables in orthogonal directions so that a combination of two or three cables will operate regardless of wave direction. However a long cylinder aligned parallel to the prevailing wave crests, with a pair of cables near each end so the two ends can move out of phase, is a further option.

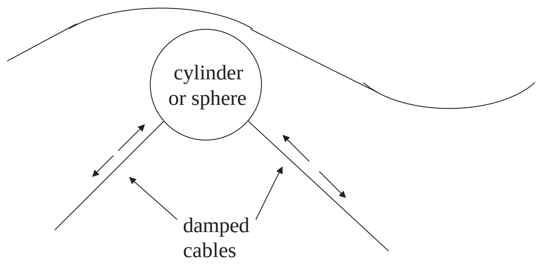

Fig. 2. The ‘‘Bristol cylinder’’ wave energy device.

A drawback of most wave energy conversion devices (with the exception of the OWC or ‘‘Oscillating Water Column’’ system which drives an air turbine and the Tapchan system which directs water through a hydro turbine) is that a slow reciprocating or orbital motion with a period of 8–12 s must be somehow converted to high speed rotary motion to drive a generator. However this is not a problem in the present application, since water can be pumped efficiently by means of inertia pumps, which can be driven directly by the tethering cables. Any upwelling device must be tethered with cables to the ocean floor to prevent it from drifting with the wind and ocean currents. Both to minimise the cost of cables and to locate the device near to markets, it makes sense to locate it in the shallowest water consistent with plentiful nutrient-rich bottom water and large swells. In the present proposal the tethering cables also serve to transmit power from the terminator to the pump, thereby reducing the cost. A submerged cylinder or sphere would have the advantage of being less susceptible to damage by storms or impact of ships than the large float on the surface required by the conventional inertia pump: there would be just a small float on the surface for easy location.

9. Feasibility of pumping 50 m^3/s

For ‘‘small amplitude’’ waves, the energy E and power P available per metre of wave crest are given by Sorensen [26] as $E = \rho g H^2 L/8$ and $P = nE/T$, respectively, where ρ= density = 1020 kg/m^3 approximately for sea water, H =wave height, L =wavelength in m, $n = 0.5$ in deep water and L = wavelength $= gT^2/2\pi$ in deep water = 1.56 T^2.

Thus for a wave height $H = 1.9$ m and period $T = 12$ s, as quoted in [11], $L = 225$ m and the power per m of wave front $P = 41.5$ kW/m.

According to Berge [27], areas of high wave energy density exist along the coast of Norway, with some sites recording average densities of 50 kW/m of crest or more. Thus the waves selected by Liu would be regarded as high energy by world standards.

It is shown in Evans [24, Fig. 14] that a maximum efficiency close to 100% can be achieved when the dimensionless wave number $v = 2\pi a/L$ is between about 0.3 and 0.8, where a =cylinder radius. Thus a cylinder of diameter $2a = vL/\pi = 21.5$ m would be suitable for $L = 225\,\text{m}$. If the cylinder is say 40 m long and its capture efficiency is say 80%, it will capture $41.5 \times 40 \times 0.8 = 1328\,\text{kW}$ of power.

The power required to raise $50\,\text{m}^3/\text{s}$ of water from 500 m depth against a density difference of $2\,\text{kg/m}^3$ is 500 kW. Thus such a cylinder would be more than adequate.

10. Conclusion

Artificial upwelling is a promising way to increase ocean food production, with other possible benefits including reduced coral bleaching and reduced typhoons (cyclones). Although Ocean Thermal Energy Conversion (OTEC) may be suitable for very large, sophisticated installations, a wave-powered inertia pump is much simpler and could be used to prove the concept. This would have the added benefit of calmer seas at the newly created fishing grounds. Design improvements to the inertia pump are proposed, including the use of flexible fabric for the delivery tube and the use of a Bristol cylinder wave energy converter to drive the pump. It is concluded that a single 21.5 m diameter cylinder 40 m long would work efficiently in 1.9 m Hawaiian swells and would be more than adequate to pump $50\,\text{m}^3/\text{s}$ from a depth of 500 m.

Appendix A. Factors reducing inertia pump performance

1. The retarding effect of gravity on the rising water column inside the tube. The water column will rise at a maximum velocity v_{max} equal to the maximum upward velocity of the float as it rises on a wave $= \pi H/T$, ignoring the effect of increased submergence of the float as it exerts an increased force on the water column to accelerate it. But as the wave passes and the float drops, the non-return valve no longer exerts an upward force and the water column's upward velocity v is retarded by gravity according to

$$v = v_{\text{max}} - g't, \tag{2}$$

where $g' = g\Delta\rho/\rho$, the reduced gravitational acceleration due to the difference in density $\Delta\rho$ between the deep water density and the surface water density ρ, as shown in Fig. 3.

Provided $v_{\text{max}} - g'T > 0$, the minimum upward velocity will be

$$v_{\text{min}} > v_{\text{max}} - g'T = \pi H/T - g'T \tag{3}$$

and to a first approximation, the mean upward velocity will be

$$v_{\text{mean}} \approx \pi H/T - g'T/2. \tag{4}$$

For $H = 2\,\text{m}$, $T = 12\,\text{s}$ and $\Delta\rho = 2\,\text{kg/m}^3$, $v_{\text{mean}} \approx 0.524 - 0.115 = 0.408$, a 22% reduction in average water velocity and therefore in pumping discharge.

This reduction in discharge will increase with longer period waves and a larger density difference between the DOW and the surface water. Thus for Liu's model

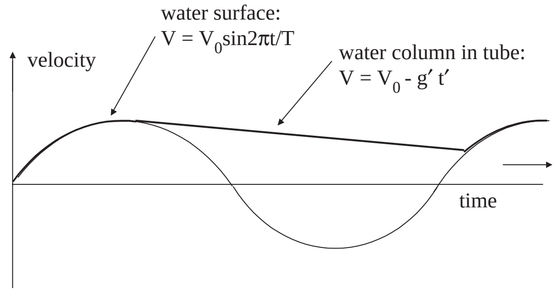

Fig. 3. Vertical velocity of water surface and water in tube.

mentioned in this article, with $T = 4$ s and $\Delta\rho$ probably no greater than $1\,\mathrm{kg/m^3}$, $g' = 9.8 \times 1/1020 = 0.0096$. $V_{\max} = \pi H/T = 0.707$ m/s, and $V_{\text{mean}} = 0.707 - 0.0096 \times 4/2 = 0.688$ m/s, only 3% less than $V_{\max}$.

But for the proposed prototype, assuming $T = 12$ s, $H = 1.9$ m and $\Delta\rho = 2\,\mathrm{kg/m^3}$, $v_{\text{mean}} = \pi H/T - g'T/2 = 0.497 - 0.115 = 0.382$ m/s, a 23% reduction.

If $v_{\text{mean}} = 0.382$ m/s, and $Q = 50\,\mathrm{m^3/s}$, then $A = Q/V = 131\,\mathrm{m^2}$ so diameter $D = 12.9$ m. So mass of water $= 131 \times 500 \times 1020\,\mathrm{kg} = 66,800,000$ kg. If the change in velocity produced by each upstroke $= g'T = 0.23$ m/s, the work done equals the change in momentum $mv = m\Delta v = 65.5 \times 10^6 \times 0.23 = 15$ MJ. This happens every 12 s, so average power $= 15/12$ MW $= 1.225$ MW.

The work required simply to raise the water, i.e. to increase its potential energy, is $Q\Delta\rho gh = 500$ kW. The difference is due to the loss of momentum of the water due to gravitational acceleration when it is not being lifted by the pump. i.e. the maximum efficiency of this pump for the amplitude, period and density difference is approximately $0.5/1.225 = 40\%$.

2. The reduced stroke due to increased submergence of the float as it lifts the water column. This reduction can be made small only by making the waterline area of the float large in relation to the force necessary to lift the water column. For example it is shown in Appendix B that a float approximately 30 m in outside diameter, 8 m deep, would be needed to lift $50\,\mathrm{m^3/s}$ of water from 500 m depth through a steel tube. The increased submergence due to the weight of water would be 0.24 m, reducing the stroke by 12.6%.

3. Truncation of the stroke if the waterline area of the float is large in relation to the wavelength of the waves. This would not be a significant problem in long wavelength waves.

Appendix B. Weight and cost of steel, concrete and fabric tubes for an inertia pump

To lift a column of water 12.9 m in diameter and 500 m deep with a submerged density of $2\,\mathrm{kg/m^3}$, a force of 1.3 MN or 130 tonnes would be needed.

For an inertia pump made of normal structural carbon steel, the plate thickness would need to be at least 10 mm to allow for corrosion, and two skins with stiffening webs would be needed to make the structure stiff enough to prevent local buckling. For a 500 m tube length with a 12.9 m inner diameter, this would require about 400 m^3 or 3120 tonnes of steel. The submerged weight of each tube would be about 2700 tonnes, necessitating 2700 m^3 of float volume in addition to the 130 m^3 needed to account for the force to lift the water. Allowing for the self-weight of the floats, they would therefore need a displacement of at least 3000 m^3. They would have to float in the top few metres of water where the maximum wave amplitude occurs. An annular float of the required volume, 6 m deep with a waterline area of 500 m^2 and a 12.9 m diameter internal space for the tube would have an outside diameter of 28 m.

Assuming the fabricated steelwork costs AUD 3000 or $US 1800/tonne, the tube alone would cost $US 4.68 million. Add the cost of supply of the floats, anchors and mooring cables and the installation cost, and the total installed cost is unlikely to be less than $US10 million, giving a 3–4 year payback period assuming (optimistically) an annual operating profit of $US 3 million based on Matsuda et al.'s [13] $3.3 million annual revenue. These figures are only exploratory and more accurate costing of the structure and assessment of the potential revenue from enhanced fish stocks at any given site would be necessary before any large scale demonstration could be justified.

Conventional reinforced concrete tubes would need a wall thickness of at least 0.2 m to protect reinforcing steel from corrosion, giving 4000 m^3 of concrete with a submerged weight of 6000 tonnes, requiring even larger floats, say 7000 m^3 and about 40 m diameter. Although the cost of the tube itself would be a lot lower, about $US 0.5 million, the sheer size and weight of the tube makes this option unattractive.

The submerged weight of a fabric tube would be almost negligible. Thus a float volume slightly in excess of 131 m^3 would be needed. However the waterline area would still need to be large, in the order of 500 m^2, to prevent excessive loss of stroke as the 1.3 MN force to lift the water is applied by the rising swell and released as the crest passes. Thus is would still need to be very large.

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