Experimental study on the performance of an air-lift pump for artificial upwelling

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A B S T R A C T

Air-lift pumps for artificial upwelling of ocean water are finding increasing use as marine primary productivity could be enhanced by pumping nutrient-rich deep water to the surface to feed phytoplankton. This paper presents experiments and theoretical analysis to obtain the performance of an air-lift pump for artificial upwelling. Experiments are performed at one submerged depth, with four different air injection nozzle designs and various injected air volume flow rates. A theoretical model is proposed taking into account the flow characteristics of air-lift artificial upwelling. The performance of the model has been confirmed by the experimental findings. The present results show that the pump capacity and efficiency are functions of the geometrical parameters of the upwelling pipe, air volume flow rate, air injection method and vertical distribution of water density. It is found that the upwelling efficiency increases with the increase of the pipe diameter due to the reduction of the frictional loss, the kinetic energy and the power demand of the sea surface rise. Moreover, the air injector design has a considerable effect on the upwelling efficiency. Further work will have to determine the optimal design of the geometrical parameters of the upwelling pipe and the air injection nozzle.

1. Introduction

The global main marine fish stocks are in jeopardy, increasingly pressured by overfishing and environmental degradation. It has recently been estimated that 75% of the world's commercial fish stocks are being fished at or above mean sustainable levels (Villasante et al., 2011; Brian, 2003). It is time to find ways to increase this resource by developing techniques which enhance productivity in a sustainable way (Brian, 2003).

Even though the aphotic zone occupies about ninety percent of the ocean, more than ninety percent of the world's marine life lives within the top and sunlit layer of the ocean. Yet there are large areas in the ocean with sufficient sunshine but little nutrients on the surface, hence very low productivity of phytoplankton which is at the bottom of most marine food chains (Nozaki, 1998). However, in the dark areas, more than 200 m below sea surface, there is more inorganic nutrients than the surface water (Maruyama et al., 2004).

Research conducted on artificial upwelling over the past few decades has made it possible to bring up deep ocean water (DOW) and distribute it in the surface waters to increase phytoplankton production in the euphotic layer and thus to enhance the open ocean mariculture (Williamson et al., 2009; Isaacs et al., 1976). Furthermore, Mcclimans et al. (2002, 2010) used a fresh water source first, and then a combined method of fresh water and bubble curtain to lift significant amounts of nutrient-rich seawater to the light zone and provide an environment in which useful algae can survive at a large-scale fjord-experiment. Pumping buoyant surface water below the pycnocline is an energy efficient alternative to the other schemes (Aure et al., 2007). On the other hand, eutrophication of water bodies frequently leads to nuisance algal growth, anaerobic hypolimnetic conditions, and a general deterioration of water quality (Fast et al., 1975). Artificial aeration and upwelling is often used to reduce eutrophication or conditions associated with eutrophication (Grochowska and Gawronska, 2004).

Various mechanical or wave powered devices have been suggested to draw up the deep ocean water. First, 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 (Isaacs et al., 1976). Liu described a similar wave-driven artificial upwelling device which could bring up a constant supply of deep ocean water to support open ocean mariculture (Liu and
A major motivation behind the concept of the Isaacs wave pump was to extract energy from the surface gravity waves in the ocean. The Isaacs wave pump consists of a buoy and a wave pump was to extract energy from the surface gravity waves (Qiao, 1995). A third type of water pump is the air-lift pump for upwelling deep ocean water (Liang, 1996). An air-lift pump is a simple pump which is powered by compressed gas. A gas, usually air, is injected in the lower part of a pipe that transports a liquid. As a result of the gas bubbles suspended in the water, the average density of the two-phase mixture in the pipe is less than that of the surrounding fluid. By fluid pressure, the liquid is taken in the ascendant air flow and moves in the same direction as the air. Air-lift pumps are used in specialized applications, where more conventional pumps fail to operate. It can be used for pumping hydrocarbons, dirty water, dangerous fluids, viscous fluids (Gerlando et al., 2010), in bioreactors (Zimmerman et al., 2009; Couvert et al., 2001), and for seabed mining (Pougatch and Salcudean, 2008). Compared with other hydraulic transport processes, the simplicity and lack of moving mechanical parts are two important advantages which make air-lift pumps useful for applications such as the manganese nodule mining from the deep ocean floor (Weber, 1976) and the upwelling of cold deep nutrient-rich ocean water. Liang and Peng (2005) described a conceptual air-lift pump as a device for upwelling deep ocean water through a vertical pipe totally submerged in the seawater, by means of compressed air introduced into the pipe near the upper end. It was estimated that the seawater flow rate can be a hundred times higher when compared to the air flow rate (Peng, 1999). However, no experimental method and data on the performance of the air-lift artificial upwelling were found in the literature.

In this paper, we evaluate the hydrodynamic performance of an air-lift artificial upwelling system, using experimental data.
and theoretical analysis. An experimental study is performed on air-lift artificial upwelling systems in Thousand-Island Lake, which lies at 29°33′51″ north latitude and 119°11′9″ east longitude. The air-lift pumping system has been tested for artificial upwelling from 30.4 m depth. An empirical model is developed to predict the water pumping rate for a given air flow rate and the air flow rate needed to obtain a prescribed water pumping rate based on theoretical energy balance. To verify the new model, simulations are compared with experimental measurements. Hopefully, the work we have done will be useful for future research of air-lift artificial upwelling systems.

This paper is organized as follows. First, we describe the experimental setup and procedure, and then, an empirical model for the prediction of the water volume flow rate as a function of the air volume flow rate is proposed. Next, the theoretical and experimental results and the analysis are given respectively. Finally, some conclusions are summarized.

2. Experimental setup

In September 2011, we traveled to the Xinanjiang Experiment Station to run field experiments with the air-lift pumping system. The Xinanjiang Experiment Station is located in the Thousand-Island Lake, Chun’an County, Zhejiang Province, China (see Fig. 1). The area we used is a hundred meter squared area with an average depth of 50 m. This facility provides pier side mooring, storage and a ship based crane for loading the air-lift pumping system. It also provides an access controlled facility for security.

The objective of this study is to examine the effects of air flow rate on the hydrodynamics of the air-lift upwelling in a 0.4 m diameter pipe in which friction effects are significant. The pump was operated with four different air injection nozzle designs and the water flow rate was measured at various flow rates of injected air. The air flow injection rate and the air injection method were varied during the experiments in order to study their effects on the performance of the air-lift pump. The air flow injection rate ranged from 1.9 to 40.0 N m⁻³/h.

Fig. 2 shows the schematic diagram of the experimental set-up. A vertical pipe of 28.3 m length and 0.4 m internal diameter was deployed. The upwelling pipe was made of nylon-reinforced PVC sheet. It was composed of a water suction pipe (h₀ = 20 m) and a gas injection section pipe (h₀ = 8 m). The pipe was totally submerged vertically in water and the submerged depth of pipe outlet was h₀ = 2.1 m. An air compressor (Model W-0.36/8) was used. Air passed from the air compressor 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). The air then went through a mass-flow meter (Model MF5619) which was used to control the constant air flow rates. Air was metered and the volume flow rate was determined from the reading of upstream pressure and the temperature together with the reading of the mass-flow meter of gas. Compressed air was delivered at point B through an external pipe.

In the suction pipe, between points B and C, there was only water flowing, while all of the gas injection section (between points B and O) was occupied by the two-phase water–air flow. Four different air injection nozzle designs were used with

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Fig. 1. The Xinanjiang Experiment Station at 29°33′51″ north latitude and 119°11′9″ east longitude, located in the Thousand-Island Lake, Chun’an County, Zhejiang Province, China.
different air flow rates (from 1.9 to 40 N m$^3$/h). The nozzles were made of stainless steel and placed at the center of the upwelling pipe so that the bubbles free themselves easier and do not cling to the pipe wall. Figs. 3 and 4 show the experimental apparatus and the air injection nozzles, respectively. A total nozzle hole area of 75.4 mm$^2$ was chosen and divided into two injection hole arrangements (24 and 384 holes) to span a large-scale experimental range. The injection holes were drilled into steel tube using plasma arc drilling. Specifications of the used nozzles are shown in Table 1. The diameter of the holes of Nozzle No.1 and Nozzle No.4 was 0.5 mm. The diameter of the holes of Nozzle No.2 and Nozzle No.3 was 2.0 mm. The inside diameter of all pipes was 8 mm. The diameter of all the nozzle configurations (cross sectional area) was 250 mm. The diameter of inject hole and the nozzle shape were the parameters that were

![Fig. 3. Photos of the apparatus setting and the research ship. (a) The upwelling pipe on the deck. (b) Installation of the gas injection section of the upwelling pipe. (c) An electromagnetic flowmeter installed in vertical upward pipe at the bottom of the gas injection section. (d) Water rising to the surface under internal hydrostatic pressure. (e) The research ship.](image)

![Fig. 4. Photos of the air injection nozzles. (a) Nozzle No.1, cross, 384 holes. (b) Nozzle No.2, cross, 24 holes. (c) Nozzle No.3, circular, 24 holes. (d) Nozzle No.4, circular, 384 holes.](image)
cold water to the upper layer, the bottom of the pipe was set at a depth of 30.4 m below the surface of the lake.

### 3. Theoretical analysis

In this section, expressions for estimating the energy requirements for the proposed air-lift artificial upwelling systems are developed from theoretical considerations.

#### 3.1. The gas void fraction in the gas injection section

The gas void fraction in the gas injection section is typically measured using a pair of quick-closing values installed along a pipe to trap the two-phase fluid, whose respective air and water volumes are then determined (Thome, 2004). The terminal rise velocity of 2–20 mm diameter bubbles in still water is about 0.25 m/s (Clift et al., 1978). Foremost, because bubbles rise at their terminal velocity relative to the surrounding flow, their velocity is greater in an upwelling flow and the transit time across the water column is reduced (Leifer et al., 2009). A stream of bubbles causes an upwelling flow which enables bubbles in the bubble stream to rise faster than if they were alone. In this paper the gas void fraction in the gas injection section is defined as:

\[
\varepsilon = \frac{V_A}{V_a + V_w} = \frac{Q_a/0.1((h_0/h_c) + 0.5(h_u/h_c)) + 1)}{Q_a/0.1((h_0/h_c) + 0.5(h_u/h_c)) + 1 + \tau_a} \times \frac{Q_w}{Q_w}
\]

where \(\varepsilon\) is the gas void fraction in the gas injection section. In this study, the values of gas void fraction under different air flow rates (from 1.9 to 40 N m\(^3\)/h) range from 2–5%. \(V_a\) is the volume of the gas injection section occupied by the air phase, \(V_w\) is the volume of the gas injection section occupied by the water phase, \(Q_a\) is the volume air flow rate at atmospheric pressure, \(Q_w\) is the volume water flow rate, given by \(Q_w = (\pi/4)D^2h_c\), \(h_c\) is the mean velocity of the water in vertical upflow, \(\tau_a\) is the mean velocity of the bubble in upwelling pipe, \(\tau_w\) is the constant 0.25 is the terminal rise velocity of 2–20 mm diameter bubbles in still water (Clift et al., 1978). \(D\) is the diameter of the upwelling pipe, \(\tau_a\) is the transit time of the bubble across the length of the gas injection section pipe, \(\tau_w\) is the transit time of the upwelling water across the length of the gas injection section pipe, \(h_c\) is the submerged depth of pipe outlet, \(h_s\) is the constant of depth \((h_s = 1\ m)\) and connected to the constant 0.1. \(\eta\) is the factor given by \(\eta = 0.1(h_0 + 0.5h_u)/h_c + 1\) and defined as the estimate of the compression of the air volume at mid-depth of the lifting pipe. \(A\) is the upwelling pipe cross-sectional area, given by \(A = \pi D^2/4\).

#### 3.2. Power balance required for air-lift artificial upwelling systems

The problem considered is the prediction of the water volume flow rate as a function of the air volume flow rate. The geometric parameters \((h_u, h_s, D)\), a submerged depth \(h_u\) and the water properties such as vertical distribution of density at the upwelling location are given as input data to the theoretical model.
equations. As the basic performance data of the air-lift artificial upwelling is computed, secondary results such as the efficiency may easily be determined. The main question is the energy flux balance, which is integrated across the upwelling pipe to assess the effects of air flow rate, water flow rate, friction loss power in the pipe and power demand of the sea surface rise. Liang and Peng (2005) theoretically modeled an air-lift pump for upwelling deep seawater. However, the model did not include the effects of the gas void fraction and the local head loss produced by devices and blockages such as nozzle, valves, pipe bends, enlargements, contractions, adhesion of marine fouling organisms on upwelling pipe, which obstructs the pipe flow. Here we extend the power balance equation for artificial upwelling (Liang and Peng, 2005) to include the effects of the gas void fraction and the local head loss. The power balance equation is as follows:

\[
E_i = E_o + E_r + E_{ru} + E_{ed} + E_t + E_r + E_{rise} + E_s
\]

where \(E_o\) is the input power as follows:

\[
E_i = \int_{P_0}^{P_D} \rho_a dP = Q_w P_0 \ln \left( \frac{P_D}{P_0} \right) = Q_w P_0 \ln \left( \frac{P_0 + \rho_a g h_u}{P_0} \right)
\]

where \(P_r\) is the pressure at the air tube outlet, \(P_0\) is the atmospheric pressure, \(\rho_a\) is the density of the air–water mixture, \(\rho_d\) is the density of water at the upwelling pipe inlet (point C, see Fig. 2), \(\rho_w\) is the density of water, \(\rho_{a'}\) is the density of air, \(h_u\) is the density of water at the upwelling pipe outlet (point O, see Fig. 2), while \(g\) is the gravitational acceleration.

\[
E_o = \int_{h_u + h_w}^{h_u + h_w} Q_w \rho_a g \left( \frac{\rho(l) - \rho_0}{\rho_0} \right) dl
\]

where \(h_w\) is the pipe length under the air injection, \(g(l)\) is the reduced gravitational acceleration, given by \(g(l) = g(\rho(l) - \rho_0) / \rho_0\), \(\rho(l)\) is the density of water at depth of \(l\) m.

\[
E_k = \frac{1}{2} A \times u_w \times v_w \times \nu_w \times \frac{\rho_d - \lambda}{2} \times \frac{q_w^3}{A^2} \times \frac{q_w^3}{A^2}
\]

where \(\nu_w\) is the mean velocity of the air–water mixtures in vertical up-flow. The mean velocities depend on the lateral distribution of the void fractions. The velocity profiles for the bubble phase and liquid phase can be found from the time-averaged velocity fields. The entrained water velocity profile follows a Gaussian distribution and the bubbly velocity profile follows a top-hat distribution (Seol et al., 2007). The Reynolds number, \(Re\), is given by

\[
Re = \frac{D_{\text{bub}}}{\nu} = \frac{DQ_w}{\nu A} = \frac{4Q_w}{\pi D^2}
\]

where \(\nu\) is the kinematic fluid viscosity. In this study, the experimental data on the air-lift pump were obtained over a range of Reynolds numbers from \(0.7 \times 10^2\) to \(2.7 \times 10^5\). So the water flow inside the upwelling pipe was typically turbulent flow in addition to the excitation due to the bubble source. \(E_{ed}\) is frictional loss power in the low pipe.

\[
E_{ed} = \frac{Q_w P_0}{P_D} \frac{h_u}{D} Q_w = \frac{h_u \rho_d Q_w^3}{2DA^2}
\]

The differences between Eqs. (7) and (10) lie in the values of the mean velocities \((u_{\text{m}}\text{ and } v_{\text{m}})\) and the pipe lengths \((h_u\text{ and } h_w)\). \(E_i\) is the local head loss produced by devices and blockages such as nozzle, valves, pipe bends, enlargements, contractions, adhesion of marine fouling organisms on upwelling pipe, which obstructs the pipe flow.

\[
E_i = \frac{2A^2 E_i}{\rho_d Q_w^3} = \frac{2A^2 Q_w^3}{\rho_d Q_w^3} = \frac{2A^2 Q_w^3}{\rho_d Q_w^3}
\]

where \(\rho_d\) means pressure drops. The experimental results indicate that the local head loss coefficient equals to 0.021 when the value of \(Q_w\) is 298.5 m³/h.

\[
E_{rise} = \text{the entrance head loss power (Liang and Peng, 2005)}.
\]

\[
E_{rise} = \frac{\rho_d Q_w}{2A^2}
\]

where \(\xi_r\) is the entrance frictional loss coefficient. The end loss depends on the shape of the entrance and its effect on creating turbulent eddies (Crowe et al., 2005). In this study, the pipe inlet is sharp-edged. Hence the streamlines converge and then diverge with consequent turbulence and relatively high head loss. Attempts should be made to minimize the head loss at the pipe inlet to improve passage.

\[
E_{rise} = \text{the power demand of the sea surface rise (Liang and Peng, 2005)}.
\]

\[
E_{rise} = \rho_d Q_w^3
\]

where \(h_r\) is the sea surface rise. Using dimensional analysis and the experimental data, Peng (1999) proposed an empirical formula for \(h_r\).

\[
h_r = \frac{13}{8} \left( \frac{Q_w h_u}{A_{\text{max}}/g} \right)^{2/3} \exp \left( -12 \frac{h_u}{h_u} \right)
\]

In an attempt to verify Eq. (15) experimentally, the water level dynamics were recorded by using a water level sensor (Modle 280-WL400). The data showed that the maximum error between the calculation values using Eq. (15) and the measured mean
values of the surface rise was less than 1.6 mm. The experiment result agreed well with the empirical relation.

\[ E_r = \text{frictional loss power of the sliding (relative) speed between the bubble and the water (Liang and Peng, 2005).} \]

The values of \( E_r \) calculated using the proposed formula (8) (Liang and Peng, 2005) account for less than 0.2% of the total loss and can be assumed to be negligible when the upwelling flow is turbulent.

Then Eq. (16) can be obtained by substituting all terms into Eq. (2).

\[
Q_w \rho_w g \left[ 1 + \left( \frac{Q_w^2 (\alpha + 0.25Q_w \eta A \rho_d + Q_a Q_w \rho_d)}{Q_w^2 \eta + Q_d Q_w + 0.25Q_w \eta A} \right) \frac{g h_u}{\rho_d} \right] = \rho_w \frac{\rho_d}{\rho_0} g \int_{h_u + h_b}^{h_d} (\rho(l) - \rho_0) dl + \frac{Q_d^2}{2 A^2} \times \rho_d \\
+ 0.01227 \rho_d \frac{Q_d^2}{2 A^2} \frac{h_u}{D} Q_w + \frac{0.7543}{(4/\pi Dv)^{0.38}} \rho_d h_u D Q_w^{0.62} \\
+ 0.01227 \times \rho_d \frac{Q_d^2}{2 A^2} + \frac{0.7543}{(4/\pi Dv)^{0.38}} \times \rho_d h_u D Q_w^{0.62} \\
+ \rho_d h_u Q_w + Q_d \frac{\rho_d}{\rho_0} g \int_{h_u + h_b}^{h_d} (\rho(l) - \rho_0) dl \\
\]

Equation (16) can address two basic air-lift design problems. First, calculation of the water pumping rate \( Q_w \) for a given air flow rate \( Q_a \). Second, calculation of the air flow rate \( Q_a \) needed to obtain a prescribed liquid pumping rate \( Q_w \).

Using the presented model, a computer program was developed in order to investigate the air-lift pump performance over an extended range of the pump operation. For prescribed values of \( h_u, h_a, h_d, D, \rho_u, \rho_w, \rho(l) \) and \( Q_a \) are assigned, \( Q_w \) can be calculated numerically from Eq. (16) by the iteration method. A calculation procedure to obtain the results using the proposed model is as follows:

1. The geometrical parameters of \( h_u, h_a, D, \) submerged depth \( h_0 \) and the vertical distribution of density at the upwelling location \( \rho(l) \), are known. Then for a known air inlet pressure the inlet air volume flow rate is assigned.
2. Assume a value of water volume flow rate \( Q_w \).
3. Compute the coefficient of the Reynolds number, \( Re \), from Eq. (9). Also calculate the friction \( \lambda \) and \( k \) from Eqs. (8) and (12).
4. Calculate the sea surface rise \( h_b \) from Eq. (15).
5. Calculate the value of the left hand side and the right hand side of Eq. (16).
6. Repeat steps 3–5 until the total difference between the left hand side and the right hand side of Eq. (16) becomes less than 0.1.

4. Results and discussion

4.1. Discharge—Air flow rate characteristics

The results of lifting water in the upwelling pipe of an air-lift pump, at various values of air volume flow rates corresponding to one atmospheric pressure are presented. In Fig. 6 the water volume flow rate is plotted versus the supplied air volume flow rate for all the injection nozzles used. The experiments show that very low air flow will just produce bubbles in the upper pipe and no water will make it to the outlet. In order to achieve an upwelling action of the air-lift system, i.e., to have the first portion of water in the gas injection section pipe, a minimum air flow rate, \( Q_{amin} \), is required. Below this \( Q_{amin} \) no water reaches the pipe outlet. However, the limiting value of the \( Q_{amin} \), when the upwelling pipe totally submerged in the water, is expected to be zero. As the air volume is increased a little more, the water will start to be taken in the ascendent air flow and flow to the outlet. Shortly beyond this point, increasing the air volume flow rate will result in the most efficient flow of water. Continuing to increase the air volume flow rate will produce increases in water volume flow rate, but at a cost of reduced efficiency. Fig. 7 shows that too much air causes an increase in the water flow rate but at a lower discharge ratio. If air is increased still further, it will result in a dramatic reduction of the interfacial drag and result in decreased water volume flow rates when the gas volume fraction increases to 6.4%. To explain this concept, we point out that water flows through a pipe of decreasing cross-sectional area with the increases of the gas volume fraction. The key to producing an efficient artificial upwelling is to find the best air flow under given conditions.
In order to evaluate the validity of the results obtained using the proposed model comparisons with the experimental results were performed. The comparisons are shown in Figs. 6 and 7 for a submergence depth of 2.1 m. It is clear from these figures that the results of the proposed model basically agree with the experimental data over a range of air mass flow rates up to 33 N m$^{-2}$/h while there is a deviation for the remainder of the pump performance curve. This is due to the upwelling pipe and the air injection nozzles in high-volume flow rate operations where they are subject to loss of useful energy due to friction. It is not taken into account in the present model. The average deviation based on root mean square values between the results of the present model and the experimental results is about 4.6% (nozzle No.2), which is acceptable if the model is used to investigate the performance in practical applications. However, the experimental data of nozzle No.4, though better at low and the experimental results is about 4.6% (nozzle No.2), which is root mean square values between the results of the present model into account in the present model. The average deviation based on

The field experiment showed the water flow rate could be 5–40 times the air flow rate (see Fig. 7). This is more energy-efficient than the oscillating inertia spar tube pumps (Liu, 1999; Vershinsky et al., 1987) and bellows pumps (Liang, 1991).

4.2. Efficiency—Air flow characteristics

In order to obtain dimensionless parameters for the air-lift artificial upwelling system without considering the energy loss through the manifold behind the air compressor injection and the injection nozzle, thus, to compare the performances of the air-lift pump when different designs of the upwelling pipe and nozzle are utilized, a suitable parameter for comparison is the efficiency. It is usual to define the efficiency of the air-lift pump as the net work done in lifting the cold, dense, nutrient-rich water, divided by the work done by the isothermal expansion of the air. Using Eqs. (3) and (5), the efficiency of the air-lift pump can be expressed as:

$$n_e = \frac{E_0}{E_t} = \frac{Q_w(\rho_d/\rho_0)g \int_{h_0}^{h_u} (\rho(t) - \rho_0)dl}{Q_a P_0 \ln(1 + ((Q_w^2 \eta + 0.25Q_w^2 \eta A)\rho_d + (Q_aQ_w^2 \rho_0)/(Q_w^2 \eta + Q_aQ_w + 0.25Q_w^2 \eta A)(gh_u/P_0)))}$$  \hspace{1cm} (17)

where $n_e$ is the efficiency of the air-lift pump.

Pump efficiency versus air volume flow rate, for a submergence depth of 2.1 m, is shown in Fig. 7. As the air volume flow rate is increased, the efficiency increases rapidly from 0 to reach a maximum value of 20.54% at an air volume flow rate equal to 1.95 m$^3$/h. However, the maximum water volume flow rate of 298.5 m$^3$/h occurs when the air volume flow rate equals to 32.8 m$^3$/h. Hence, it is important to notice that the maximum efficiency does not occur at the maximum water volume flow rate for all air injection nozzle designs.

Estimation of head losses due to friction in the upwelling pipe is an important task in optimization studies and hydraulic analysis of air-lift upwelling system. When the adhesion of marine fouling organisms on upwelling pipe, which increases as time goes by, becomes so thick, compared to the original irregularities on pipe surfaces, it will increase the pressure drop and the friction losses in the upwelling pipe. Pipes with less smooth walls will create larger eddy currents which will sometimes have a significant effect on the frictional resistance. When the air volume flow rate for upward flow is high enough to induce significant turbulence in the water, the energy loss begins to rise rapidly. For example, Figs. 7 and 8 show that at injection rate of 1.95 N m$^3$/h, nozzle No.1 showed the highest maximum efficiency where a maximum efficiency of 20.54% was obtained and 66.7% of input power was dissipated into friction. However, the efficiency decreased rapidly by 12.93% and the power dissipation due to fluid friction increased by 17.5% when the air volume flow rate increased to 10.98 N m$^3$/h. $E_f$ is defined as the total frictional loss, as shown in Fig. 8:

$$E_f = E_{fu} + E_{cd} + E_t + E_c$$  \hspace{1cm} (18)

4.3. Mixing—Water flow characteristics

The performance of an artificial upwelling system includes how effective the upwelled water mixes with the ambient surface water. This depends on the spectrum of the turbulent kinetic energy in the flow that leaves the outlet. The specific turbulent kinetic energy (TKE) is perhaps the most relevant quantity in terms of the ability of the flow emerging from the upwelling pipe to mix with surface water. Here we consider the TKE defined as (Kim et al., 1987)

$$k = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right)$$  \hspace{1cm} (19)

where $\overline{u'}$, $\overline{v'}$, and $\overline{w'}$ denote the fluctuations of the three velocity components, and the overbars indicate time averaging. By definition, the average of the (stochastic) fluctuating variable is zero. The average of the square of the fluctuations is always positive. Furthermore, for isotropic turbulence (the usual assumption), the fluctuations in all three directions have the same absolute value. Thus, the specific turbulent kinetic energy $k$ is given by $k = 3 \times \overline{u'^2}/2$. Cold deep seawater discharged upwards into ambient water bodies can exhibit complex flow processes, such as
The air-lift pump has been working continuously at a water flow rate of 298.5 m³/h. The theoretical efficiency curves at different air flow rates are presented in Fig. 10. They have similar trends as the one presented in Fig. 7 for a pipe diameter of 0.4 m. The measured vertical distribution of density and temperature is shown in Fig. 9. The air-lift pump has been working continuously at a water flow rate of 298.5 m³/h for 2 h at the moment. As the cold deep water fell through the ambient upper layer, its volumetric flow rate increased and its mean density decreased. Before intrusion at about 18 m depth, the width of upwelling plumes increased at the cost of reduced vertical velocity. It could be seen that the most intense mixing in the ambient appeared within 2.7 m around the upwelling pipe, because of the potential energy of the dense surface water and the pronounced vertical velocity sheared between the vertical negatively buoyant jet and the ambient surface water, which enhance mixing. Future experimental and numerical work associated with the artificial upwelling will focus on these issues, and their relationship to the structure of the turbulent field, in order to more fully understand the behavior of the upwelling plume, and the mechanisms responsible for mixing in the region.

4.4. Efficiency—The pipe diameter characteristics

The most significant geometric parameter is the diameter of the upwelling pipe and which has great effect on the efficiency of the air-lift upwelling. The theoretical efficiency curves at different values of pipe diameter are presented in Fig. 10. They have similar trends as the one presented in Fig. 7 for a pipe diameter of 0.4 m. It is evident that the upwelling efficiency increases with the increase of the upwelling pipe diameter due to the reduction of the frictional loss power in the pipe, the kinetic energy and the power demand of the sea surface rise. The maximum efficiency increased to 73.5% when the pipe diameter is increased to 2.0 m as presented in Fig. 10. It can be seen that the difference between the 2 and 0.4 m diameter cases for the upwelling pipe is about 39% on average, which is quite significant. The shape of the curves shows that the efficiency increase rate decreases with further growth of the air flow rate. That occurs due to the cross-sectional area required by air as it goes up increases linearly and the cross-sectional area available for water decreases. Thus the water velocity increases as we go up (Awari et al., 2004; William et al., 1994). Higher values for the average velocity of water will require a greater friction loss and therefore less efficiency. Water flow rate of 4.5 m³/h, or greater, would create turbulent flow and back pressure in a 0.4 m inner diameter upwelling pipe. A water flow rate of 200 m³/h would generate significant back pressure in a 0.4 m inner diameter upwelling pipe. When using high air flow rates, we should increase the diameter of the pipe to allow water to flow better since part of the pipe area is blocked by the air. In other words, to efficiently increase the flow of water, one should use a larger diameter upwelling pipe instead of putting more air into a small-diameter upwelling pipe. However, that makes it significantly more difficult to deploy a long, heavy pipe in maritime operations. Moreover, large diameter pipes are easier to bend or break under the action of ocean currents. When all the above factors are considered simultaneously, a midrange pipe diameter is optimum. Clearly, for the design of the air-lift artificial upwelling system, an investigation needs to be performed based on the particular operating conditions to obtain optimal air-lift performance.

Comparing the water volume flow rate results presented in Fig. 11 with the efficiency results presented in Fig. 10, it is important to notice that the maximum efficiency does not occur at the maximum water flow rate for all values of pipe diameter.

4.5. Efficiency—The air injection method characteristics

The effect of air injection method on the efficiency of the air-lift upwelling was also studied preliminarily in the present study. This was done by fixing the pipe diameter and varying the air injection method by changing the air injection nozzles. The results presented in Figs. 7, 10 and 11 shows that not only the geometric parameters, such as pipe diameter and pipe length, affect the air-lift pump performance but also the air injection method.

The results for all injection arrangements indicate a common pattern of variation. For all of the air injection methods tested, the water volume flow rates corresponded closely to the numerical model used (see Fig. 7). Experimental results for air injection nozzles, labeled N1, N2, N3 and N4, showed the ratio profile...
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. Based on a theoretical analysis, the lifting efficiency increases with an increase of the pipe diameter, which is due to a reduction of the friction in the upwelling pipe. Further work will have to determine the influence of the pipe diameter on the air-lift efficiency. Moreover, the air injector design has a considerable effect on the upwelling efficiency as well as on the whole performance of air-lift artificial upwelling system. The optimal design of air injector may enhance the performance of the air-lift pump and should be investigated. Furthermore, analysis of the energy losses in lifting deep water in the upwelling pipe and energy consumption for compressing air has made it possible to resolve the problem of optimum air-lift artificial upwelling design, providing maximum efficiency and water flow rate with minimum construction costs. On the other hand, the increased lifting efficiency does not necessarily translate to an increased mixing of deep water with the surface water. Rapidly raising large volumes of cool dense deep sea water may cause it to sink again to large depth without much mixing with the ambient water. In our experiment (Fig. 9), the selective withdrawal of about 300 m$^3$/h of water at approximately 30 m depth mixed with about 1200 m$^3$/h of upper layer water to create a nutrient-enhanced intrusion at about 18 m depth. Further study aiming at the upwelling flow control and the physical mixing processes is needed.

Experimental results confirm that the air-lift artificial upwelling is an effective method 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. However, as a new and primitive ocean fertilization method, air-lift artificial upwelling needs further improvement and perfection.

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