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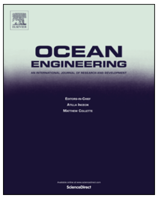

Hydrodynamic design of deep ocean water discharge for the creation of a nutrient-rich plume in the South China Sea

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ABSTRACT

Open ocean mariculture can be established by the artificial upwelling of deep ocean water (DOW). However, one of the major obstacles is the difficulty of containing a nutrient-rich DOW plume without significant dilution. In this paper, the hydrodynamic design of DOW discharge for the creation of the DOW plume in the South China Sea (SCS) is presented. The trajectory and DOW concentration of the plume in a stratified ocean environment where a sharp density interface exists is investigated relative to the current speed, pumped water flow rate, pipe diameter and optimal depth of DOW discharge. A mathematical model is presented to ensure that a desirable nutrient concentration in the DOW plume can be maintained under specific ocean stratification and current conditions. The validity of the mathematical model is verified by a computational fluid dynamics (CFD) analysis on the flow and nutrient transport of the DOW plume. The results show that the volume concentration of DOW in the plume can be controlled by setting up the flow rate, pipe diameter and corresponding optimal DOW discharge depth. In this way, the nutrient-rich DOW plume can be sustained in the open ocean to stimulate marine primary productivity.

1. Introduction

Deep ocean water (DOW) at a depth of 200 m or higher is cold, nutrient-rich, clean, and free of pathogenic bacteria. Research conducted on artificial upwelling over the past years has made it possible to bring up DOW and distribute it in the surface waters to increase phytoplankton production in the euphotic layer and thus to enhance the open ocean mariculture (Brian, 2003; Williamson et al., 2009). Considerable interests in recent years have been directed towards the study of various mechanical devices to draw up the DOW. In particular, attention has focused on the hydrodynamic performance of perpetual salt fountain, wave-driven and air-lift artificial upwelling devices (Stommel et al., 1956; Isaacs et al., 1976; Liu and Jin, 1995; Liang and Peng, 2005; Fan et al., 2013). However, one of the major obstacles limiting the development of artificial upwelling is the difficulty in maintaining the DOW plume without significant dilution (Masuda et al., 2011). Furthermore, the uplifted high density DOW will sink down out of the euphotic zone after it is discharged out of the pipe (Liu et al., 2003).

When the uplifted DOW is discharged through a pipe outlet, it undergoes three stages of the turbulent mixing process (Koh and Brooks, 1975. Fig. 1). First, the DOW rises and descends as a negatively buoyant plume, entraining and mixing with the ambient ocean water. The first stage of mixing carries the diluted plume to its neutral buoyancy level at the sharp density interface, which is the thin transition layer, sandwiching and thus bridging the gap between the fairly consistent mixed and deep layers. Second, the trajectory of the DOW plume spreads horizontally and collapses vertically. When it is trapped at the density interface, the uplifted plume tends to spread out horizontally because the interface prevents it from collapsing vertically. The third stage refers to the period of dynamically passive turbulent diffusion by combined waves and currents. The degree of DOW dilution depends on a number of hydrodynamic factors, some of which could be controlled in the first and second stages, such as the discharge depth, the neutral buoyancy depth of the DOW plume, the pumped water volume flow rate and the pipe diameter (Liu et al., 2003). Zhang et al. (2004) developed a model to predict the average velocity of the uplifted DOW flow in a perpetual salt fountain driven upwelling. Williamson et al., (2009) simulated the transport of nutrient-

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Nomenclature

A	cross-sectional area of the upwelling plume
r	radius of upwelling pipe (m)
C	DOW volume concentration of the upwelling plume
$C(x_i)$	mean DOW volume concentration of the upwelling plume at its downstream x_i
C_{mh}	DOW volume concentration of the plume
u_o	fluid velocity of the pipe outlet
u_∞	velocity of the ambient crossflow
x_i	downstream distance
$r(x_i)$	radius of the upwelling plume at its downstream distance x_i
ζ	effluent plume exit velocity to ambient crossflow ratio
g	gravitational acceleration (m/s^2)
h_m	maximum height of the upwelling plume
h_r	sea surface rise
$z_{\text{optimal}}(0)$	optimal depth of DOW discharge
β	empirically determined spreading coefficient
M	vertical momentum flux of the DOW
F	buoyancy flux of the DOW
Q_w	volume of pumped water flow rate (m^3/s), given by $Q_w=(\pi/4)D^2U_0$
$z(0)$	submerged depth of pipe outlet (m)

Greek symbols

ρ_m	mean density of the plume
ρ_0	density of the mixed layer water
ρ_1	density of the thermocline water
ρ_d	density of the DOW

Subscripts

o	referred to pipe outlet
∞	referred to ambient crossflow

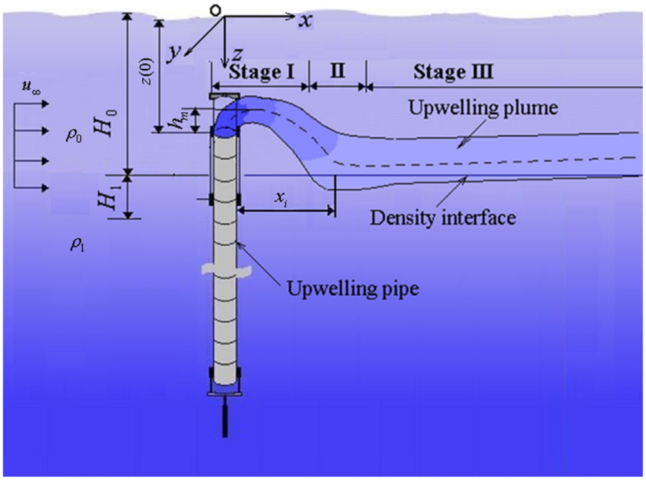

Fig. 1. Flow configuration and coordinate system of an artificial upwelling in a density stratified crossflow.

rich DOW from an artificial upwelling pipe and found that the DOW concentration would be maintained at approximately 0.1% of their inlet concentration in a 6 m diameter plume. Thus, according to Zhang and Williamson's results, the DOW volume concentration in the plume is too small to sustain the minimum nutrient concentration requirements of an ocean farming project.

There are few systematic studies of the DOW dilution control method for creating a nutrient-rich plume by far, let alone any consistent design recommendations. In studies on the most common existing discharge practices such as marine disposal of wastewater (Jones et al., 2007; Akar and Jirka, 1994, 1995; Doneker et al., 2004), concentrated brine effluents into coastal waters (Roberts and Toms, 1987; Jirka, 2008; Gungor and Roberts, 2009) and cooling water discharge from liquefied natural gas plants, the principal design objective is to achieve a higher degree of effluent dilution, contrary to the objective of an artificial upwelling system.

In this paper, the effect of the hydrodynamic design of DOW discharge on creating a nutrient-rich DOW plume in the euphotic layer is studied by using data from the station in the SCS. The dependence of the trajectory and DOW volume concentration in the plume on the distance of the pipe outlet from the density interface, the pumped water flow rate and the current speed would be simulated. Special efforts are made to derive a mathematical model for the optimal depth of DOW discharge to ensure the appropriate dilution and maintain the concentration of the nutrient in the surface water.

2. Mathematical model formulation

2.1. The best depth and season for DOW discharge in the SCS

The South China Sea (SCS) is the largest marginal sea in Southeast Asia with an area of approximately 3.5 million km^2. In large areas of the SCS, the standing stock and production of phytoplankton are very low, even though there is ample light penetration to drive photosynthesis (Ning et al., 2004). The primary production in the SCS is limited by the availability of nutrients.

The mixed layer depth (MLD) in the SCS varies from day to day and from season to season. The MLD deepens from November to February, stratifies from March to April, and is then maintained throughout the summer (Duan et al., 2012). Meanwhile, the phytoplankton bloom in the nutrient-rich mixed layer in spring causes the stratified surface layer to become nutrient limited as summer progresses and then nutrient depleted by mid-summer. The MLD in many parts of the SCS in summer is approximately 20 m, especially in times of strong heating and weak winds. On the other hand, the light could extend from 40 to 50 m in middle latitudes during summer and to 100 m or more in low latitudes if the water is fairly clear (Kirke, 2003). It is worth to note that the primary production enhancement is not only related to the available nutrient amount and its N:P ratio but also the light intensity. For photosynthesis to occur, the need for light intensity varies considerably from specie to specie. An artificial upwelling in an oligothropic ocean might result in some sort of stimulation but it could lead to a bloom of undesirable species. Further work will have to determine the appropriate technical parameters of a controlled artificial upwelling to simulate non-toxic algae and thereby creating a promising way to enhance primary production and reduce the accumulation of anthropogenic carbon dioxide in the atmosphere.

Although phytoplankton taxonomic structure under the influence of artificial upwelling would be very complicated and direct observations are too sparse to determine the community structure