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NUMERICAL MODELING OF OTEC THERMAL DISCHARGES IN COASTAL WATERS

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ABSTRACT

Thermal discharge from industrial outfalls is categorized into two major classes based on their density. First class is the effluent that has a higher density than that of the ambient water body. The second class is the effluent that has a lower density than that of the ambient water body. Due to the effect of several factors such as tides, waves, winds, river discharges, thermal effluents etc., the mixing characteristics of OTEC (Ocean Thermal Energy Conversion) thermal plume is much complicated. In this study we try to identify the mixing and dispersion characteristics of coastal waters to consider their physical properties using a field observation and a three-dimensional numerical modeling with FVM (Finite Volume Method). A plume model and observed CTD data was used to predict the mixing behavior of thermal discharges in coastal waters. The elevation, current, temperature and salinity boundary conditions on the open boundary and thermal effluents at the specific boundary are considered in this study. Various turbulence models have been applied in the numerical model to assess the accuracy of turbulence models in predicting the effluent discharges in submerged outfalls. The model successfully reproduced well known the plume behavior in coastal waters. These works illustrate the challenging nature of OTEC environmental studies.

KEY WORDS : Ocean Thermal Energy Conversion, Finite Volume Method

INTRODUCTION

Ocean Thermal Energy Conversion(OTEC) technology is based on the principal that energy can be extracted from any two thermal energy reservoirs having different temperatures(Vadus and Giannotti, 1980; Vega, 1992). A temperature difference as low as 20℃ can potentially be exploited to produce usable energy. Temperature differences of this magnitude prevail between ocean waters at the surface and a depth of 1,000m in many areas of the world.

In tropical areas, the surface layers of the ocean are heated to around 25℃. But deep layers, from about 600 m, have a temperature of around 5℃. This temperature difference can be exploited on thermodynamic principles to run what is in effect a heat engine that produces electrical power. The principle used is called the Rankine closed cycles. Warm surface water is pumped through a heat exchanger (evaporator) where it gives up its heat to a working fluid, usually ammonia. The liquid vaporizes and expands to drive a generator. The vapor then flows through a second heat exchanger (condenser) and is liquidized, having given up its heat to cold water extracted from 600 to 900m depths. The ammonia is then pumped back to the evaporator and the cycle is repeated.

Three basic OTEC designs have been pursued: closed cycle, open cycle, and hybrid cycle. In the closed-cycle system, a working fluid with a low boiling point (such as ammonia) is converted to vapor through heat exchanger, with warm seawater drawn from just below the ocean’s surface. In the open-cycle system, warm seawater becomes the working fluid when it enters a vacuum chamber and boils rapidly. In both system, the resulting vapor drives a turbine.

In 1979, a consortium of the State of Hawaii, Lockheed Missile and Space Corporation, and the Dillingham Corporation developed a 50kW, closed-cycle OTEC facility called Mini-OTEC off Keahole Point, Hawaii. It became the world’s first successful closed-cycle OTEC plant to produce net energy at sea. In 1981, Global Marine and TRW deployed OTEC-1, a 1 MW closed-cycle floating OTEC facility, offshore of the big island of Hawaii. In 1984, a 40 MW land based closed-cycle OTEC pilot plant was sited near Kahe Point, Oahu (Lewis et al., 1987; Lewis et al., 1988).

The only OTEC plant in the world is operated by the Pacific International Center for High Technology Research (PICHTR) on the Island of Hawaii. This 210 kW open-cycle experimental plant has been operational since 1993, and has produced the highest outputs of electricity and desalinated water ever achieved. The work has been sponsored by the U.S Department of Energy (DOE) and the State of Hawaii (Kim, 2013).

Due to the effect of several factors such as tides, waves, winds, river discharges, thermal effluents etc., the mixing characteristics of OTEC (Ocean Thermal Energy Conversion) thermal plume is much complicated. Thermal discharge from industrial outfalls is categorized into two major classes based on their density. First class is the effluent that has a higher density than that of the ambient water body and is hence defined as negatively buoyant jet. The second class is the effluent that has a lower density than that of the ambient water body and is hence defined as a positively buoyant jet. Negatively/Positively buoyant jets are found in various ocean and environmental engineering projects. Studies of the temporal and spatial structures of a coastal plume are of considerable interest not only because of their influences on the physical processes of the coastal circulation but also because of their close relationship to coastal ecosystem and environmental pollution problems.

In this study we try to identify the mixing and dispersion characteristics of coastal waters to consider their physical properties using a field observation and a three-dimensional numerical modeling with FVM (Finite Volume Method).

MATERIALS AND METHOD

We have developed a 3-D unstructured-grid, free-surface, primitive equation, Finite-Volume Coastal Ocean circulation Model (called FVCOM) (Chen et al., 2006) (Figure 1). Unlike the differential form used in finite-difference and finite-element models, FVCOM discretizes the integral form of the governing equations. Since these integral equations can be solved numerically by flux calculation (like those used in the finite-difference method) over an arbitrarily sized triangular mesh (like those used in the finite-element method), the finite-volume approach is better suited to guarantee mass conservation in both the individual control element and the entire computational domain. From a technical point of view, FVCOM combines the best attributes of finite-difference methods for simple discrete coding and computational efficiency and finite-element methods for geometric flexibility. This model has been successfully applied to study several estuarine and shelf regions that feature complex irregular coastline and topographic geometry, including inter-tidal flooding and drying (see http://fvcom.smast. umassd.edu for descriptions of these initial applications).

Figure 1 shows the model domain of the coastal waters of Kosrae, Micronesia. This realistic bottom topography has a maximum depth of 4,900 m. The model consists of 9,934 nodes, 18,527 elements and 11 vertical levels like Figure 1. The horizontal grid is varied from 50 m to 4 km in both x and y directions. It can be considered to the tidal elevation boundary condition of the main 8 tidal harmonic constituents (M2, S2, K1, O1, N2, K2, P1 and Q1) from NAO.99b on the open boundary. The initial conditions of temperature and salinity were specified using Global HYCOM system (Figure 2). This global system (labeled 90.0) has been using atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS. It has been replaced by the NAVy Global Environmental Model (NAVGEM). The Naval Oceanographic Office switched this system to NAVGEM forcing on August 20, 2013 (labeled 91.0).

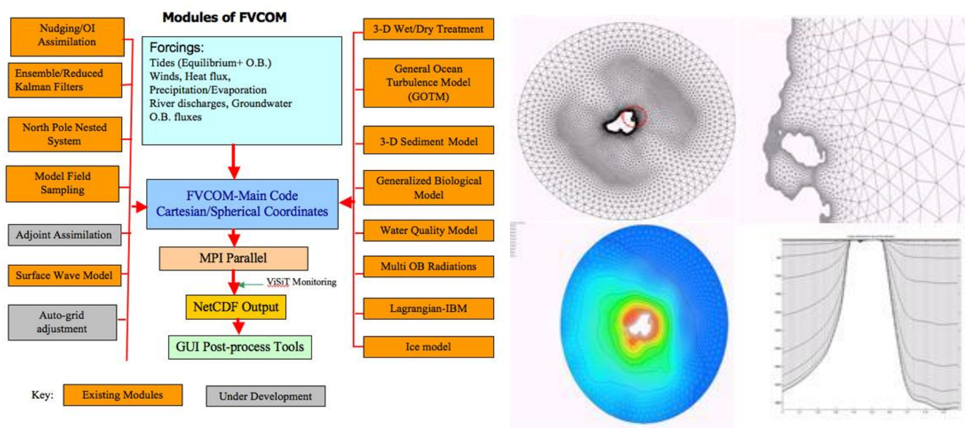

Figure 1. Modules of FVCOM (Left) and Model Domain (Right)

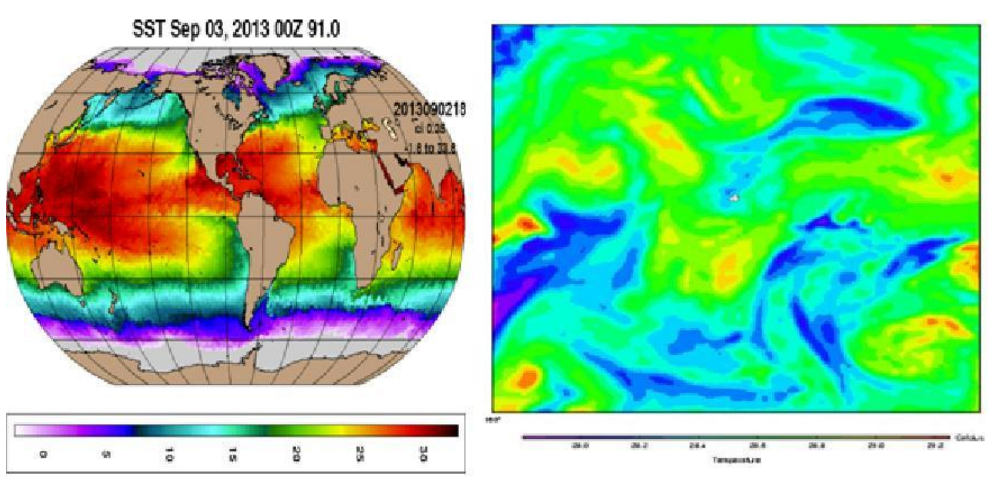

Figure 2. Initial condition (HYCOM : Sea Surface Temperature)

RESULTS AND DISCUSSION

In this study we try to identify the mixing and dispersion characteristics of thermal discharges in coastal waters of Kosrae, Micronesia to consider their physical properties using a field observation and a three-dimensional numerical modeling with FVCOM (Finite Volume Coastal Ocean Model). More detailed computational fluid dynamics (CFD : Flow-3D) model was adopted to provide a more robust assessment of the near-field plume dynamics particularly very close to the discharge ports (Figure 3). Various turbulence models have been applied in the numerical model to assess the accuracy of turbulence models in predicting the effluent discharges in OTEC outfalls (Mellor et al., 1982; Smagorinsky, 1963).

The computed currents appeared a little smaller than the HYCOM modeled one but the direction of a major current is consistent. The FVCOM is capable of reproducing surface elevation and current velocity not only for instantaneous components but also for the residual components. The present application of the three-dimensional coastal circulation model gives information of physical transport process in good agreement with the observations, which can be used for Kosrae coastal circulation modeling.

The spreading pattern of thermal effluent, according to the location of the OTEC outfall was compared. Figure 4 shows the horizontal distribution of the difference of temperature between the background water and the thermal effluent that flowed out from the OTEC outfall during the model run (30 days). The main direction of the spreading was along the deep area because of the density of the thermal effluent. The residual current also might have had an influence on the transport and dispersion of thermal effluents from the outfall (Kim, 2003).

The model successfully reproduced well known the plume behavior in coastal waters of Kosrae, Micronesia. The degree of impact of an OTEC facility will depend on location and design. The ocean and plume model are helping us make design decisions. These works illustrate the challenging nature of OTEC environmental studies.

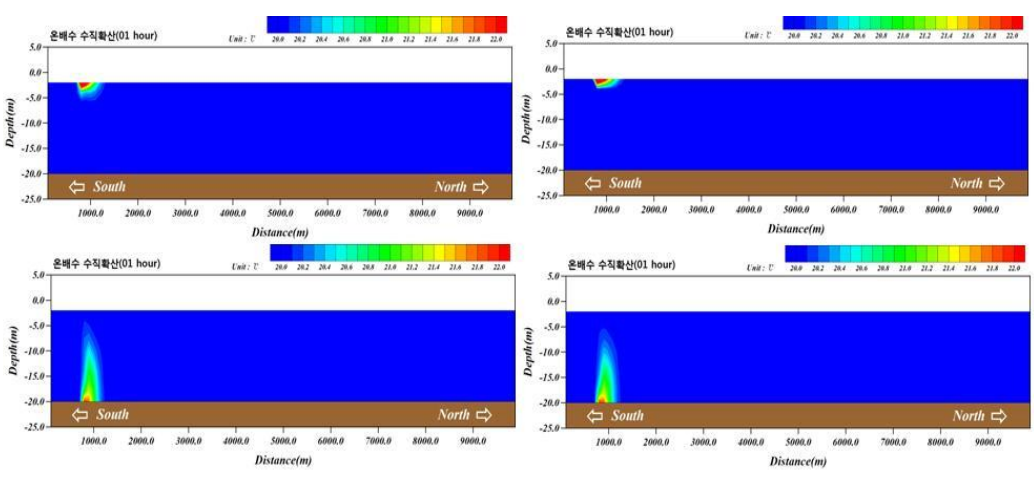

Figure 3. Longitudinal plume evolution : ambient vertical diffusion

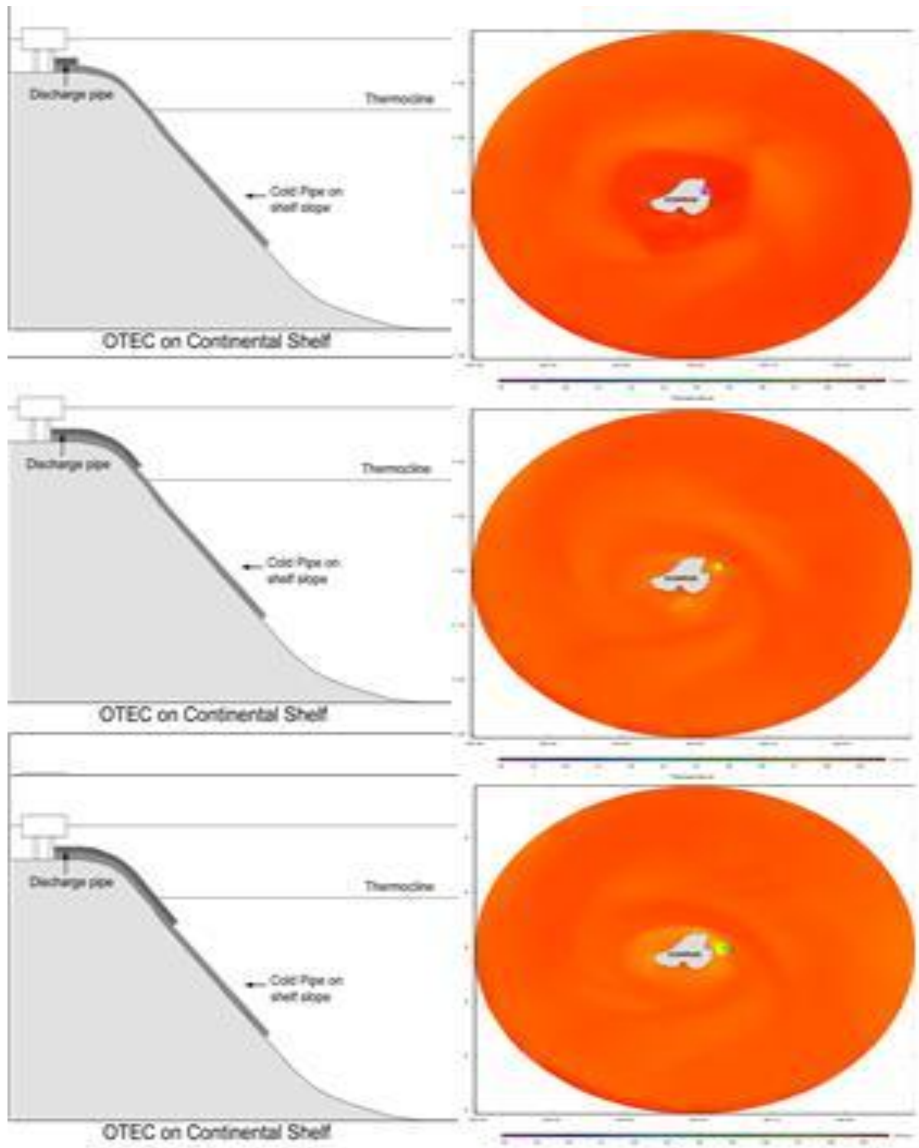

Figure 4. Horizontal distributions of temperature discharged from the different outfall locations according to the layer of the outfall : Surface layer(Upper), Thermocline layer(Middle), Deep layer(Lower)

CONCLUSIONS

FVM (Finite Volume Method) is a useful tool for the understanding the plume behavior of thermal effluent from an OTEC outfall and for determining the location that best minimizes its impact upon the coastal waters of Kosrae, Micronesia. The model successfully reproduced well known the plume behavior in coastal waters. These works illustrate the challenging nature of OTEC environmental studies. Further studies are being carried out to analyze the three dimensional nature of fluid flow and to develop better numerical models.

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