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Response of current, temperature, and algae growth to thermal discharge in tidal environment

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ABSTRACT

This paper is a numerical analysis on response of current, temperature, and algae growth to thermal discharge in tidal environment. Three-dimensional distribution of current, temperature, and dimensionless specific growth rate of *Nannochloropsis oceanica* was simulated, based on realizable $k-\epsilon$ model for turbulence closure, and a light-inhibition model for prediction of algae growth. Numerical results of temperature are in good agreement with experimental observations. Numerical results show that vertical position of trajectory, maximum velocity, and minimum dilution are subject to the distribution of power function for near field with distance to injector less than jet-penetrating length. The power exponent is a function of time for the vertical position of trajectory, while it keeps constant for the maximum velocity and minimum dilution. Numerical results also show that the dimensionless specific growth rate of *N. oceanica* does not change with temperature rise monotonously, which implies that the distribution of temperature rise may not reflect to what extent does thermal discharge influence algae growth. The amplitude and phase of the dimensionless specific growth rate of *N. oceanica* change in the vertical direction, even for uniform and constant pH, nutrient concentration, and dissolved oxygen concentration.

1. Introduction

A large number of thermal power plants in operation and under construction are located in the coastal region to meet the increasing requirements of electricity consumption in the development of coastal economy (Zhao et al., 2013). Due to the limitation of conversion efficiency of heat engine, a large amount of waste heat is discharged into natural water body by thermal outfall from the power plants (John, 1971). The initial mixing zone with high temperature occurs in the vicinity of the outfall (Jiang et al., 2003; Tang et al., 2008). In the initial mixing zone, current and temperature may change greatly due to buoyant jets, which may result in profound ecological effects, such as mortalities and low reproduction rate of certain fish species, local elimination of benthic animal, variation of phytoplankton community structure, and loss of biodiversity (Poornima et al., 2005; Ingleton and McMinn, 2012; Li et al., 2014). Algae, as an important link of ocean food chain, is sensitive to variation of ambient temperature (Middlebrook et al., 2012; Ukabi et al., 2013; Béchet et al., 2013). For ecological risk assessments of thermal emission associated with algae, an important issue is to determine the response of current, temperature, and algae growth to thermal discharge in tidal environment.

Ecological effects of thermal discharge on algae growth are related to current and temperature closely (Middlebrook et al., 2012; Ukabi et al., 2013; Béchet et al., 2013; Wu and Chen, 2014a,b). Regarding the spread of thermal effluents in the steady flow, there have been various theoretical analysis, numerical simulation, and experimental measurements, with focus on velocity distribution in axial and radial directions (El-Amin et al., 2010), gradient of hydrothermal field(Jiang et al., 2003; Tang et al., 2008), fluxes of mass, momentum, and buoyancy (El-Amin et al., 2010), bifurcation of jet (Wang et al., 2012), coherent vortex structures (Yuan et al., 1999), trajectory and cling length (Gildeh et al., 2014), entrainment (McGuirk and Rodi, 1979), and obstructed buoyant jets (Huai and Fang, 2006; Huai et al., 2006). Similar investigations were also been performed for contaminant discharge (Lee and Cheung, 1986; Jirka and Akar, 1991; Yoda et al., 1994; Méndez-Díaz and Jirka, 1996; Roberts et al., 1997, 2001; Arakeri et al., 2000; Diez et al., 2005; Papanicolaou et al., 2008; Lai and Lee, 2012; Lee, 2012; Abessi and Roberts, 2014).

Prediction of three-dimensional distribution of algae growth rate in the tidal flow is challenging due to the complex of

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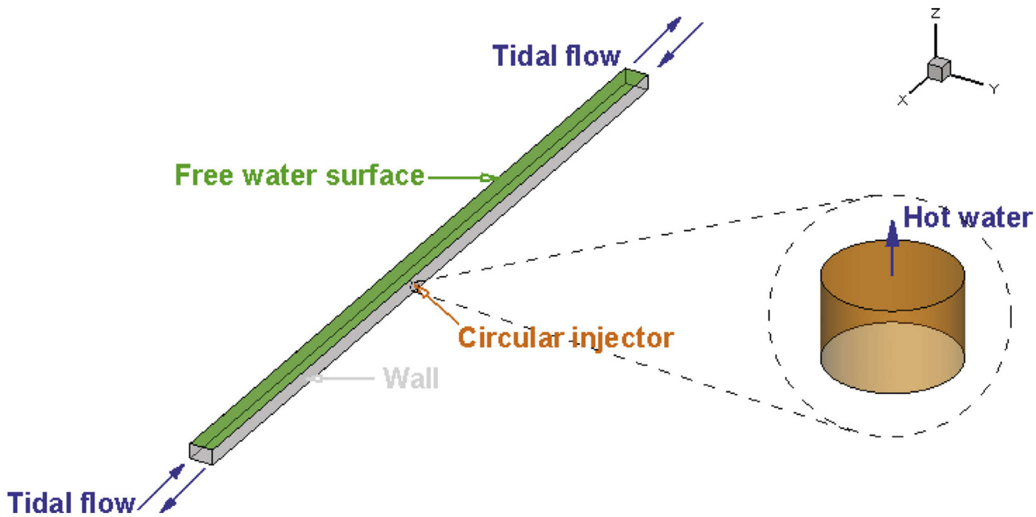

Fig. 1. Sketch of flume configured with a circular injector.

photosynthesis of individual cells (Béchet et al., 2013) and initial mixing of thermal effluent (Tang et al., 2008). Regarding the algae growth rate, substantial efforts have been made with focus on the relationship of temperature, light intensity, and photosynthesis (Sandnes et al., 2005; Bernard and Rémond, 2012; Béchet et al., 2013). Due to the strong three-dimensional characteristics of buoyant jet in the initial mixing zone, a three-dimensional non-hydrostatic pressure model is necessary to simulate the velocity and temperature fields. Xia (1998) simulated the velocity structure of turbulent jet and concentration distribution based on RNG $k-\epsilon$ turbulent model. In the numerical study performed by Xia (1998), the magnitude of inlet velocity changes periodically. Ma (2006) simulated the buoyant jet in an unsteady crossflow by use of standard $k-\epsilon$ model and RNG $k-\epsilon$ model. The results obtained by Ma (2006) shows that numerical results given by RNG $k-\epsilon$ model are closer to the experimental results. Yang et al. (1993) modeled the free water surface of unsteady flow as a moving rigid cover with vertical velocity. Tang et al. (2014) developed a coupling model to predict the thermal transport in an actual tidal flow, and the model can distinguish and capture the multiscale phenomena of costal ocean currents. Moreover, Purnama and Kay (1999) presented some theoretical solutions of contaminant transport in a tidal estuary. Up to now, the characteristics of initial mixing of thermal effluent and corresponding ecological effects on the growth of *Nannochloropsis oceanica* have not been understood well.

This work is to investigate the response of current, temperature, and algae growth to thermal discharge in tidal environment. The specific objects are: (I) to analyze the characteristics of centerline trajectory, maximum velocity, and minimum dilution, (II) to model the temporal and spatial distribution of the dimensionless specific growth rate of *N. oceanica*, and (III) to illustrate the typical distribution of velocity, temperature, and the dimensionless specific growth rate in the tidal flow.

2. Formulation

2.1. Governing equations

The governing equations for three-dimensional tidal flow, under the Boussinesq hypothesis (Hinze, 1975), can be adopted as (FLUENT Inc., 2003; Versteeg and Malalasekera, 2007)

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\rho(\nu+\nu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_l}{\partial x_l}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij}\right]-\frac{\partial p}{\partial x_i}+\rho g_i \qquad (2)$$

where ρ is the density of water, t is time, u_i, u_j, and u_l are the velocity components in i-, j- and l-direction respectively, x_i, x_j and x_l are the Cartesian coordinates in i-, j- and l-direction, respectively, ν is the kinematic viscosity, ν_t is the kinematic turbulent viscosity, $\delta_{i,j}$ is the Kronecker delta function, k is the turbulent kinetic energy, p is the pressure, and g_i is the gravity acceleration component in i-direction.

Governing equation for thermal transport in the tidal flow can be adopted as (FLUENT Inc., 2003; Versteeg and Malalasekera, 2007)

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p\frac{\partial}{\partial x_i}(u_i T)=\frac{\partial}{\partial x_i}\left[\left(\kappa+\frac{\rho c_p \nu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_i}\right] \qquad (3)$$

where c_p is the specific heat, T is the temperature, κ is the thermal conductivity, and Pr_t is the turbulent Prandtl number for temperature. Realizable $k-\epsilon$ model (Gildeh et al., 2014; FLUENT Inc., 2003; Shih et al., 1995) is adopted for turbulence closure.

The governing equations for momentum and thermal transport, and realizable $k-\epsilon$ model are numerically solved using FLUENT (FLUENT Inc., 2003). The discretization schemes for temporal term, convective term, and diffusive term are first-order implicit scheme, second-order schemes, and second-order scheme, respectively. PISO algorithm is adopted for pressure–velocity coupling. The time step is specified as 0.01 s.

2.2. Computational domain and mesh

Consider thermal transport due to thermal discharge in a tidal flow through a rectangular flume with length L = 20 m, height H = 0.6 m, and width W = 0.6 m, in a Cartesian coordinate system with x-axis along flow direction, y-axis perpendicular to side wall, and z-axis vertical to the bottom, as shown in Fig. 1. Hot water with temperature T_0 = 303.35 K is injected into the tidal flow with temperature T_a = 293.55 K through a circular injector located at (10.3846, 0.3, 0.0). The diameter D of the injector is equal to 0.015 m. The longitudinal velocity of tidal flow ranges from −0.108 m/s to 0.144 m/s, while the velocity through the injector keeps constant 0.637 m/s.