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Microscopic numerical simulation of convective currents in aquatic canopies

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Abstract

In the present study, convective currents between open water and aquatic canopies are investigated numerically. These currents are produced due to differential radiation absorption between the two regions. The unsteady three-dimensional Navier-Stokes equations are solved together with the energy equation, using the Boussinesq approximation. The vegetation is simulated by rigid cylinders. The absorption of radiation during the daytime is simulated by an additional source term in the energy equation. Three cases with different vegetation porosity are examined for comparison purposes. Numerical results for the current velocity and the water temperature are presented and compared for cases with different vegetation porosity.

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Keywords: drag resistance; heat transfer; natural convection; Navier-Stokes equations; vegetation.

1. Introduction

Convective currents are thermally-driven exchange flows which are produced due to temperature difference in a fluid. In nature, this flow can be observed either between shallow and deep water or between open water and aquatic vegetation. The latter occurs due to differential surface heating between the two regions during the daytime. In

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particular, the vegetation prevents the solar radiation from entering into the water body and thus, the water temperature in the open area is higher. These convective currents are observed in natural lakes [1,2,3].

Convective flow, which is produced due to differential absorption of radiation between two regions of water, was initially investigated by [4]. Also, [5,6] studied convective currents in a cavity, using a more realistic model for the absorption of radiation. In this model, the radiation absorption is simulated by an internal heating source which was varied with the water depth. Moreover natural convection in a triangular enclosure due to differential absorption of radiation is examined both experimentally and numerically by many researchers [7,8,9].

In shallow aquatic systems, vegetation is often present and can influence the propagation of the currents. The vegetation porosity ranges from 0.55 (mangroves) to 0.99 (water lily) [10], while the most common values in field are between 0.70 and 0.90 [11]. The convective flow in a cavity with open water and aquatic canopy is examined experimentally by [12].

In the present study, convective currents between open water and aquatic canopies are investigated using a microscopic numerical model, in order to examine the effect of differential heating and vegetation on the hydrodynamics. The simulation is referred to lock-exchange flow in a tank partially covered by cylinders which represent the emergent vegetation. The surface of the open water is heated with constant surface radiation intensity. The radiation absorption of the water during the daytime is simulated by an internal thermal source. This thermal source is included in the model through User Defined Functions and is not used for the water in the vegetated region where it is assumed that the water does not absorb any radiation. Three cases with different vegetation porosity are studied for examining its effect on the flow. The unsteady three-dimensional (3D) Navier-Stokes equations together with the energy equation are solved using the Fluent CFD code. Numerical results for the current velocity and the water temperature are presented and are compared for cases with vegetation porosity. The numerical results are also compared against available experimental data [12] and are found to be in agreement.

2. Numerical model

2.1. Governing equations

The 3D Navier-Stokes equations, Eq. (1) and Eq. (2), for unsteady, incompressible flow, in conjunction with the energy equation, Eq. (3), are solved. The Boussinesq approximation is used which treats the density as constant in all equations apart from the buoyancy term of the momentum equation, in which it is varied due to temperature difference. The radiation absorption of the water body is simulated by an additional term in the energy equation (source term S_h in Eq. 3). The vegetation is simulated by an array of rigid cylinders of a given diameter *d* and porosity φ.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho U_i)}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial(\rho U_i)}{\partial t}+U_j\frac{\partial(\rho U_i)}{\partial x_j}=-\frac{\partial P_{eff}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right)+\rho\beta(T-T_0)g_i \tag{2}$$

$$\frac{\partial(\rho c_p T)}{\partial t}+U_j\frac{\partial(\rho c_p T)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\kappa\left(\frac{\partial T}{\partial x_j}\right)\right)+S_h \tag{3}$$

where ρ is fluid density; *t* is time; U_i is fluid velocity in the i direction; P_{eff} is effective pressure (the difference between static and hydrostatic pressure); μ is fluid dynamic viscosity; β is thermal expansion coefficient (= 0.00021 K^{-1}); *T* is fluid temperature; T_0 is initial fluid temperature; *g* is gravity acceleration; c_p is specific heat of water (= 4182 $J\times kg^{-1}\times K^{-1}$); and κ is thermal conductivity (= 0.6 $W\times m^{-1}\times K^{-1}$).