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Research paper

Large eddy simulation of 3-D flow structure and mass transport in open-channel flows with submerged vegetations

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Abstract

In natural rivers, a lot of aquatic plants are often observed and they have significance effects on hydrodynamic properties. In such vegetated open-channel flows, velocity profiles are largely changed in the vertical and spanwise directions. The vegetated canopies generate large-scale coherent structures near the vegetation top and these coherent motions promote the mass and momentum transport between the within- and over-canopies. However, it is fairly difficult to investigate the relation between coherent structure and mass diffusion property only by experimental methods, such as PIV and laser Doppler anemometer (LDA), because the submerged vegetated flows have 3-D complex patterns. Therefore, in the present study, 3-D large eddy simulation (LES) was conducted in vegetated canopy open-channel flows, in which six kinds of the submergence depth *H/h* were changed systematically including emergent vegetation. The vegetation elements were calculated exactly by the non-slip condition by using fine grids without introducing any additional drag force term. The effects of submergence depth on turbulence structure and scalar transport were examined numerically and compared with the measured values. The former part of the present study focused on the mean-flow and turbulence structures. The latter part examined an interaction between 3-D coherent structure and mass transport.

Keywords: Vegetation; Mass transport; Coherent structure; 3-D flow structure and LES

1. Introduction

Aquatic plants are fundamental components of water environment in rivers and wetlands. Vegetation induces an additional flow resistance but may reduce sediment transport because of the local reduction in the bed shear stress. The vegetated canopies cause significant shear instability near the canopies, and consequently coherent turbulent motions are generated, which promote mass and momentum transfer significantly, as pointed out by Raupach et al. (1996) and Finnigan (2000). It is therefore important for water environment and river management to investigate hydrodynamic characteristics and coherent structure in open-channel flows with vegetated canopies.

Raupach et al. (1996) have revealed the turbulent kinetic energy (TKE) budget and coherent structure in terrestrial air canopy flows, and pointed out an analogy between the vegetated canopy flow and pure mixing layer flow. Nepf and Vivoni (2000) have conducted acoustic Doppler velocimetry (ADV) measurements in vegetated open-channel flows by changing the submergence depth, and compared turbulence structure and momentum transfer in submerged vegetation flows with those in emergent ones. Furthermore, they found that a horizontal diffusion is dominant in the lower canopy layer, called the "longitudinal exchange zone", and in contrast, a vertical transport of mass and momentum is promoted significantly in the upper canopy layer, called the "vertical exchange zone". Ghisalberti and Nepf (2002) have conducted some turbulence measurements in open-channel flow with flexible vegetation models by using both laser Doppler anemometer (LDA) and ADV. They found that the coherent vortex dominates the vertical transport of momentum and the downstream advection

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of these vortices causes the coherent waving of aquatic vegetations, which is called the ''Monami'' phenomena. Poggi et al. (2004) have classified the whole flow depth region into three sublayers, i.e., the first is the lower layer in which Karman vortices behind vegetation elements are dominant, the second is the middle layer in which $K-H$ vortices are generated by the inflectional instability and the third is the upper layer which is similar to boundary layers. They suggested that even the first-order closure models might be able to reproduce the mean velocity and Reynolds stress distributions in vegetated canopy flows.

Ghisalberti and Nepf (2005) conducted continuous-dye-injection experiments to characterize vertical mass transport in submerged vegetation flow. They suggested that the vertical mass transport has strong periodicity and the coherent vortices dominate the turbulent diffusion in shear layers. Recently, Nezu and Sanjou (2008) have conducted LDA and PIV measurements in open-channel flows with rigid vegetation canopies. They pointed out the importance of the double-averaging method (DAM) of both *time-average* and *space-average* for canopy flows. They also revealed that the large-scale vortices such as ejections and sweeps appear periodically in the large submergence depth and such coherent motions govern the momentum transfer significantly.

On the other hand, there are a lot of numerical studies on such vegetated canopy flows because it has been difficult to measure them accurately due to various instrumental limitations, as reviewed by Nezu and Sanjou (2008). As terrestrial canopy study, Shaw and Schumann (1992) conducted a large eddy simulation (LES) in which terrestrial plants were modeled approximately as a bed friction term in the N–S equation. The calculated vertical distributions of Reynolds stress, turbulent kinetic energy (TKE) and velocity skewness were in good agreement with the field measured data. They revealed numerically that features of computed turbulence patterns matched reasonably those observed in the atmosphere at forest sites. Dwyer et al. (1997) conducted LES to study the TKE budget for air layers and within a forest. They predicted that turbulent energy (TKE) transport shows a loss at the canopy top and a gain within the canopy. They also calculated the pressure diffusion term directly and revealed that the pressure diffusion term is smaller than the turbulent energy diffusion term. By using LES model, Watanabe (2004) has also reproduced canopy turbulence characteristics reasonably, in which typical ramp structures of coherent motions appeared in time variations of the scalar concentration near the top. Fitzmaurice et al. (2004) conducted LES to simulate turbulence structure within and above a forest canopy under neutral stability. They revealed that the features shown in the 3-D scalar microfront system matched of previous field measurements. Their calculation model overcame the data deficiency of field observations.

In contrast, as aquatic canopy study, Fischer-Antze et al. (2001) have calculated 3-D velocity profiles in partly vegetated open-channel flows by using a $k-\epsilon$ turbulence model. They showed the relation between the vegetation density and flow characteristics. Lopez and Garcia (2001) have computed the mean-flow and turbulence structures in open-channel flows with rigid submerged vegetation by using two-equation closure schemes such as $k-\epsilon$ and $k-\omega$ model. They found that both of these models predicted the experimental values of mean flow and turbulence reasonably and evaluated the shear production term, diffusion term and dissipation term reasonably in the TKE budget numerically. Xiaohui and Li (2002) have developed a $k-l$ LES model to simulate the hydrodynamic behavior in partly vegetated open-channel flows. They showed that large-scale eddies occur at the interface between the vegetated and non-vegetated regions, and such organized motions have a life cycle. At the interface, the transverse velocity profile showed a steep gradient, which induced significant mass and momentum transfer between these regions. Defina and Bixio (2005) have calculated the vegetated open-channel flow by using a modified $k-\epsilon$ model. They evaluated the penetration depth of Reynolds stress and compared with the experimental values as a function of the vegetation density. Choi and Kang (2005) have conducted 3-D numerical simulation of partly-vegetated open-channel flows using a Reynolds-stress model (RSM) and found that these numerical results were in good agreement with LDA measurements by Nezu and Onitsuka (2001).

Hinterberger et al. (2007) have simulated three different shallow water flows by using 3-D and 2-D depth-averaged LES. They found that the 3-D LES reproduced the realistic results in fairly reasonable agreement with experiments, especially concerning the evolving large-scale horizontal structure and the mass exchange governed by the coherent structure. Cui and Neary (2008) examined the effects of submerged vegetation on mean-flow structure by using LES, with a focus on understanding the role of coherent structure on momentum transfer. They found that the sweep events became the dominant contribution within the vegetation layer and also that the roller vortices might be generated by Kelvin-Helmholtz (K–H) instability at vegetation interface, which are in consistent with measured data of Nezu and Sanjou (2008).

Recently, Awad et al. (2009) investigated numerically the horizontal mixing process for quasi-2D turbulence in shallow confined shear flows. The Smagorinsky model is not a proper model for the quasi-2D turbulence, because the model doesn't take into account the effect of the bottom friction on the turbulent kinetic energy. They developed the two-length scale model, in which the mixing length does not depend on the filter width, and this two-length scale approach is validated with experimental data. Kang et al. (2009) investigates the characteristics of the solute transport in the depth-limited open-channel flows with submerged vegetation. The algebraic scalar flux model is used to solve the transport equation. They revealed that for the vegetated flow, the solute is diffused faster near the vegetation edge compared with the flow without vegetation.

As mentioned above, these vegetated open-channel flows as well as terrestrial canopy flows have been received much attention in various numerical studies. However, significant relations between coherent eddies and scalar diffusion properties have not been investigated sufficiently. Especially, in almost of previous numerical studies, the effects of submerged