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NUMERICAL INVESTIGATION OF DISSOLVED OXYGEN TRANSFER TO PERMEABLE ORGANIC SEDIMENTS BY TURBULENT FLOWS

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ABSTRACT

We investigated the high-Schmidt-number mass transfer of dissolved oxygen (DO) from turbulent flows to a permeable microbial sediment bed by large eddy simulations over the Schmidt number range of $100 \le Sc \le 690$. The new model strategy is that the underlying permeable sediment is described by a Darcy-Brinkman-Forcheimer model combined with a biogeochemical model. Dynamic SGS models for the turbulent stresses and mass fluxes were used to close the governing equations. The dependence of the mass transfer on the intrinsic variable of the sediment bed (permeability, porosity, and microbial biomass) were analysed using the statistical turbulent quantities including the mean velocity, mean concentration, turbulent intensity, and instantaneous flow and scalar characteristics, such as the fluctuating velocity and DO concentration fields, especially near the sediment-water interface. This study revealed that the role of turbulence in the DO transfer process increases with the Darcy number and with increasing porosities of the permeable sediment bed. Concerning DO transport from turbulent flows to a highly permeable sediment bed, the turbulent diffusion by large-scale motion is more important than viscous diffusion in the mass transfer process near the sediment/water interface. This process can be further accelerated with an increase in the turbulence intensity. An increase in the microbial biomass and a reduction in the Schmidt number leads to an enhanced sediment oxygen demand.

INTRODUCTION

Dissolved oxygen (DO) is significant for the survival and reproduction of organism in rivers, lakes, and oceans. DO comes from the supply of oxygen in the air and photosynthesis of phytoplankton. The complex phenomena of DO are high-Schmidt-number passive scalar transports (Calmet and Magnaudet, 1997; Scalo et al., 2012), which is connected with the salinity, barometric pressure, and especially temperature. The oxygen content in freshwater exceeds that in seawater; the DO content decrease with an increase in water temperature and a decrease in atmospheric pressure. Oxygen is also consumed by organic matter decomposition of DO-absorbing bacteria in the sediment layer and the respiration of aerobilet and reducing substances, such as sulfide, nitrite and ferrous ion. Once the oxygen uptake becomes unsustainable for an aquatic organism, anoxic "dead zones" (Diaz and Rosenberg, 2008) are formed that result in excessive propagation of anaerobic bacteria.

Because of the significance of monitoring the DO for an ecotope and its aquaculture, it is necessary to understand how DO transfers through the sediment-water interface (SWI) and how much DO is consumed by DO-absorbing microbes in the sediment layer. Some researchers have paid special attentions to studying DO transport in the sediment layer—diffusion, advection and dispersion of boundary-layer turbulence across the SWI by field observation, laboratory experiments, and numerical simulations.

As far as the DO transfer and consumption process are concerned, most of the numerical investigations assumed that the typical sediment bed has a low permeability. However, in other cases, the sedimentary layer is composed of fine gravels or sands rather than cohesive silt. The flow overlying sediment is turbulence with higher Reynolds number, and the interstitial velocity underlying bed is faster than that in lowly Permeable bed. The velocity is not linearly dependent on the hydraulic gradient. Thus, Darcy's law is not applicable to describe the kind of the flow of the sediment bed (Bear, 1972). This is why we apply a more generalized model of porous flow that was derived from the Darcy-Brinkman-Forchheimer (DBF) model (Nithiarasu et al., 1997) to describe the flow in a highly permeable sediment bed. In the present study, in which we again consider the flow in a plane channel with a more permeable wall, the large eddy simulation (LES) technique was employed to investigate the turbulence for high wall permeability at which there is exchange of momentum and a scalar across the SWI. The three-dimensionally volume-averaged Navier–Stokes (VANS) equations with the DBF model and the DO concentration equation were simultaneously solved by the fractional-step method (Dong et al., 2002).

RESULT AND DISCUSSION

In this study, we aim to reveal the interactions among the processes involved in DO transfer across the sediment-water interface (SWI) and absorption by a highly permeable sediment bed. We consider the flow geometry as sketched in Fig. 1. The upper boundary is a free surface. The lower wall is a microbial sediment bed. The lower side of the sediment bed is bound by a solid wall. The continuum approach has the flow inside the permeable sediment bed modeled as a continuum, which is coupled to the flow over the SWI. Below, we discuss how the flow is described in each region. As already mentioned in Section1, the approach followed here has been successfully validated in Breugem and Boersma (2006) and Tang et al. (2014).

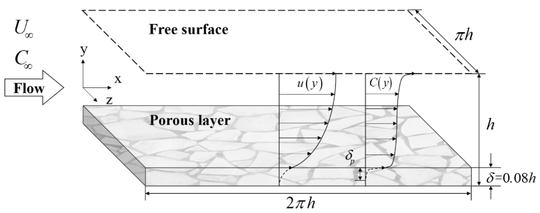

Fig. 1. Sketch of DO transfer to permeable microbial sediment bed.

First, the numerical study is designed to allow a comparison to the laboratory data from O'Connor and Hondzo (2008). The mean concentration profile computed in good agreement with those from the experiments under the condition $Sc = 373$. We investigated the effects of the sediment bed's intrinsic properties on the DO concentration fields and the relationship between the transport of momentum and the DO scalar concentration at the SWI. Figure 2 displays the profiles of the time-averaged streamwise velocity which relates to the bulk-mean velocity. The mean velocity still obeys the law of wall which is not affected by the presence of the sediment layer. Figure 3 shows the rms profiles of the velocity components, and the Reynolds stresses. This also exhibits that the sediment bed leads to a significant increase in the wall-norma. To examine the above phenomena, we provide the instantaneous streamwise vortices near the SWI with the Q-criterion as shown in Fig. 4. The vortex structures reduce, and the turbulence motion is more moderate at the sediment layer as the Darcy number or porosity decreases.

We further investigated the effects of Schmidt number and microbial biomass on the DO concentration field. For a better understanding of the mechanisms affecting the turbulent mass transfer from the SWI, it is helpful to simultaneously examine the concentration and velocity fluctuations and their correlations. In Fig. 5, the mean DO concentration profiles and *rms* fluctuations are shown for Schmidt numbers of 291, 373, and 690. In figure 6, we give the Schmidt number dependence of turbulent mass transfer coefficients at the free surface as well as at SWI.

We examined the relationship between the dissolved oxygen concentration and the microbial biomass concentration of oxygen absorbing organisms. The oxygen consumption rate at the sediment-water interface is dependent on the biomass concentration of oxygen-absorbing bacteria. The sediment-oxygen demand and DO penetration depth display nearly a linear relationship with bacterial concentration as shown in Fig. 7. Thus, the turbulent diffusion animates strong biochemical activities consuming large amounts of dissolved oxygen.

The instantaneous and time-averaged flow and DO concentration fields were investigated in the present study, which showed that the turbulent diffusion is the major mechanisms to DO transport. The flow speeds up in the sediment layer as the Darcy number and porosity increases, and large amplitudes of velocity fluctuations are associated with an increased oxygen concentration and fluctuations. A higher temperature (lower Sc) results in a lower DO concentration, a more intense DO diffusion and more DO consumption. Strong microbial activities in the sediment layer produce a greater SOD, shallower DO penetration and a stronger DO diffusion. Increase in the concentration fluctuation near the SWI follow move along the direction from the sediment layer to the water layer when the flow velocity is slower. For a large permeability, the wall is classified as a highly permeable wall near which viscous effects are of minor importance. Therefore, turbulent diffusion is the prime mechanism of DO transfer and it is an order of magnitude greater than viscous diffusion. The supply of DO is faster from the atmosphere because of more DO demand and a stronger DO diffusion.

ACKNOWLEDGEMENTS

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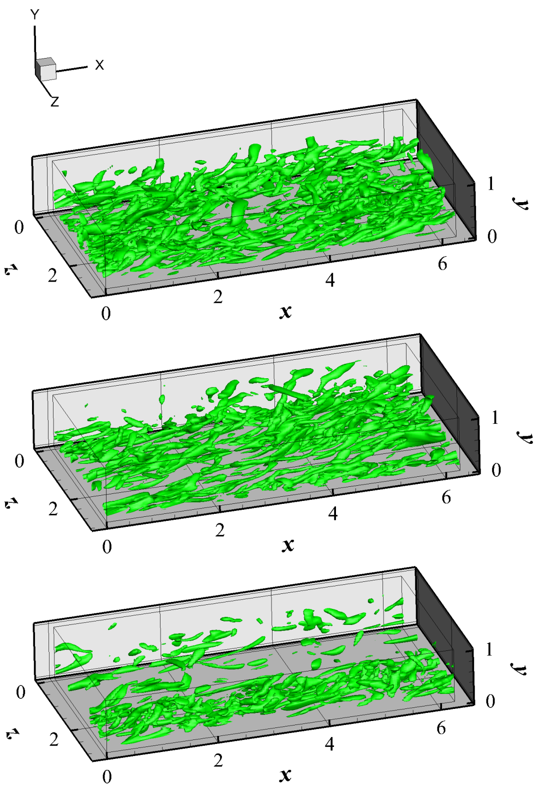

Fig.4. Distributions of vortex structures via the Q-criterion (Q=2.0): (a) $Da=10^{-4}$, $\varphi=0.9$, (b) $Da=10^{-4}$, $\varphi=0.5$ (c) $Da=10^{-5}$, $\varphi=0.7$.

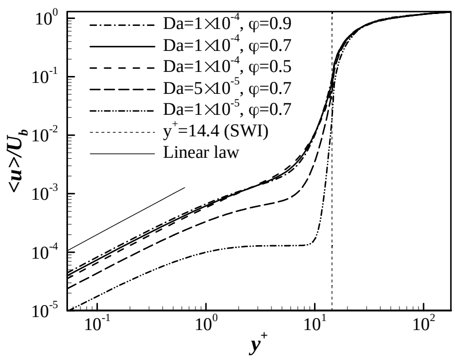

Fig. 2. Mean streamwise velocity normalized by the bulk velocity at different Da and φ

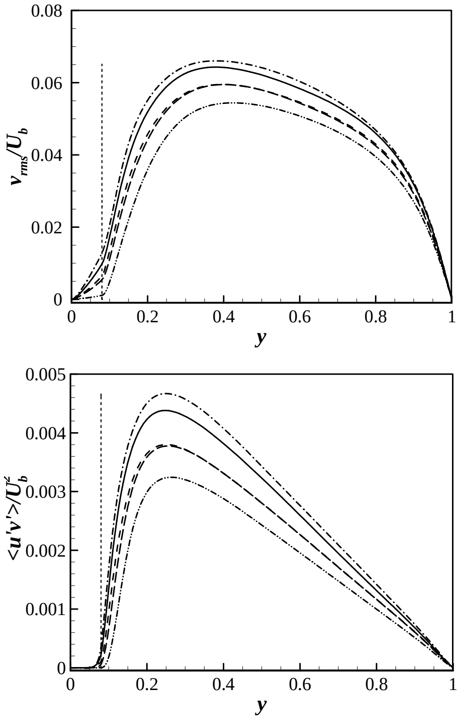

Fig.3. Distributions of turbulent intensities and Reynold stress along vertical directions

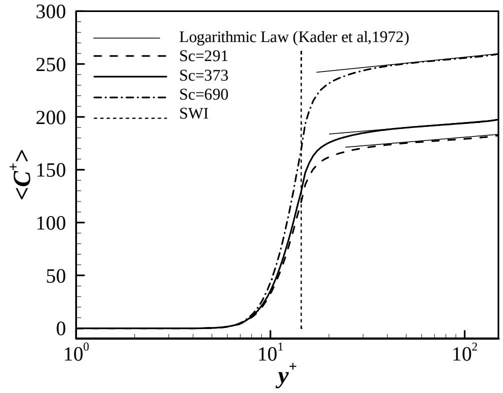

Fig. 5. Distributions of DO mean concentration, at different Schmidt numbers.

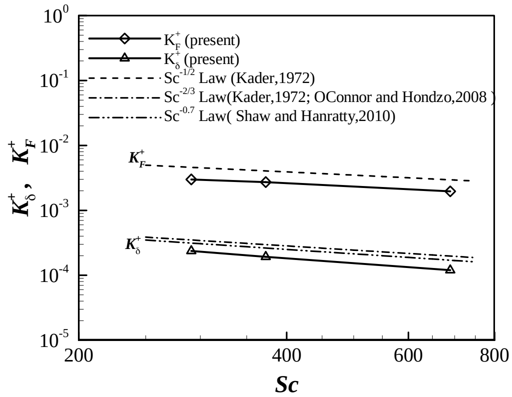

Fig. 6. Distributions of DO transfer coefficient for free surface and SWI at different Schmidt numbers.

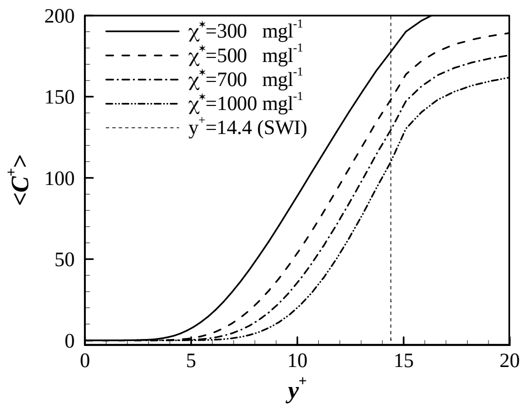

Fig. 7. Distributions of the DO mean concentration