

Numerical Investigation of the Effects of Surface Shear Stress and Thermal Stratification on Surface Divergence in Open-Channel Flow

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Abstract

In order to accurately estimate the scalar transport at the water surface, it is significant to reveal characteristics of turbulent structure on the water surface. The divergence of horizontal velocities on the water surface, i.e., the surface divergence is an important parameter for analyzing the air-water scalar transports such as heat and gas. We numerically simulate the open-channel flow including the effects of the surface shear stress and the thermal stratification by using the direct numerical simulation, and compare the numerical results with an existing experimental model for the surface divergence. In addition, it is found that the surface divergence can be expressed by the Taylor microscale in spite of a wide range of variations of the surface shear stress and the thermal stratification.

1. Introduction

The accurate estimation of the climate change is one of the most important issues in global environmental studies. The scalar transports across the water surface such as heat and gas become to be significant factors controlling the climate change. It is believed that the scalar transports depend on near-surface turbulence, which is affected by various environmental factors. For example, in natural environments there are the shear stress acting on the water surface and the thermal stratification. The surface shear stress makes the velocity gradient near the water surface steep, whereas the thermal stratification forms the stable stratification and unstable stratification. The surface divergence on the water surface has been reported to be an important turbulent characteristic quantity in describing the scalar transport^{[1][2]}. However, the relation between the scalar transport and the surface divergence has not been clarified when the effects of the surface shear stress and the thermal stratification change the water surface condition. The purpose of this study is to analyze how both effects of the surface shear stress and the thermal stratification change the turbulent structure on the water surface by means of the direct

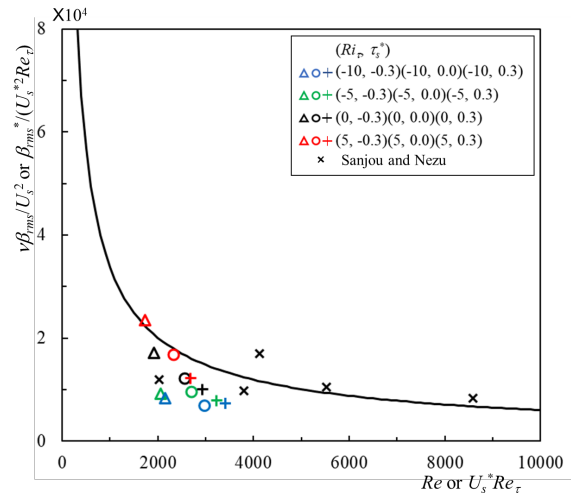


Figure 1. Relation between the surface divergence and Reynolds number numerical simulation, i.e., the DNS.

2. Outline of Numerical Simulation

The basic equations for DNS are the continuity equation of incompressible fluid, the heat transport equation, and the Navier-Stokes equation under the Boussinesq approximation. Dimensionless parameters controlling the flow state are the Reynolds number Re_τ , the Froude number Fr_τ , the Richardson number Ri_τ , the nondimensional surface shear stress τ_s^* and the

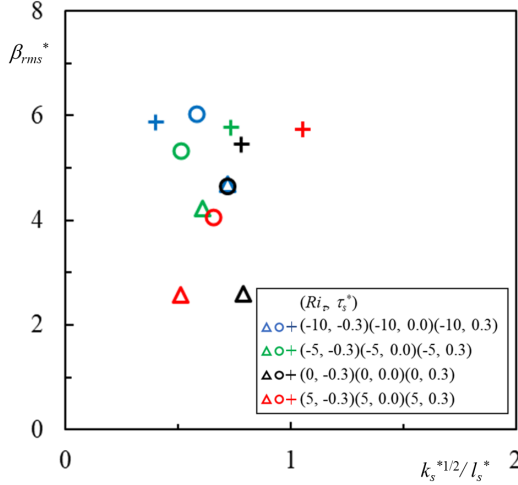


Figure 2. Relation between the surface divergence and macro length scale.

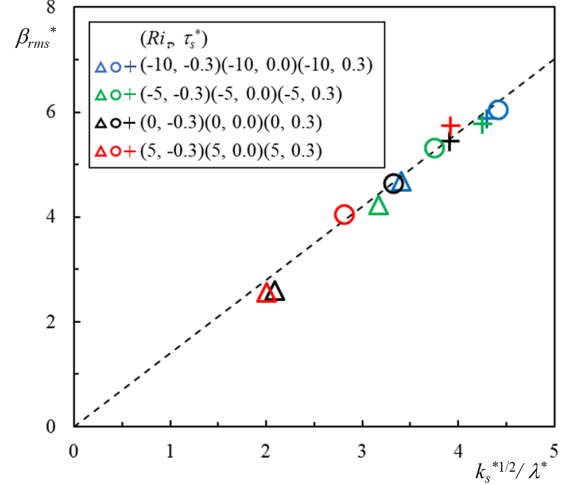


Figure 3. Relation between the surface divergence and Taylor micro scale

Prandtl number Pr . In this study, the value of Re_τ is fixed at 150. In the case of the negative value of Ri_τ is caused by the unstable stratification, whereas in the case of the positive value, the fluid field becomes the stable stratification. The definition of the surface divergence in this study is expressed by the following equation:

$$\beta^* = \frac{\partial u_1^*}{\partial x_1^*} + \frac{\partial u_3^*}{\partial x_3^*} \bigg|_{\text{surface}} \quad (1)$$

3. Results and Discussion

Sanjou and Nezu^[3] quantified the surface divergence in an open channel flow as follows:

$$\frac{\nu \beta_{rms}}{U_s^2} = 6.0 \times 10^2 Re^{-4/3} \quad (2)$$

where β_{rms} is the rms of the surface divergence, ν the kinematic viscosity and U_s the surface velocity, and Re is a Reynolds number based on the surface velocity and the water depth. Figure 1 shows the comparison of the present numerical results with the Sanjou's experimental data and his experimental model (the solid line). It can be seen from this figure that the relation from the numerical results depends on the action of the surface shear stress on the water surface, though the numerical results agree approximately with the experimental ones.

A macro length scale of turbulence is expressed by the following relation:

$$l_s^* = k_s^{*3/2} / \varepsilon_s^* \quad (3)$$

where k_s^* and ε_s^* denote the turbulent energy and the dissipation rate at the water surface, respectively. Figure 2 displays the scaling relation of the rms of the surface divergence based on the turbulent macro length scale. It is found to be difficult to express universally the surface divergence using the macro length scale.

Figure 3 also shows the relation of the surface divergence with the Taylor microscale λ^* . From this figure, it can be seen that there exists a proportional relation between both despite the action of the water surface shear stress and the thermal stratification. This fact suggests that the Taylor microscale may become a universal parameter in defining the surface divergence.

References

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