Computational Science of Turbulence in Atmospheric Boundary Layers

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To understand the fundamental nature of turbulence in atmospheric boundary layers, we performed the large-scale direct numerical simulations (DNS) of turbulent boundary layers (TBL): (1) DNS of the motion of inertial particles in TBL; (2) DNS of turbulent boundary layer on rough walls; (3) DNS of multiphase wall turbulence toward estimation and control of wind-blown sand in the atmosphere. The results of these simulations show the following: (1) The inertial particles tend to accumulate near the turbulent/non-turbulent interface of the TBL; (2) In the turbulent boundary layer flow over the sinusoidal wavy wall, the decrease of the correlation functions of the velocity and the mass concentration are observed at the region over the downslope and the valley of the wavy wall; (3) Particle-fluid and particle-particle interactions are demonstrated in low-Reynolds-number turbulent flows by using our DNS code of particle-laden turbulent channel flows. To advance the research about the risk estimation on the dispersion problems of hazardous materials within the canopy layer, the preliminary LES has been carried out for the urban boundary layer over the roughness blocks. Also, the three-dimensional aerodynamic characteristics for a circular cylinder in the critical Reynolds number region are investigated.

Keywords: High-resolution DNS, turbulent boundary layer, rough wall, wind-blown sand, LES, urban turbulent boundary layer

1. Direct numerical simulations of turbulent boundary layer

Turbulent diffusion phenomena of small particles (dust, yellow sand, PM2.5, etc.) in the atmosphere relate to our daily life and are the objects of public concern. The spatial distribution of the concentration of these small particles is generally quite inhomogeneous and often changes sharply at the boundary of the turbulent flows. The motions of such particles in the atmosphere are highly complex, because they are diffused by highly nonlinear turbulent flows and they do not necessarily obey the fluid motion, depending on the inertia of the particles. Large-scale direct numerical simulation (DNS) of turbulence is effective tool to study the properties of the highly non-linear turbulence as well as the properties of the motion of the inertial particles in such turbulent flows.

Recently Ishihara et al performed DNS of turbulent boundary layer (TBL) and analyzed the conditional statistics near the turbulent and non-turbulent (T/NT) interface of the TBL.[1] The DNS showed that the external velocity fluctuations near the T/NT interface are partially blocked at the interface. Also, recent numerical simulations by Sardina et al suggest that the inertial particles in TBL accumulate near the T/NT interface as well as near wall region, depending on the Reynolds number of the TBL and the Stokes number of the particles.[2]

To deepen our understanding of the properties of the motion of inertial particles near the T/NT interface, we developed a parallel code of particle tracking for the DNS of the TBL, and tracked the inertial particles in the velocity field of the TBL. The values of the momentum- thickness-based Reynolds numbers, $Re\theta$, used for this study, are 600-800. We tracked 245760(=10×128×192) particles for each value of 6 different Stokes numbers.

In data analysis, the T/NT interface is determined as the iso-surface of vorticity defined by $\omega_I = 0.7U\infty / \delta 99$ (Fig. 1). Here $U\infty$ is the free stream velocity and $\delta 99$ is the boundary layer thickness. The DNS data showed that the average value of the vorticity of the inertial particles that were initially released above the T/NT interface is an increasing function of time and tends to approach ω_I. This result quantitatively indicates that the inertial particles tend to accumulate near the T/NT interface by being blocked partially at the T/NT interface.

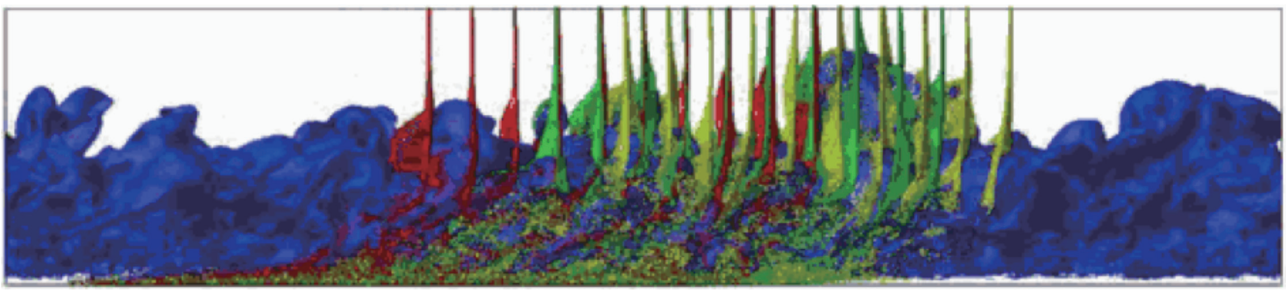


Fig. 1 T/NT interface (blue) in the turbulent boundary layer (TBL), and inertial particles (with three different Stokes numbers), which are advected in the velocity field of the TBL.

2. DNS of turbulent boundary layer on rough walls

Turbulent boundary layer flow is one of canonical flows and is of importance for the practical engineering application and the environmental problem. Since the surface roughness is known to enhance the mass transfer from the wall, we focus on the turbulent boundary layer flow over the sinusoidal wavy wall. The sinusoidal wavy wall is a simple model of the roughness and four different wavelengths are investigated in this study ($\lambda / 2a$ =12.5, 15, 22.5 and 45). A direct numerical simulation (DNS) code for the flow is optimized for the ES2.

Figure 2 shows the geometry of the boundary layer flow over the wavy wall surface. The computational domain consists of a main and a driver parts. The driver part is provided to generate the inflow condition of the main part. Here we used the recycle method.[3] The lower wall of the main part forms the wavy wall represented by the immersed boundary layer method. The parallel and vectorization efficiencies of the present DNS code are 98.43% and 99.50%, respectively.

According to the results in previous years, we found the dissimilarity between momentum and mass transfers. In order to clarify this dissimilarity quantitatively, we evaluate it by using a correlation function defined as,

$$R(-u_n T) = \frac{\overline{-u_n T}}{\sqrt{\overline{u_n^2}}\sqrt{\overline{T^2}}}, \quad R(u_t T) = \frac{\overline{u_t T}}{\sqrt{\overline{u_t^2}}\sqrt{\overline{T^2}}}.$$

Note that the velocities are projected onto the coordinate system defined by the local mean velocity vector: u_t and u_n are the velocity component of the tangential and normal to the local mean velocity vector. And T denotes the mass concentration. Figure 3 shows the distribution of the correlation functions for the wavy wall surface of $\lambda/2a$=15. The correlation functions are

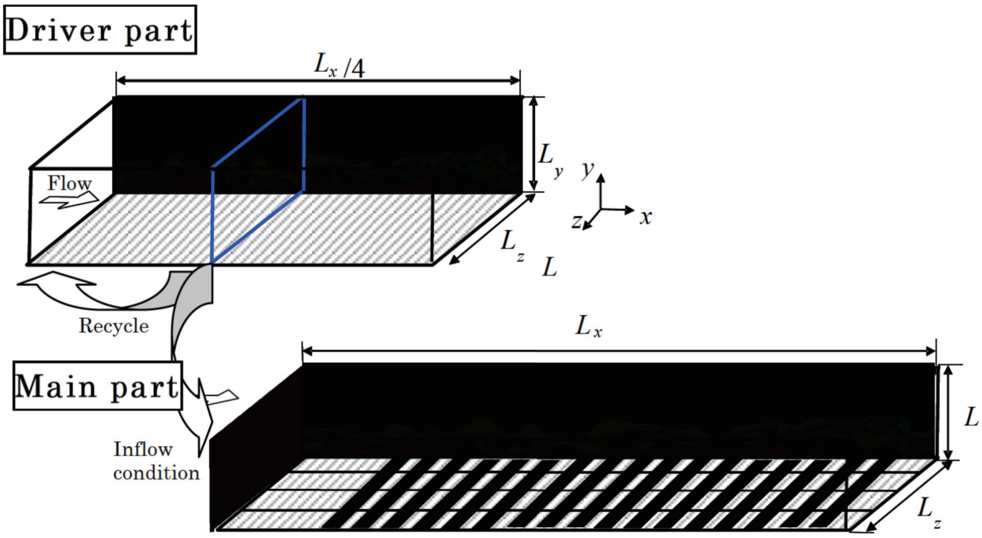


Fig. 2 Computational domains for turbulent boundary layer flow over the wavy walls.

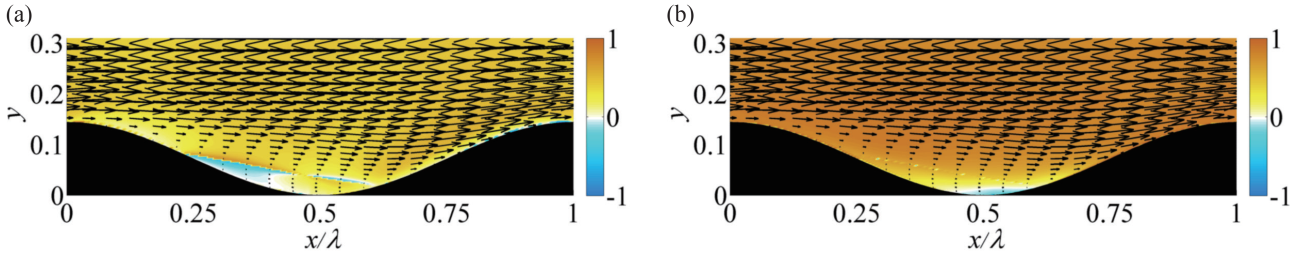


Fig. 3 Distributions of the correlation functions of (a) $R(-u_nT)$ (b) $R(u_tT)$ for the wavy wall surface of λ / 2a =15.0 at the middle of the main part.

found to decrease in the regions close to the valley and over the downslope, which implies the dissimilarity between momentum and mass transfers.

3. DNS of multiphase wall turbulence toward estimation and control of wind-blown sand in the atmosphere

The wind-blow sand in ABL (atmospheric boundary layer) is a cause of the desertification, which is one of the serious global environmental issues, and its dynamics has been studied by many researchers for combating desertification. The sand movement triggered by wind on desert would result in sand storms, yellow dust, and atmospheric pollution such as PM 2.5 and 10. The wind-blown sand movement itself occurs as a result of complicated combinations of several factors of the sand-bed surface, ambient turbulent airflow, sand particles, and so on. The mechanism of the wind-blown sand movement with the background of turbulent flow remains an issue to be addressed.

The present work we have carried out so far is four-way coupling simulations of two-phase turbulent flow in a channel with a moderate volume fraction (less than 1%) of solid particles. The present simulations to consider particle-particle and particle-wall interactions have been done using the immersed boundary method. The obtained results were in good agreement with existing numerical works in the literature.[4] Figure 4 shows typical snapshots of vortex structures identified as iso-surfaces of the second invariant of deformation tensor, where the cases of with and without particles at the same Reynolds number are given in (a) and (b), respectively. The particle size is a tenth of the channel width and the particle volume fraction is 0.78%. The particles distribute almost uniformly in the channel central region without the settling effect. From the figure, it can be conjectured that the particles in the present case works as an activator of turbulence in the near-wall region, while being an inhibitor in the core region.

4. Application of LES of turbulent flows to urban environmental and strong wind disaster problems

The preliminary LES has been carried out for the urban boundary layer over the roughness blocks in order to advance the research about the risk estimation on the dispersion problems of hazardous materials within the canopy layer.

The three-dimensional aerodynamic characteristics for a circular cylinder in the critical Reynolds number region are investigated.[5] Based on the computed results by LES analysis using high grid resolution, the flow mechanism for maintenance of asymmetric flow around a symmetric circular cylinder is studied. Consequently, it is clarified that an asymmetric flow pattern is brought about as a result of the interference

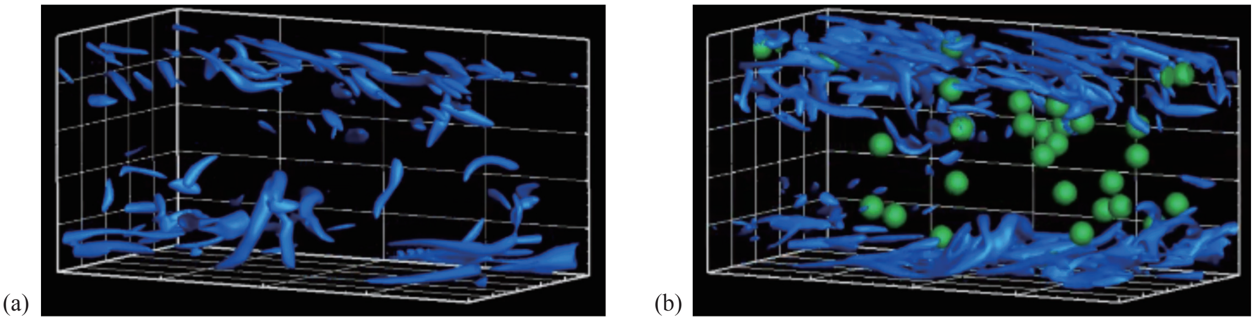
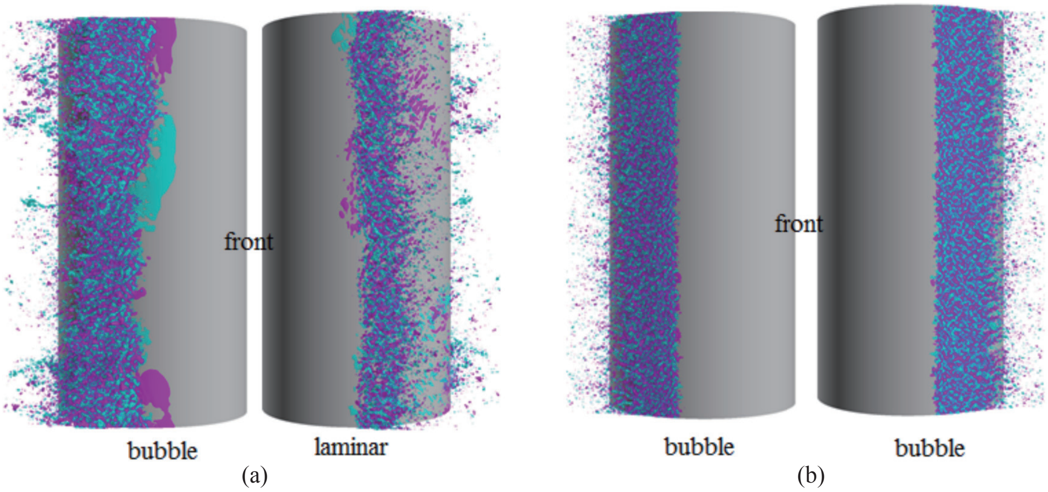


Fig. 4 DNS results of single-phase and two-phase flows in a channel: (a) single-phase flow at the bulk Reynolds number of 5000, (b) particle-laden flow at the same Reynolds number. Blue iso-surface indicates vortex, and green spheres are solid particles. The mean flow moves left to right.



(a) (b)

Fig. 5 Iso-surface of vorticities (ω_x= -100,100): (a) critical Re region (Re=2.2×10^5), (b) super critical Re region (Re=6.0×10^5).

of the flows on the bubble and non-bubble sides in the wake. The frontal stagnation point shifts to the non-bubble side, keeping the balance of the volumetric flows of both sides. The development of attachment flow on the bubble side causes an imbalance between the centrifugal forces and the pressure gradient. The instability in the flow causes the re-attachment points to be unstable and leads to the separation bubble taking on a span-wise wavy shape (Fig. 5). Accordingly, the various timings of the formation in the span-wise direction for the wake vortex on the bubble side prevent the laminar shear layer on the other side from approaching the base of the cylinder. The laminar shear layer extends away from the cylinder and does not reattach to the cylinder surface. These flow characteristics on the both sides stably maintain the asymmetric flow state in the critical Re region.

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大気境界層乱流現象解明のための計算科学

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大気境界層乱流の基本的な性質を理解するために、我々は大規模乱流境界層の直接数値シミュレーション（DNS）を実施した：（1）乱流境界層における慣性粒子の運動のDNS、（2）正弦波状の壁上の乱流境界層のDNS、（3）大気中の飛砂の推定と制御に向けた多相壁乱流のDNS。これらのDNSにより、以下の結果が得られた：（1）慣性粒子がTBLの乱流 / 非乱流界面付近に蓄積する傾向がある（2）正弦波状壁上の乱流境界層の流れでは、速度と質量濃度の相関関数の減少は、ダウンスロープと波状壁の渓谷の領域に観察される（3）粒子 - 流体と粒子 - 粒子間相互作用は、粒子を含んだチャネル乱流の開発したDNSコードの使用により、低レイノルズ数乱流で現象が再現可能である。また、応用問題として、キャノピー層内の有害物質の分散の問題のリスク推定に関する研究を進めるため、粗さのブロックの上に都市境界層のため予備的なLESを実施した。さらに、臨界レイノルズ数領域での円柱のための三次元の空力特性を解析した。

キーワード : 大規模直接数値計算 , 乱流境界層 , 粗面 , 飛砂 , LES, 都市型乱流境界層