Computational Science of Turbulence in Atmospheric Boundary Layers

Project Representative

Takashi Ishihara Graduate School of Engineering, Nagoya University

Authors

Takashi Ishihara Graduate School of Engineering, Nagoya University

Kaoru Iwamoto Mechanical Systems Engineering, Tokyo University of Agriculture and Technology

Hiroya Mamori Mechanical Systems Engineering, Tokyo University of Agriculture and Technology

Tetsuro Tamura Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology

Yasuo Kawaguchi Department of Mechanical Engineering, Tokyo University of Science

Takahiro Tsukahara Department of Mechanical Engineering, Tokyo University of Science

To understand the fundamental nature of turbulence in atmospheric boundary layers, we performed two kinds of direct numerical simulations (DNS) of turbulent boundary layers (TBL); one is the TBL along a flat plate and the other is the TBL with sinusoidal wavy wall. The data analysis of the former showed that the turbulent/non-turbulent interface of the TBL has a double structure which consists of a turbulent sub-layer with thickness of the order of the Taylor micro scale and its outer boundary (super layer) with thickness of the order of the Kolmogorov length scale. In the latter DNS, we observed the streaky structure at the downslope of the wavy wall, where the wall shear stress is negative due to the flow separation while the Sherwood number is positive. For the purpose of the estimation and control of the wind-blown sand in the atmosphere, we developed a code to simulate three-dimensional two-phase flow in conjunction with the four-way coupling. Using the code we successfully obtained basic statistics (e.g., the drag coefficient of a spherical solid particle) and demonstrated particle-particle interactions in low-Reynolds-number turbulence. We also performed LES of turbulent flows for dealing with urban environmental and strong wind disaster problems.

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

1. Data analysis based on the DNS of turbulent boundary layers

There are many environmental problems in which turbulent flows have sharp interfaces between turbulent region and non-turbulent region. To predict high-Reynolds-number turbulence phenomena more accurately, we need to understand the properties of such sharp interfaces. Recently turbulent and non-turbulent (T/NT) interface has been studied actively both in experiments and computations. A recent review is given by da Silva et al.[1]. However there are still open questions about the interfaces.

This year we studied the properties of the T/NT interface of turbulent boundary layers (TBL) using a series of DNS data of TBL. The values of the momentum-thickness-based Reynolds numbers, Re_θ, used for this study, are 500−2200. Figure 1 is a contour plot of vorticity magnitude near the boundary on a plane parallel to both the streamwise and wall-normal directions. As the figure shows, there is a sharp change of vorticity and we can define the T/NT interface of the TBL using a threshold like $\omega=\omega_c=0.7(U_\infty/\delta)$, where U_∞ is the free stream velocity and δ is the boundary layer thickness.

Analysis of the conditional statistics near the T/NT interface of the TBL shows that there is a small peak in the span-wise vorticity, and an associated small jump in stream-wise velocity. The velocity jump near the T/NT interface of the TBL is of the order of the *rms* value of velocity fluctuations near the interface. The results of the conditional statistics and their Reynolds number dependence show that the interfacial layer has a double structure that consists of a turbulent sub-layer with thickness of the order of the Taylor micro scale and its outer boundary (super layer) with thickness of the order of the Kolmogorov

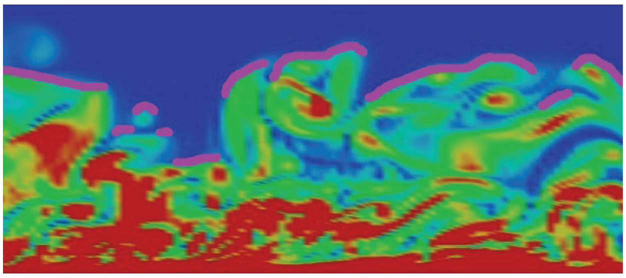


Fig. 1 A contour plot of the magnitude of vorticity near the wall of turbulent boundary layers. The contour curve (pink) defined by $\omega=\omega_c=0.7(U_\infty/\delta)$ captures well the T/NT interface of the TBL.

length scale. An approximate profile of the conditional average of span-wise vorticity near the interface fits well to the DNS data. Conditional cross correlation of the streamwise or the wall normal velocity fluctuations changes sharply across the interface. This result is consistent with the blocking mechanism (proposed by Hunt and Durbin [2]) of the vortical layers.

2. DNS of turbulent boundary layer on rough walls

Turbulent thermal boundary layer flow over a sinusoidal wavy wall surface is of importance in view point of the practical engineering application and the environmental problem. In order to investigate the effect of the sinusoidal wavy wall on the turbulent thermal boundary layer flow, we use the DNS code optimized for ES2. The sinusoidal wavy wall is a simple model of the roughness. The different wavelengths are investigated for $\lambda / 2a$ =12.5, 15, 22.5 and 45. Here, the amplitude of the sinusoidal wavy wall, a, is kept constant.

Figure 2 shows the computational domain that consists of a main and a driver parts. Both domains are the boundary layer flows. The driver part generates the inflow condition of the main part by means of the recycle method [3]. The lower wall of the main part forms the sinusoidal wavy wall. The parallel and vectorization efficiencies of the present DNS code are 98.43% and 99.50%, respectively.

Figure 3 shows the visualization of the vortical structure over the wavy wall surface ($\lambda/2a$=15). The direction of the base flow is from left to right. The color contour on the wall indicates the wall shear stress (left) and the Sherwood number (right). The large wall shear stress and the Sherwood number are observed on the top of the wavy wall. At the downslope of the wavy wall, the wall shear stress is negative due to the flow separation while the Sherwood number is positive and the streaky structure is observed. This phenomenon implies the dissimilarity between the momentum and the mass transfers.

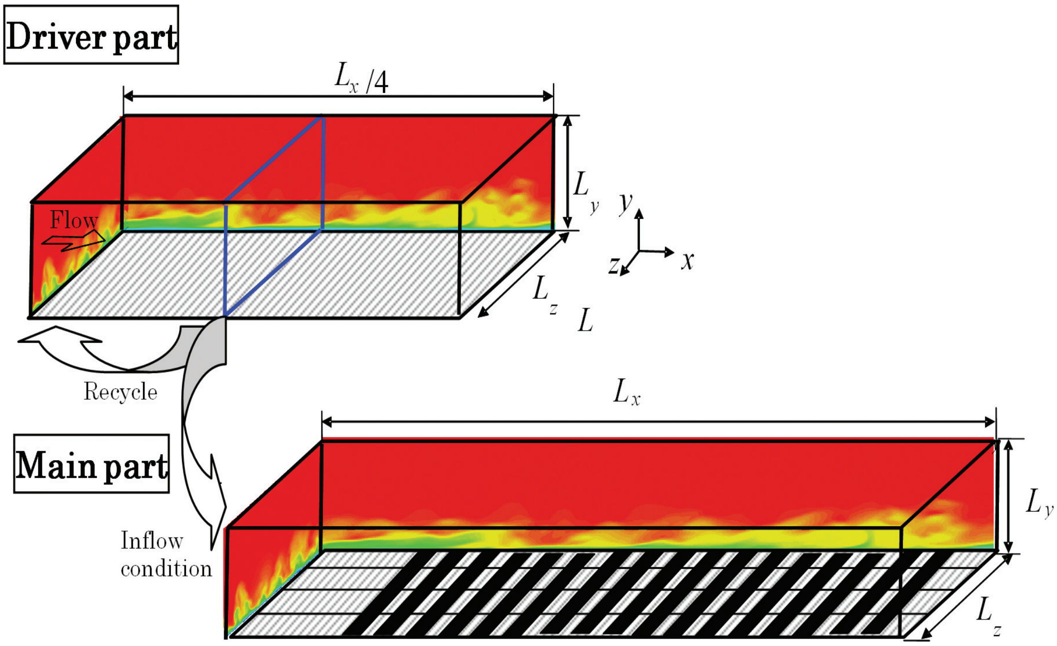


Fig. 2 Computational domains for turbulent boundary layer on several sinusoidal wavy walls.

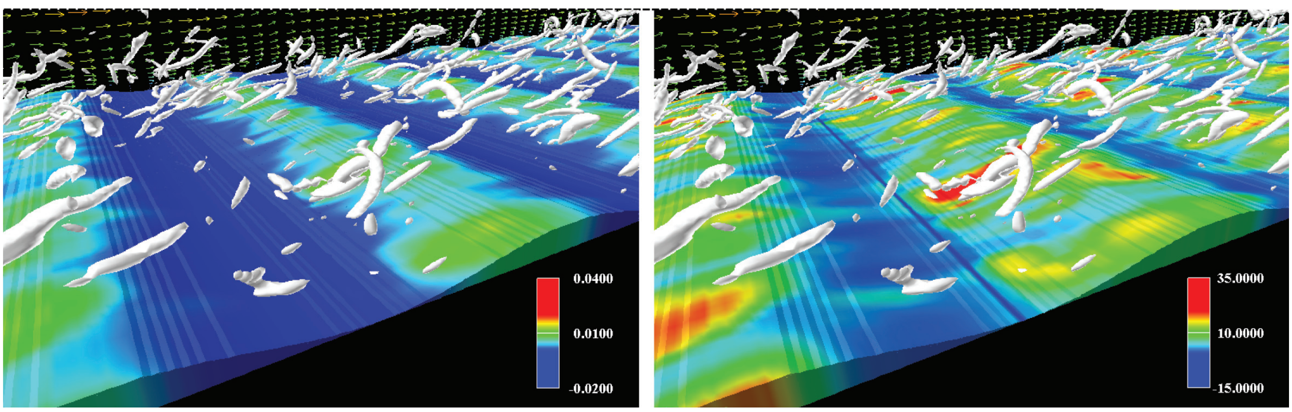


Fig. 3 Visualization of the vortical structure with the wall shear stress (left) and the Sherwood number (right) on the wavy wall surface ($\lambda / 2a$ =15.0).

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

The dynamics of wind-blow sand in ABL (atmospheric boundary layer) have been investigated by many researchers with the aim of combating desertification. The desertification is one of the serious global environmental issues, and its major cause is the sand movement triggered by wind on desert. This phenomenon is the most significant cause of sand storms and yellow dust, and it eventually induces further desertification, health damage, 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, dune and ripple topologies, ambient airflow, sand particles, and so on. In the context of these issues, it is important to clarify the mechanism of the wind-blown sand movement with the background of turbulent flow.

Preliminary works we have carried out so far are four-way coupling simulations of various two-phase laminar flows. The present numerical simulations considering particle-particle and particle-wall interactions have been done using the immersed boundary method to simulate three-dimensional viscous incompressible flows interacting with a moving, solid boundary, as shown in Fig. 4. These computed results were in good agreement with experimental measurements. Moreover, the effect of rotational motions of spherical particles was found to be significant when we analyzed the particle-particle interactions by the intermediary of ambient fluid without any collision of particles. This emphasizes the importance of rotational motions in four-way coupling simulations.

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

The objective of this chapter is to elucidate turbulence characteristics of the wind flows around the structure or over the undulating ground surface with various types of roughness. Actual terrain has been selected for the LES of wind over the hills covered densely by trees. Using the canopy model or the logarithmic law based on the roughness length, the bottom boundary condition is imposed. The effect of the boundary treatment for the roughened undulating surface on the turbulence structures in the near-wall region has been discussed.

Next, based on the computed results, the turbulent flow characteristics around the curved surfaces such as a windmill and a complex terrain are investigated. Here, as a typical and a fundamental case in such a curved surface, a circular cylinder is focused on.

Ono and Tamura [5] performed LES analysis and investigate the asymmetric flow coupled with steady lift force around a circular cylinder in the critical Reynolds number (Re) region. Figure 5 shows the time histories of the drag coefficient (C_D) and the lift coefficient (C_L). Mean drag indicates to be equal to about 0.8 that is consistent with the previous experimental data [6]. Lift is largely fluctuating and its mean value is larger than mean drag. Figure 6 illustrates the time-averaged velocity field around a circular cylinder in the critical Reynolds number region. It can be recognized that the higher velocity occurs only on the upper side of the cylinder and the wake is located on down side. It means that the mass flow rate becomes larger on

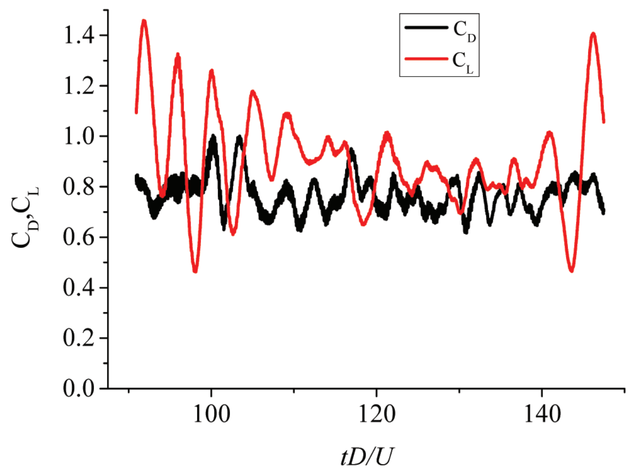
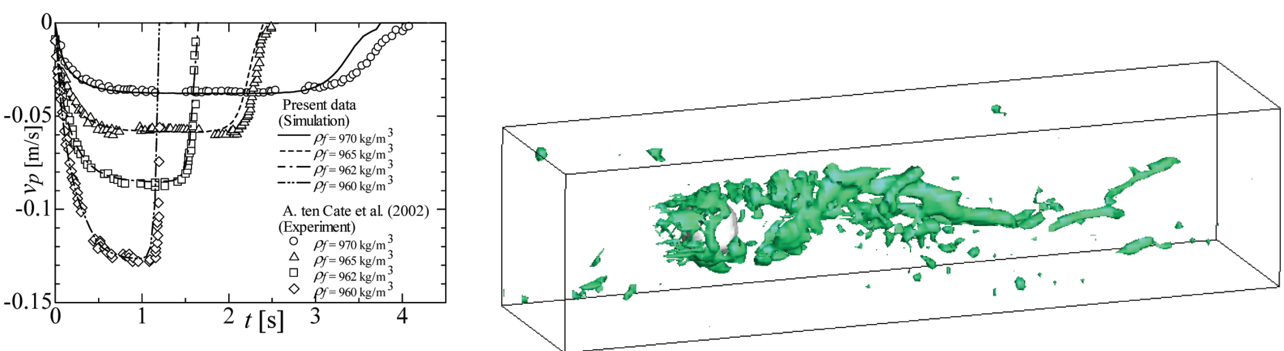


Fig. 5 The time histories of drag and lift coefficients.



(a) Settling velocity of a solid particle.

(b) Turbulent eddies around a solid particle.

Fig. 4 Results of preliminary simulations of solid-air two-phase flows using the immersed boundary method: (a) Temporal variation of the vertical velocity of a solid sphere settling in an initially static viscous fluid. Compared with experimental data [4]. (b) Visualization of eddies around a solid sphere suspended in a channel flow. The mean flow moves left to right.

the upper side. These physically important phenomena in the critical region such as the asymmetric flow and large value of the steady lift beyond to the drag coefficients could be simulated only in the case of using very fine grid resolution in the circumferential direction in addition to the span-wise direction.

Also, based on the computed flow, the time-averaged flow and pressure distributions in the critical Re region are investigated. As a result, the shifts of the stagnation points are recognized associated with imbalance of the flow on the both sides of the cylinder [5].

Ono and Tamura [5] clarified that the asymmetric flow in the critical Re region is not induced only the difference of the flow characteristics on the both sides of the cylinder. It is clarified that the asymmetric flow was brought about by the 3D interaction of the flow on the both sides. This 3D flow characteristic results in stable formation of the asymmetric flow state in the critical Re region.

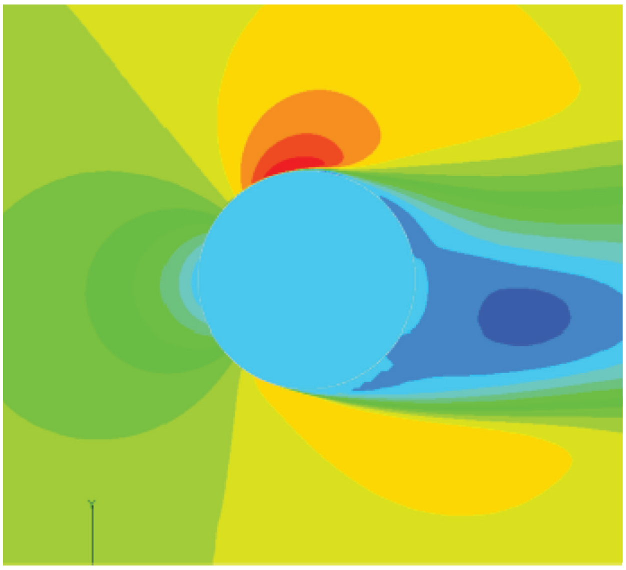


Fig. 6 The contours of time-averaged velocities.

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大気境界層乱流現象解明のための計算科学

課題責任者
石原　　卓　　名古屋大学　大学院工学研究科
著者
石原　　卓　　名古屋大学 大学院工学研究科
岩本　　薫　　東京農工大学　工学府
守　　裕也　　東京農工大学　工学府
田村　哲郎　　東京工業大学　大学院総合理工学研究科
川口　靖夫　　東京理科大学　理工学部
塚原　隆裕　　東京理科大学　理工学部

大気境界層における乱流の性質を理解するため、我々は乱流境界層の 2 種類の直接数値計算（DNS）を実施した。そのうちの 1 つは平らな平面上の乱流境界層であり、もう一つは正弦波状の壁上の乱流境界層である。前者の DNS のデータ解析により、乱流境界層の乱流・非乱流界面が二重構造を持っており、それは幅がテイラー長でスケールする乱流・非乱流遷移層とコルモゴロフ長でスケールする表層部（スーパーレイヤー）から構成されていることが分かった。また、後者の DNS では、正弦波状の壁の下り坂部では、シャーウッド数が正であるのに対し、壁剪断応力は流れの剥離により負になることが分かった。大気による飛砂の評価と制御のため、我々は固 - 固、固 - 気の相互干渉を考慮した 3 次元二相流の DNS コードを開発した。開発したコードにより、球状粒子の抵抗係数などの基本的な統計量の妥当な結果が得られ、低レイノルズ数乱流中の複数粒子の追跡も可能であることが分かった。我々は、さらに、都市環境における環境問題や強風災害問題に対処する目的のための乱流のラージ・エディ・シミュレーション（LES）も実施した。

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