Direct Numerical Simulations of Fundamental Turbulent Flows with the World's Largest Number of Grid-points and Application to Modeling of Engineering Turbulent Flows

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We performed high-resolution direct numerical simulations (DNSs) of canonical turbulent flows on the Earth Simulator. They include (i) magneto-hydrodynamic (MHD) turbulence at low magnetic Reynolds number under a uniform magnetic field, and (ii) turbulent boundary layer with the momentum-thickness Reynolds number at inflow approximately 1980. The DNSs provide invaluable data for the study of (i) the large scale statistics in MHD turbulence and (ii) turbulent structure in the outer region of turbulent boundary layer. A new efficient numerical scheme for DNS of wall bounded turbulent flows was proposed. We also made Large Eddy Simulation of turbulent boundary layer over urban-like and homogeneous roughness to accurately estimate environmental impact on large cities covered by buildings and vegetations, and developed a DNS code to study the turbulence in non-Newtonian surfactant solution between parallel plates.

Keywords: High-resolution DNS, incompressible turbulence, channel turbulence, turbulent boundary layer, urban-like roughness, quasi-periodic boundary layer, non-Newtonian fluid, drag reduction

1. High-resolution DNS of canonical turbulent flows

1.1 Examination of numerical schemes for high-resolution DNS of turbulent channel flow

Turbulent channel flow is one of the most canonical wall-bounded turbulent flows, and the DNS of the flow provides us with detailed data free from experimental uncertainties. The DNS therefore gives invaluable data for the investigation of wall-bounded turbulent flows. In fact, there have been extensive studies, of turbulent channel flow by DNS. In particular, Iwamoto *et al*. [1] and Hoyas and Jimenez [2] recently performed very large-scale DNSs of turbulent channel flow. Both of the studies used a Fourier spectral method in the stream-wise and span-wise directions, but in the wall normal direction they used methods different from each other; Iwamoto et al. used a Chebyshev-tau method, while Hoyas and Jimenez used a spectral-like compact difference method. Such a difference gives rise a question "What is the most efficient numerical scheme for high-resolution DNS of turbulent channel flow?"

In order to get some idea on this question, we examined the accuracy of the numerical methods used in [1] and in [2]. In Chebyshev-tau method, truncated Chebyshev polynomial expansions are used to approximate functions defined over a finite domain ($-1 < y < 1$). Our analysis showed that the polynomial expansion of order n can approximate $\sin(k\pi y)$ and $\cos(k\pi y)$ well, but it also revealed that the approximation loses its accuracy remarkably at $k > n/4$. Our analysis also showed that the accuracy of the approximation for derivatives based on the polynomial expansions of order n is much better than that based on spectral-like compact difference method with n grid points.

1.2 A new numerical scheme for DNS of turbulent boundary layer

We have developed a new efficient numerical scheme for DNS of turbulent boundary layer. The method is similar to that used in Spalart *et al*. [3], but it uses a Sinc-Galerkin method instead of Jacobi polynomial expansions.

Theoretical computational cost is $O(N \log N)$ in the Sinc-Galerkin method, in contrast to $O(N^2)$ in the Jacobi polynomial expansions, where N is the number of grid points in the wall normal direction. Simple test problems showed that the Sinc-Galerkin method with appropriate parameter values yields results with a high accuracy.

1.3 The decay of low magnetic Reynolds number turbulence

In a previous study [4], we examined the validity of Loityanskey's hypothesis in isotropic decaying turbulence by high-resolution DNSs in large computation domain. In order to get better understanding on the universality of the large-scale statistics in turbulence, we extended the study to decaying magneto-hydrodynamic (MHD) turbulence at low magnetic Reynolds number under a uniform magnetic field, which is one of the most representative anisotropic turbulences of practical importance. The study was performed under the collaboration with Prof. P. Davidson (Cambridge). DNSs were performed with the number of grid points up to 1024^3, in a periodic domain whose dimensions, l_{box}, are much larger than the integral scales $l_\perp$, $l_\parallel$ of the turbulence, where $l_\perp$ and $l_\parallel$ are integral scales perpendicular and parallel to external homogeneous magnetic field, respectively. Detailed analysis of the DNS data is now under way.

2. DNS of the turbulent boundary layer

Since boundary-layer flows are the technical matter of concern for so many engineering applications and environmental processes, many decades of study have been performed by use of experimental approach. On the other hand, DNS of turbulent boundary layer have been barely performed compared with that of other wall-bounded turbulence such as channel turbulence. Spalart[5] conducted the DNS of turbulent boundary layer up to the momentum-thickness Reynolds number of 1410. However, the turbulent structure in the outer region was not discussed.

In this study, we calculated DNS of the turbulent boundary layer on a flat plate, with zero pressure gradient, up to the momentum-thickness Reynolds number at inflow of $Re_{\delta 2} = 1980$ where $Re_{\delta 2}$ is based on the free stream velocity U_∞ and the momentum-thickness δ_2. For the spatially developing boundary layers, turbulent inflow conditions are generated by rescaling the turbulent boundary layer at some distance downstream of inflow and reintroducing the recycled mean profile and fluctuation field. This technique follows that of Lund *et al*. [6]. A number of the total grid points used in the calculations were up to about 10^9. In order to verify the numerical results, turbulent statistics obtained from the present study were compared with the previous experimental and numerical results. The present results were in good agreement in experimental ones.

A bird's eyes view of an instantaneous flow field at $Re_{\delta 2} = 1980$ is shown in Fig. 1 to grasp the three-dimensional characteristics of the turbulent structure. The streaky structures in the near-wall region are observed. Its spanwise wavelength is around 100 viscous wall units. On the other hand, large low-speed regions exist and lift up from bottom in the outer layer. These regions of low-momentum fluid are located below and upstream of the hairpin vortex head, which is induced by the flow associated with the vorticity in

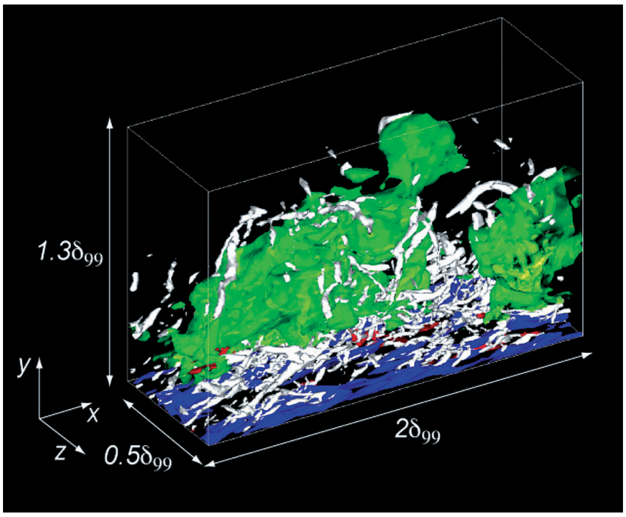


Fig. 1 Bird's eyes view of instantaneous flow field for $Re_{\delta 2} = 1980$. Red, high-speed region in near wall ($u'^+ > 3.0$); blue, low-speed region in near wall ($u'^+ < 3.0$); light-green, low-speed region far from wall ($u'^+ < 2.5$); white, vortex region extracted by using the second invariant of the velocity gradient tensor.

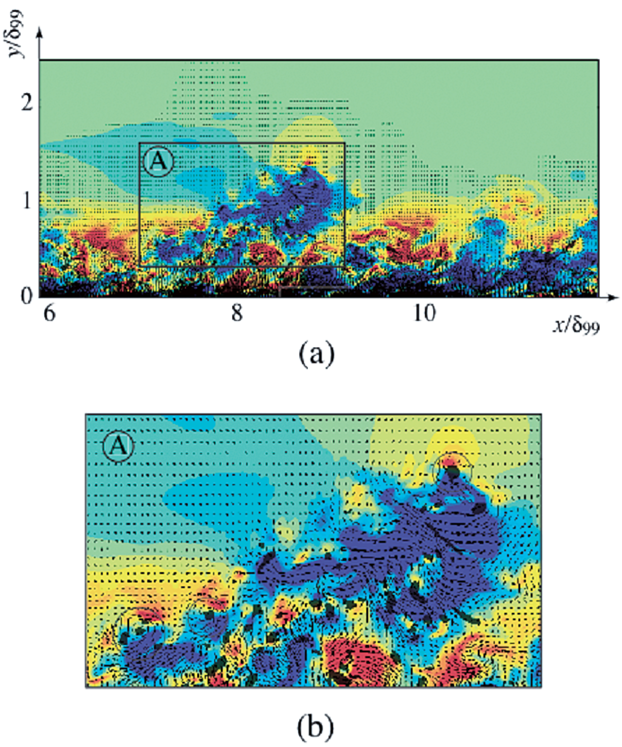


Fig. 2 A velocity fluctuation vector field in x-y cross-section for $Re_{\delta 2} = 1980$. Streamwise velocity fluctuations u'^+, Blue to red, –2.5 to 2.5; Vectors, velocity fluctuation field.

the head and neck of the hairpin vortex.

A velocity fluctuation vector field in x-y cross-section for $Re_{\delta 2}$ = 1980 are shown in Fig. 2. The border of turbulent region is clear and vortex heads located near its border (circled in Fig. 2) are raised up from below and upstream to upper and downstream with a finite angle. Below the vortex head, a large low-momentum region exits. Evidences are obtained from this study that these large-scale structures far from wall affect structures in the near-wall layer.

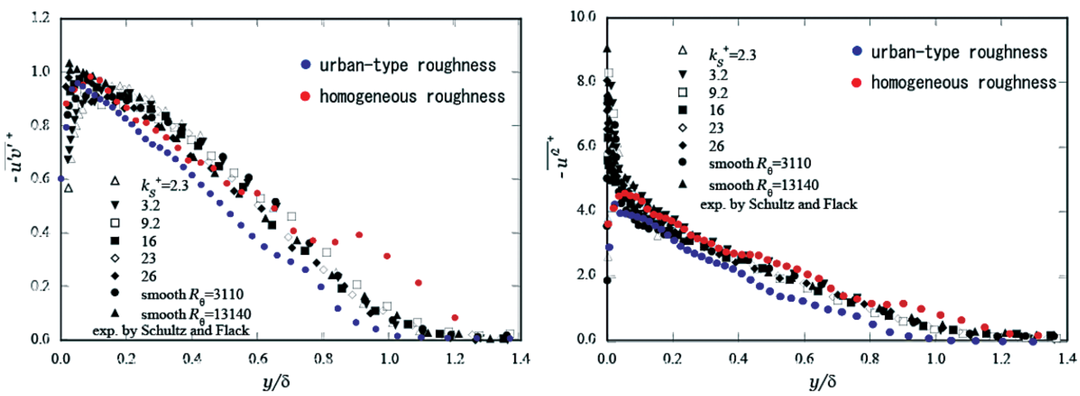
3. Turbulent boundary layer flow simulations over urban-like and homogeneous roughness using LES

In the atmospheric fields, which determine thermal environment such as an urban heat island and behavior of pollutant diffusion in large city, a size or a distribution of the roughness elements changes the turbulence structures in the canopy and accordingly affects on the pollutant concentrations and the temperature distributions. In order to accurately estimate environmental impact on large cities covered by buildings and vegetations and also deduce the scale similarity law for urban flows, the flow over large-scale inhomogeneous (urban-type) roughness (δ/h = 6, δ: boundary layer thickness, h: roughness height) has been studied using LES and compared the turbulence characteristics with that over homogeneous roughness (δ/h = 36). The quasi-periodic boundary condition [7] is introduced in longitudinal direction to simulate the spatially developing boundary layer flows. Table 1 shows computational domains and grid numbers for LES of rough turbulent boundary layers.

The vertical profile of longitudinal and shear stresses of urban-like roughness flow don't collapse with those of the homogenous roughness flow and experimental ones [8] (see Fig. 3). So, the similarity law for urban-type roughness cannot be obtained even in the outer layer apart from ground surface. For the homogeneous rough turbulent boundary layer, the longitudinal large-scale coherent structures identified by low-speed area are formed above the roughness layer and surrounded by small-scale vortices (see Fig. 4).

Table 1 Computational domains and grid numbers.

	Computational domain (longitudinal) × (vertical) × (spanwise)	Grid numbers (longitudinal) × (vertical) × (spanwise)
Homogeneous roughness	524 h × 80 h × 160 h	3,520 × 160 × 1,600
Urban-type roughness	88 h × 20 h × 40 h	1,760 × 160 × 800



(a) Longitudinal stress (b) Shear stress

Fig. 3 Spatially averaged stresses normalized with friction velocity.

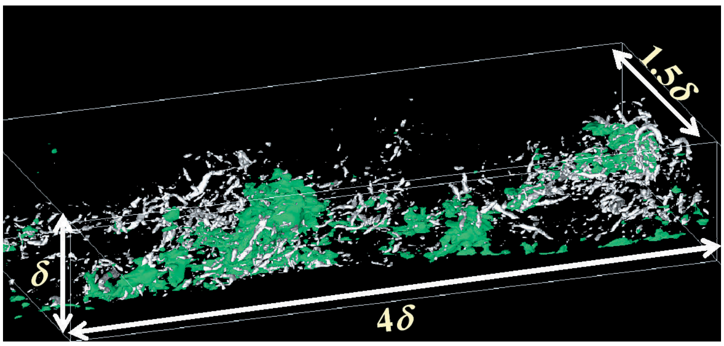


Fig. 4 Large-scale coherent structures above a roughness layer of the homogeneous roughness, green area: low-speed region, white area: vortical structures.

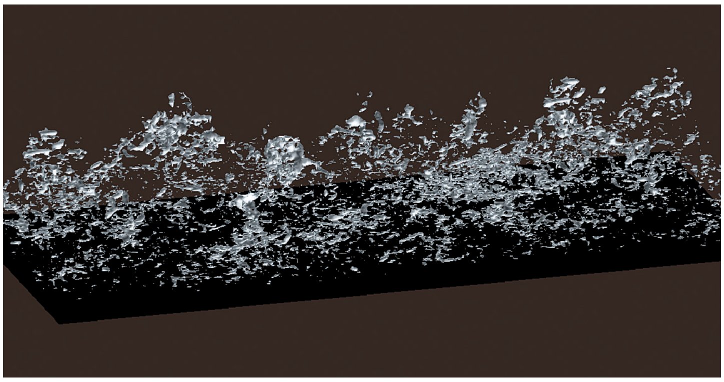


Fig. 5 Instantaneous iso-surfaces of the second invariant of velocity gradient tensor normalized with its standard deviations for urban-type turbulent boundary layer.

However for such a weak rough surface we could not find clearly the coherent packets of hairpin vortices which have been generally found in the smooth channel flows. For the urban-type boundary layer (see Fig. 5), longitudinal large-scale coherent structures are also recognized as a result of concentration of small-scale vortices identified by the iso-surface of the second invariant of velocity gradient tensor.

4. DNS of turbulence in non-Newtonian surfactant solution between parallel plates

It is known that small amount of surfactant additives modifies the turbulence in water through its Rheological characteristics. One of the attractive point from the application is that turbulent drag coefficient in pipe is reduced to 30% compared with water flow at the same flow rate. The necessary amount of surfactant is order of 0.1%. The large benefit of this method in energy conservation in water circulation system is obvious. However, because the drag reduction mechanism is still not clear, optimization of surfactant, flow system and heat exchanger, which is sometimes necessary component of water circulating system is not clarified. Extensive investigation to find the missing links between the chemicals, Rheology, turbulence and real components through the large scale numerical analysis are needed.

The purpose of this subproject is to contribute to the energy conservation experiments with surfactant additives in the real-scale air-conditioning systems in buildings through the DNS analysis. The analysis will be performed for the turbulence in non-Newtonian surfactant solution between parallel plates. The result will be used for elucidating the drag reduction mechanism and estimation of heat transfer. Especially, Reynolds number dependency of drag reduction and Prandtl number dependency on heat transfer will be the major targets of this analysis.

In FY 2007, careful check of DNS code and pre-analysis in PC was made. The optimization to increase the vectorization rate has been finished. Presently, the code is under the optimization to suit the multi-CPU machine. The achievement of this year is 55%.

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乱流の世界最大規模直接計算とモデリングによる応用計算

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我々は地球シミュレータ上で規範的（カノニカル）な乱流の大規模直接計算(DNS)を行った。ひとつは一様磁場中の低磁気レイノルズ数の磁性流体(MHD)乱流であり、もうひとつは流入部での運動量厚さレイノルズ数Reθ = 1980の乱流境界層である。これらの大規模DNSは各々、MHD乱流の大スケールの統計法則、及び、乱流境界層における外層の乱流構造を調べるための大変貴重なデータを提供するものである。我々はまた、壁のあるカノニカルな乱流場のDNSのためのSinc関数を用いた新しい効率的な計算手法の提案も行った。

我々はまた、応用計算として、ビルや植生に覆われた大都市に対する環境影響を正確に評価するために、都市を想定した一様ラフネス上の乱流境界層のラージエディシミュレーション(LES)を行い、乱流統計量や乱流構造について調べた。さらに、平行平板間の非ニュートン界面活性剤溶液における乱流を調べるためのDNSコードを開発した。今後、抵抗低減メカニズムの解明と伝熱性能の評価を行い、実規模のビル省エネ実験に貢献する計画である。

キーワード：大規模直接数値計算, 非圧縮性乱流, チャネル乱流, 乱流境界層, 都市型ラフネス, 準周期境界層,
非ニュートン流体, 抵抗低減