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 2. They include (i) turbulent channel flow, (ii) turbulent boundary layer with zero pressure gradient, and (iii) turbulent thermal boundary layer on a rough wall. The DNSs provide invaluable data for the studies of (i) the small-scale statistics in the log-law layer of turbulent channel flow, (ii) small-scale statistics and related vortex dynamics in turbulent boundary layer, and (iii) turbulent heat transfer in turbulent thermal boundary layer on a rough wall, respectively. We also performed (i) a detailed analysis of the results of Large Eddy Simulation of turbulent boundary layer over an area around Tokyo railroad station to study effects of actual shape of urban roughness on turbulence statistics of atmospheric boundary layer, and (ii) a preliminary analysis of the flow in non-Newtonian surfactant solution between parallel plates equipped with successive ribs.

Keywords: High-resolution DNS, incompressible turbulence, turbulent channel flow, turbulent boundary layer, turbulent thermal boundary layer, rough wall, LES, urban turbulent boundary layer, non-Newtonian fluid, drag reduction

1. Large-scale spectral direct numerical simulation (DNS) of canonical turbulence

1.1 High resolution DNS of turbulent channel flow

Turbulent channel flow (TCF) is one of the most canonical wall-bounded turbulent flows, and there have been therefore extensive studies on TCF by DNS. High-resolution DNS of TCF may provide us not only with detailed practical data for modeling of wall-bounded turbulence but also with detailed fundamental data to explore universality in the small-scale statistics of high- Reynolds- number wall-bounded turbulence.

In the present study, we optimized our DNS code of TCF on the Earth Simulator 2 (ES2), achieved the sustained performance of 5.9Tflops (11.3% of the peak performance) in DNS of TCF on 1024x1536x1024 grid points using 64 nodes of ES2, and attained R_τ =2560, where R_τ is the Reynolds number based on friction velocity and 2560 is the world's largest R_τ so far achieved in DNS of TCF. The analysis of the DNS data shows that one-dimensional longitudinal energy spectrum obtained in the log-law layer is consistent with the prediction of Kolmogorov's theory (K41), but shows also that local isotropy, which is a key hypothesis in K41, does not necessarily hold.

1.2 Large-scale and high-resolution DNS of turbulent boundary layer

Spatially-developing turbulent boundary layer (TBL) over solid boundary is another representative phenomena observed in a wide class of flows in science and technology. Although extensive studies, especially those by large-scale DNSs [1, 2, 3], have been therefore made on TBL, much still remains unknown.

In the present study, we first examined the applicability of the so-called fringe method proposed by Spalart et al. [4], on the basis of DNS of TBL under various flow conditions. We then studied the statistics and related vortical structures of high Reynolds number TBL by a large-scale and high-resolution DNS on ES2 by using the fringe method.

In the method, Spalart et al. [4] introduced a region called fringe region in the computational domain, where the growth of the TBL is artificially suppressed so that one may apply the Fourier spectral methods not only in the spanwise (y-) but also the streamwise (x-) directions. In the wall-normal (z-) direction, a method based on Jacobi polynomial expansion is used after an appropriate variable transformation. Their numerical method is, therefore, spectral accurate. However, the influence of the introduction of the fringe region on the flow is not known a priori. In order to assess the applicability of the method to a large-scale DNS, we first examined the method by several preliminary DNSs in which the DNS results at the same Reynolds number under different flow conditions are compared. Among the observations by the DNSs are the following:

(i) Various statistics such as the shape factor, the friction coefficients, and the root-mean-square of velocity fluctuations in a region approximately $300\theta_0$ downstream from the fringe region are insensitive to the conditions in the fringe region, and are consistent with the experimental results so far reported at the similar Reynolds numbers. Here θ_0 is the momentum thickness at the exit of the fringe region.

(ii) Grid spacing in the streamwise direction should be less than 10 wall units in order to appropriately resolve the fluctuations of the gradients of pressure in the TBL.

On the basis of these observations, we have developed a parallel DNS code of TBL on the ES2, and also determined appropriate parameters to be used in the DNS of TBL. We achieved 6.2Tflops (48% of the peak performance) in the DNS of TBL on 4608x512x768 grid points using 16 nodes of the ES2, and attained the Reynolds number R_θ =835 ~ 2443 outside the fringe region. Here R_θ is the Reynolds number based on the momentum thickness. The number of grid points is the world's largest in DNS of TBL so far performed on the basis of the spectral method.

Among the observations by the analysis and visualization of the TBL flow fields are the following:

(i) Three-dimensional visualization of iso-surface of vorticity normalized by the mean and standard deviation of vorticity well demonstrates the existence of packets of coherent hairpin-like vortices, the idea of which was proposed by Adrian et al. [5] on the basis of their two-dimensional experimental data. Here the "mean" refers a time average over z (spanwise)- direction for given x and y. (See Fig. 1)

(ii) Nested hierarchy of the packets of coherent hairpin vortices is observed in the TBL flow field at R_θ ~2000.

(iii) A short log-law-like region is observed in the TBL of flow field at R_θ ~2000.

(iv) It is suggested that in the log-law-like region of TBL, coalescence of the same-signed cane-type neighbor vortices is one of the typical mechanisms of the growth of the packets of hairpin-like vortices.

2. DNS of turbulent thermal boundary layer on a rough wall

Turbulent thermal boundary layer on rough plate is an important problem in fundamental turbulent heat transfer research, practical engineering applications and environmental processes. DNS of turbulent thermal boundary layer on rough wall has been only rarely performed compared with that of other wall-bounded turbulence such as turbulent channel flow.

In this study, we performed DNS of the turbulent thermal boundary layer on a rough plate with zero pressure gradient. Several turbulent thermal boundary layers with the different Prandtl numbers, such as Pr = 0.71 and 2, were simultaneously simulated. In the DNSs of spatially developing boundary layers on a rough wall, we provided a driver section with a flat wall and an analysis section with a rough wall as shown in Fig. 2.

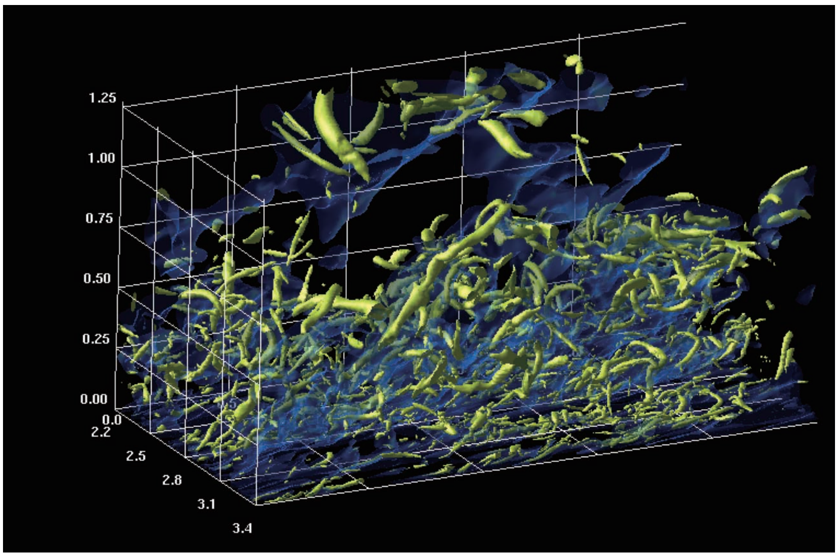

Fig. 1 Iso-surface of normalized vorticity (yellow) and low-speed zone (blue) obtained by the DNS of TBL at R_θ ~2000.

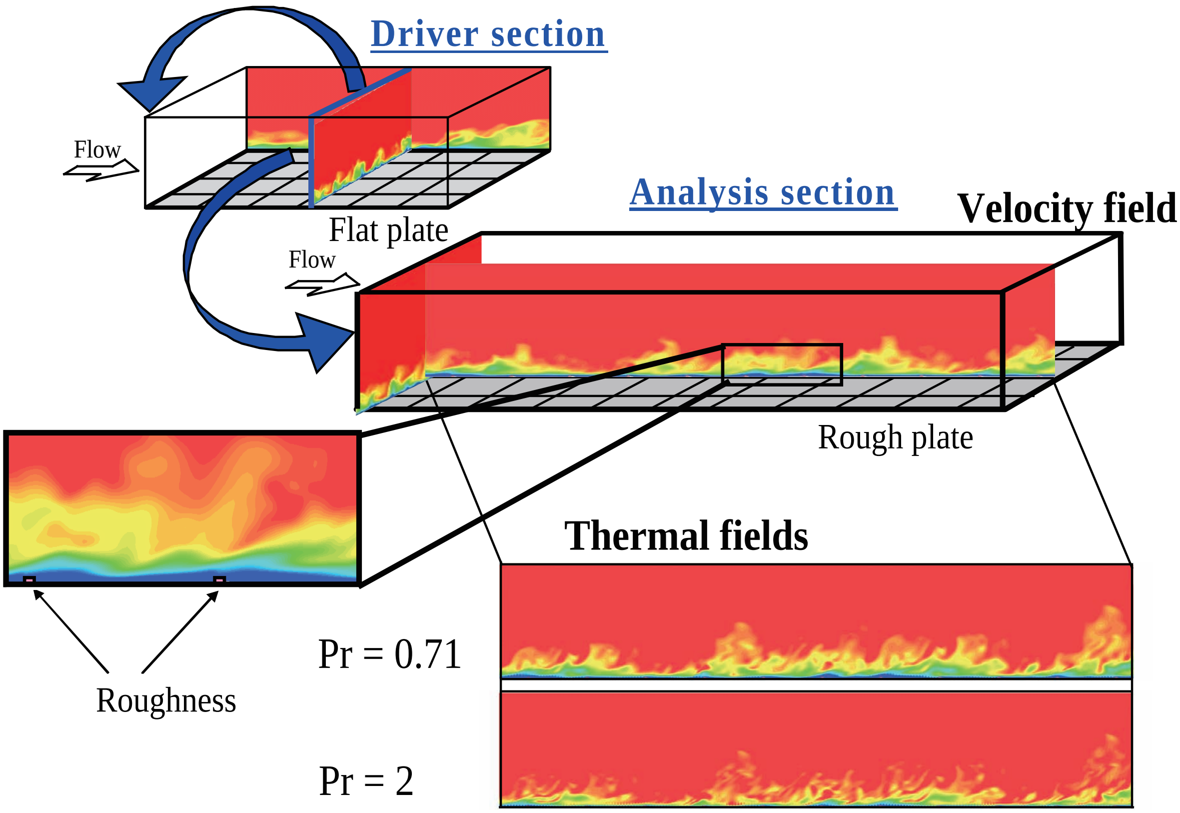

Fig. 2 Computational domains for turbulent thermal boundary layer on a rough plate.

Turbulent inflow conditions for the driver section were generated by rescaling the turbulent boundary layer at some distance downstream of the inflow and by reintroducing the recycled mean profile and fluctuation field. This technique follows those of Kong *et al*. [6] and Lund *et al*. [7]. Turbulent inflow conditions for the analysis section, on the other hand, were generated by exactly copying a turbulent field of the driver section. The parallel and vectorization efficiencies are 98.43% and 99.50%, respectively.

3. High resolution LES study on urban roughness effects on turbulence statistics of atmospheric boundary layer

Turbulent boundary layer over actual shape of urban-city was studied using large eddy simulation (LES)[8]. The area around Tokyo Railroad Station at the center of Tokyo was selected as the computation domain which has Marunouchi area in the west and Yaesu area in the east (Fig. 3). Currently the Marunouchi area has changed its aspect where many tall buildings are built year by year, while the Yaesu area is occupied by low-rise and

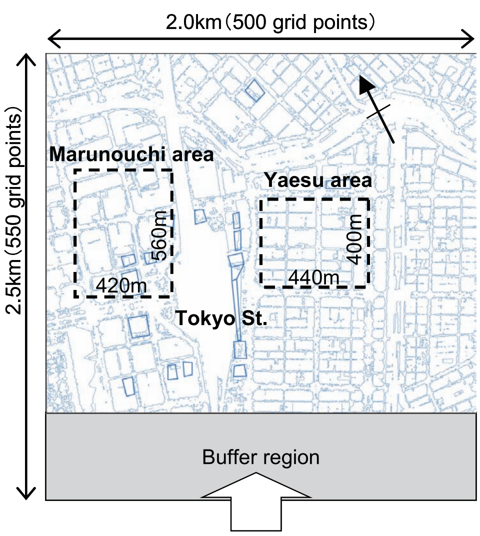

Fig. 3 Computational region.

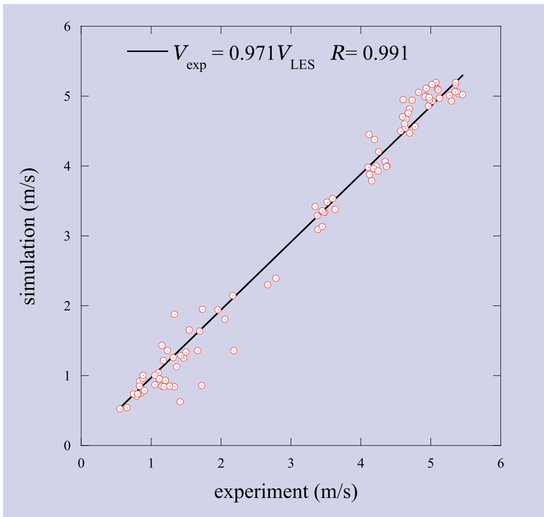

Fig. 4 Mean velocity correlation between experiment and LES.

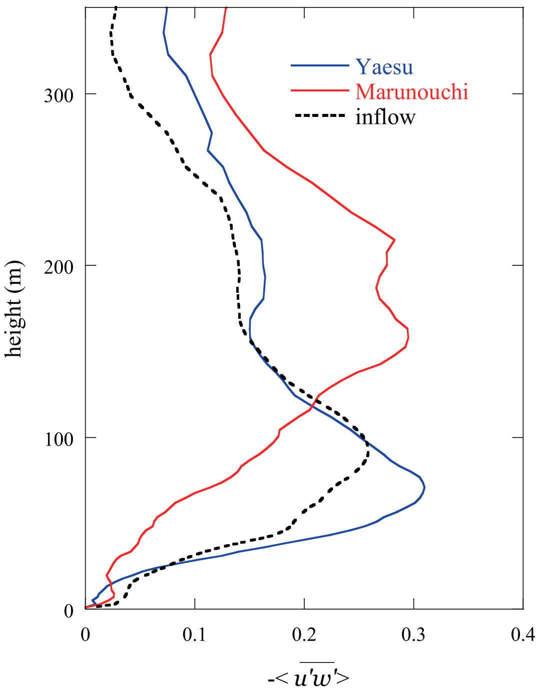

Fig. 5 Reynolds shear stress profiles.

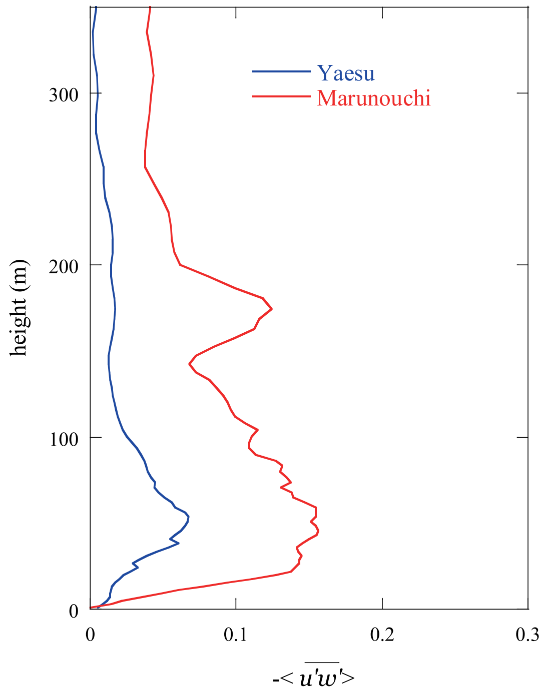

Fig. 6 Dispersive shear stress profiles.

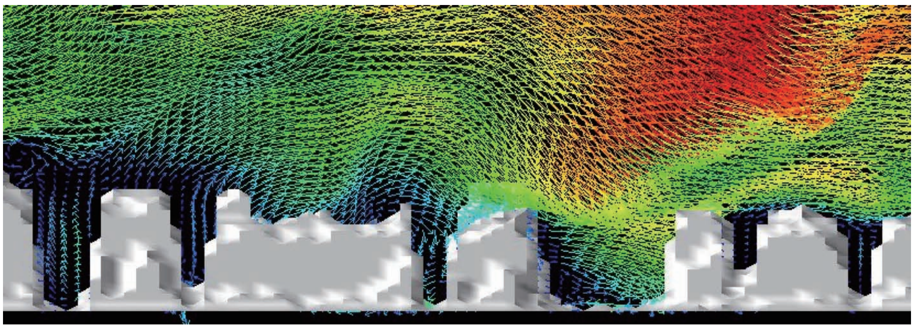

Fig. 7 Sweep-like event blow out the circulation flow in the street canyon.

middle-rise buildings. The computational region has horizontally 2.5 km length in streamwise direction and 2 km width in transverse direction. The horizontal mesh size is 4 m in the both directions and the height of the lowest mesh is around 1m. The total grid number is more than 3 x 10^7. The oncoming turbulent inflow was generated using the quasi-periodic method[9]. The Reynolds number based on the free stream velocity and the boundary layer thickness is 93,000. The buildings are modeled using immersed boundary method.

Through this research we obtained the following results.

(i) The mean wind speed profiles of the simulations and experiments were compared at each measurement point. They agree well with each other (Fig. 4).

(ii) The effect of roughness was examined in the Marunouchi area and the Yaesu area. The Reynolds shear stress increases where there is strong shear approximately at the building height in the mean velocity profile (Fig. 5).

(iii) The dispersive shear stress is small compared to the spatially averaged Reynolds shear stress at the locations above the maximum height of each region, although it is comparable at the locations below the maximum height. The heights of the peaks are higher compared to those of past studies on uniform roughness. The results suggest that in order to predict the spatially averaged time-mean velocity it is necessary to construct a model of dispersive shear stress profile (Fig. 6).

(iv) The sweep-like flow events occur intermittently and they strongly influence the streamwise velocities in the street canopy parallel to the wind direction. Unexpected high wind gust is recognized. The sweep-like flow events also occur in the broad orthogonal street and blow out the circulation flows formed there (Fig. 7).

4. DNS of the turbulence in non-Newtonian surfactant solution

It is known that a small amount of surfactant additives modifies significantly the turbulence in water through its Rheological characteristics. One of the most attractive points from the view point of application is that turbulent drag coefficient in pipe is reduced to 30% compared with water flow at the same flow rate. The amount of surfactant necessary for this reduction is order of 0.1%. The large benefit of this reduction 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 neither clear. Extensive investigations to find the missing links between the chemicals, Rheology, turbulence and real components through the large scale numerical analysis are wanted.

The purpose of this sub-project 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 and also between parallel plates equipped with successive ribs. The result will be used for elucidating the drag reduction mechanism and estimation of heat transfer in heat exchangers.

In FY 2009, modification of DNS code for parallel computing was made. It contains installation of successive solid ribs in the channel. Preliminary analysis of the flow has been made. The results were presented in the symposium but the most important results will be achieved after large-scale simulations on ES2 with changing the Reynolds number, Weissenberg number, rib geometry etc. systematically.

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乱流の世界最大規模直接数値計算とモデリングによる応用計算

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地球シミュレータ（ES2）を用いて、乱流の規範的（カノニカル）な問題の大規模直接数値計算（DNS）を実施した。具体的には（i）スペクトル法を用いた、世界最大レイノルズ数の平行二平板間乱流 DNS、（ii）乱流境界層のスペクトル法における世界最大自由度 DNS である。また、（iii）プラントル数の異なる複数の場の同時計算が可能な、粗面上の乱流熱境界層 DNS のコード開発と最適化を実施した。これらの DNS は各々、（i）高レイノルズ数平行二平板間乱流の対数領域の小スケールにおける普遍的統計法則、（ii）乱流境界層の小スケールにおける統計法則と関連する渦動力学、及び（iii）粗面上の乱流熱境界層における熱（スカラー）輸送の統計を調べるための貴重なデータを提供するものである。また、応用計算として、ES2 上で実施した、東京駅周辺の領域の地表被覆状態を再現した乱流境界層のラージエディシミュレーションの結果を詳細に解析し、実験結果との一致を確認したほか、抵抗低減メカニズムを調べるため、界面活性剤溶液の境界にリブ構造のある平行平板間乱流の DNS コードを開発し、予備的解析を行った。

キーワード: 大規模直接数値計算, 非圧縮性乱, 平行二平板間乱流, 乱流境界層, 乱流熱境界層, 粗面,
都市型大気乱流境界層, 界面活性剤, 抵抗低減