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

Project Representative
Yukio Kaneda Graduate School of Engineering, Nagoya University

Authors
Yukio Kaneda Graduate School of Engineering, Nagoya University
Takashi Ishihara Graduate School of Engineering, Nagoya University
Kaoru Iwamoto 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

In order to understand universal nature of turbulence, we performed large-scale direct numerical simulations (DNS's) of canonical incompressible turbulent flows on the Earth Simulator, including those of (i) turbulent channel flow and (ii) turbulent thermal boundary layer. The DNS data were analyzed to study the Kolmogorov scaling in the so-called log-layer of (i) and the statistics of temperature fluctuation in (ii).

We also performed numerical simulations of turbulent flows on the ES from the view point of engineering applications. We made large eddy simulations of urban turbulent boundary layer. The area around Tokyo Station is selected to study urban-type of wind flows as a computed domain. The result suggests that the wall similarity hypothesis is not applicable to the flow over large roughness, such as urban surface condition. We also developed a DNS code to study the turbulence in non-Newtonian surfactant solution between parallel plates.

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

1. High-resolution DNS of the turbulent channel flow

It is commonly believed that there is a certain kind of universality in the statistics at small scales in the so-called log-layer of wall-bounded turbulence. The Kolmogorov theory [1] suggests that the statistics in the log-layer may attain local isotropy and yield the so-called $k^{-5/3}$ spectrum at sufficiently small scales and at sufficiently high Reynolds number. The validity of the local isotropy or the Kolmogorov spectrum in wall bounded turbulence has been studied experimentally. [2-4] However, it has been difficult to examine them by direct numerical simulation (DNS) because of the lack of computational resource, and as far as we know, there has been no study on the Kolmogorov spectrum by DNS of wall bounded turbulence.

In this study, we performed high-resolution DNSs of turbulent channel flows using the Earth Simulator (ES) and investigated the Kolmogorov scaling in wall bounded turbulence. The largest DNS was done on 1024^3 grid points using 64 nodes (512 cores) of the ES, and the friction Reynolds number Re_τ ($\equiv u_\tau h/\nu$) = 2560 was attained (u_τ, h, and ν are the wall friction velocity, the channel half-width, and the kinematic viscosity, respectively). The number of grid points in the wall-normal direction as well as the attained Re_τ are the largest among those so far achieved in the world.

Figure 1 shows the y^+ dependence of the Taylor microscale Reynolds number defined by

$$R_{\lambda uu}^{(x)} = \frac{u'\lambda_{uu}^{(x)}}{\nu},$$

where $y^+ = yu_\tau/\nu$ is the non-dimensional distance from the wall, u' is the rms of streamwise velocity fluctuation, and $\lambda_{uu}^{(x)}$ is the Taylor microscale defined by

$$\left.\frac{d^2 R_{uu}^{(x)}(r)}{dr^2}\right|_{r=0} = -\left(\lambda_{uu}^{(x)}\right)^{-2},$$

where $R_{uu}^{(x)}(y, r)$ is a longitudinal two-point velocity correlation in the streamwise direction.[5] Each curve in Fig. 1 has two local maximum values except the case with $Re_\tau = 320$.

The first local maximum value occurs at y^+ ~10 and is about 180 for all cases, which is consistent with previous observation in the low Reynolds number DNS. [6] On the other hand, the second local maximum value occurs at the outer end of the log-layer, and magnitude of this value increases with Re_τ. The positions of the first and second local maxima approximately correspond to those of u' and $\lambda^{(x)}_{uu}$, respectively. The largest value of $R^{(x)}_{\lambda uu}$ for the case of Re_τ = 2560 is about 300 at y^+ ~800.

Figure 2 shows the non-dimensional one-dimensional longitudinal spectra of velocity fluctuations at the outer end of the log-layer. It can be observed that there is a wavenumber range in which each spectrum is close to the Kolmogorov scaling. The results are consistent with the experiments. [7, 8]

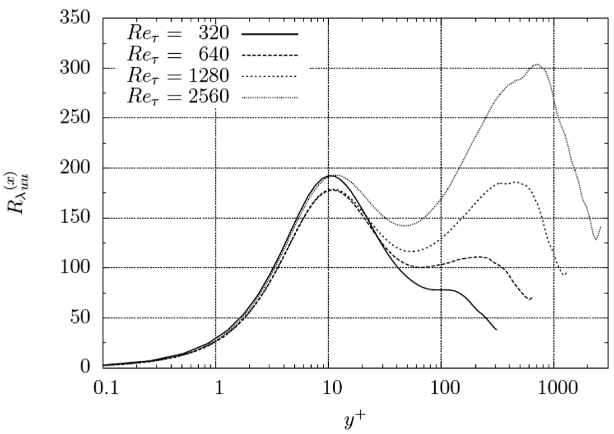

Fig. 1 y^+ dependence of Taylor microscale Reynolds numbers for Re_τ = 320, 640, 1280, and 2560. (From Ref. [5])

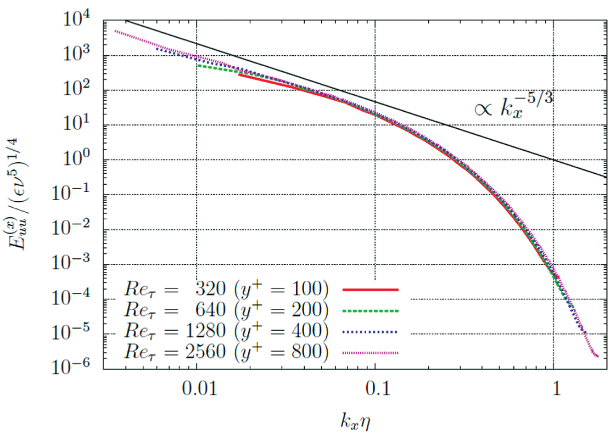

Fig. 2 One-dimensional energy spectra by the DNSs at Re_τ = 320, 640, 1280, and 2560.

2. DNS of the turbulent boundary layer

A turbulent thermal boundary layer on a flat plate is one of the most important problems in fundamental turbulent heat transfer research, practical engineering applications and environmental processes. DNS of turbulent thermal boundary layer has been barely performed compared with that of other wall-bounded turbulence such as channel turbulence. The first attempt of the DNS was performed by Kong *et al.* [9] for Prandtl number Pr = 0.71. The DNS for a higher Pr has not been performed yet.

In this study, we calculated DNS of the turbulent thermal boundary layer on a flat plate, with zero pressure gradient, up to Pr = 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 those of Kong *et al.* [9] and Lund *et al.* [10]. 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.

First, the budget of the transport equation for the temperature variance is compared for thermal boundary layer and a channel flow with constant temperature difference (CTD) [11]. The profiles of the budget of temperature variance agree well with that of turbulent channel flow (CTD) in the near wall region (not shown here). In the outer region, on the other hand, the production in the boundary layer is much smaller than the channel flow (CTD), since, in the latter case, the mean temperature gradient doesn't tend to zero even in the channel center. Second, skewness and flatness factors of the temperature fluctuation is calculated and compared with those of the channel flow. The skewness factor becomes negative away from the wall, while the one in channel flow (CTD) stays positive. Finally, from the instantaneous temperature and velocity fields, it is shown that the negative intermittent temperature structures are associated with the large-scale spanwise vortex in the outer region.

3. LES of the turbulent boundary layer flow over an urban area

The turbulent boundary layer flow over an urban area is studied using large eddy simulation (LES). The area around Tokyo Station is selected to study urban-type of wind flows as a computed domain which has Marunouchi area in the west and Yaesu area in the east. Currently Marunouchi area is surrounded with many tall buildings with various heights, while Yaesu area is occupied by low- and middle-rise buildings. The computational region has horizontally 2.5 km length in streamwise direction and 2 km width in transverse direction (Fig. 3). In the computed case of this study the wind is

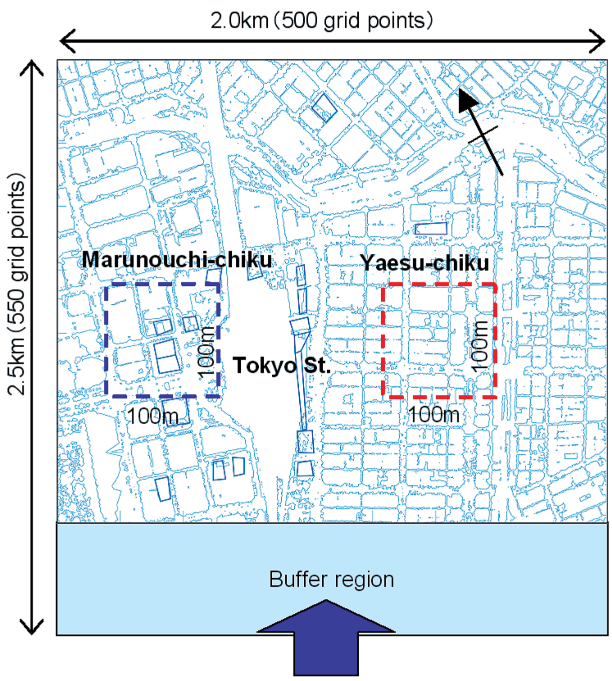

Fig. 3 Computational region of an urban area.

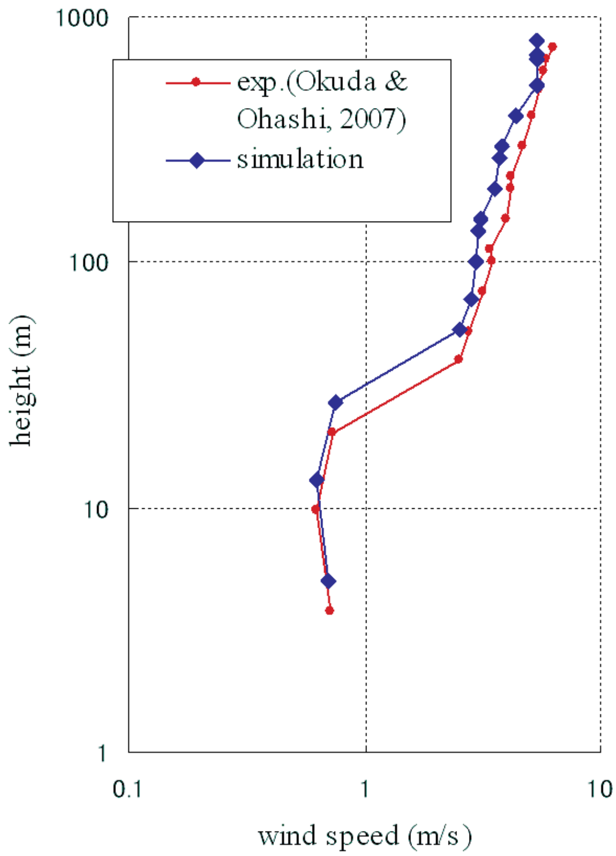

Fig. 4 Mean velocity profiles at inlet.

assumed to flow from south-southwest. The horizontal mesh size is 4 m in the both directions and the height of lowest mesh is around 1 m. The oncoming turbulent inflow is generated using the quasi-periodic method proposed by Lund. In this method, the flow data at recycle station are rescaled and reintroduced to the inlet according to the development of the boundary layer thickness and the friction velocity. The boundary layer thickness has developed to almost 800 m while the height of the computational domain is 3 km (Fig. 4).

Figure 5 compares mean velocity profiles at both Marunouchi and Yaesu areas with experimental data (Okuda & Ohashi, 2007). Both profiles are sufficiently in good agreement with experimental data. The spatially-averaged Reynolds shear stress profiles and Reynolds shear stress profiles based on spatial deviation are compared for various types of urban roughness in Figs. 6 and 7. Spatially averaged value is obtained by computing over 100 m × 100 m region in Marunouchi or Yaesu area. Spatially-averaged Reynolds stress profile at the Yaesu area has a broad peak, while that at Marunouchi area has a sharp peak at the building heights. Reynolds shear stress based on spatial deviation at Yaesu area has a peak around averaged height of the buildings and continues to decrease at two or three times height of the averaged height of the buildings. On the other hand, the Reynolds shear stress at Marunouchi area decreases rapidly and its change occurs at limited area. The range of roughness effect does not reach at 1.5 times height of the tallest building in Marunouchi area. It shows a certain level of possibility that the turbulent wind over relatively large-scaled urban roughness can be represented by the urban-canopy model based on spatial averaging technique such as LES.

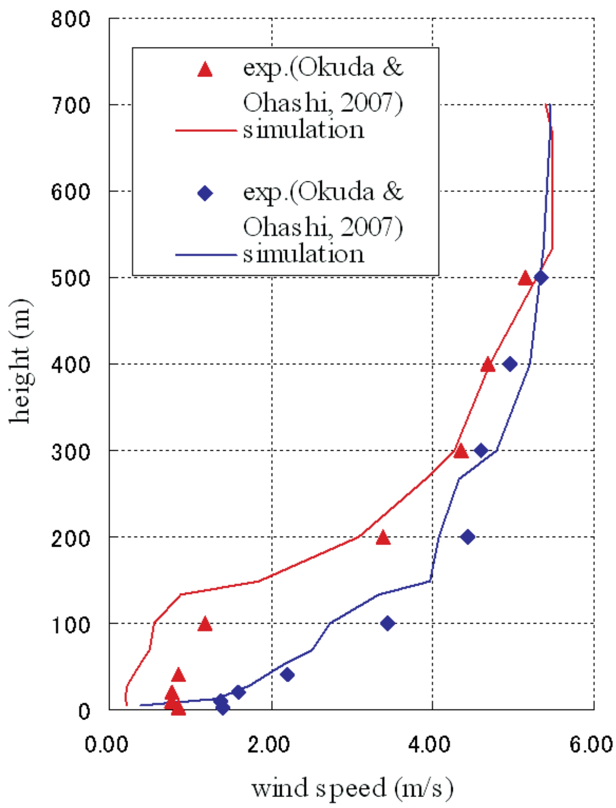

Fig. 5 Mean velocity profiles at Marunouchi area (red) and Yaesu area (blue).

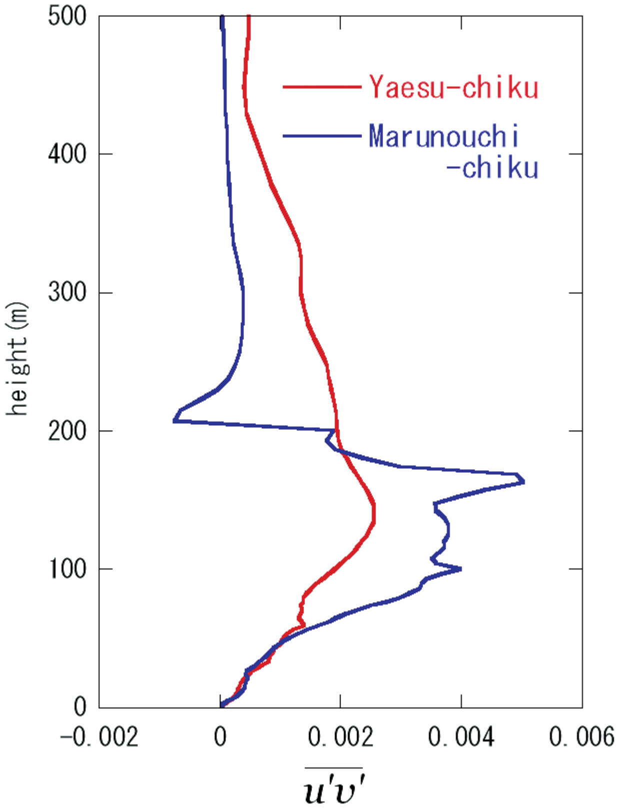

Fig. 6 Vertical profiles of spatially-averaged Reynolds shear stresses.

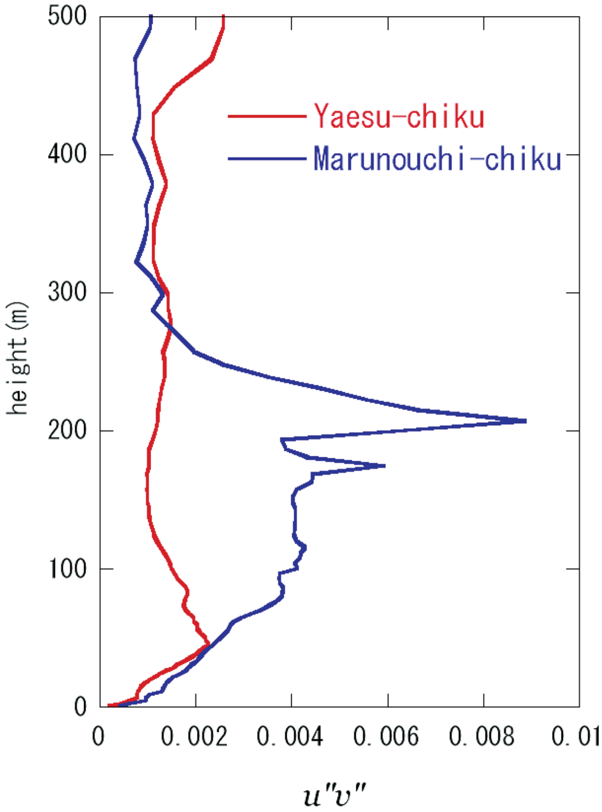

Fig. 7 Vertical profiles of Reynolds shear stresses based on spatial deviations at a specific region.

In order to investigate the influence of large- or small-scaled roughness on the turbulence structure, the turbulent boundary layer flows over urban-like roughness and homogeneous roughness are simulated using LES. The ratio of roughness height (h) and boundary layer thickness (δ) of urban-like roughness is set to almost δ/h = 6, while that of homogeneous roughness is δ/h = 36. Schultz and Flack (2007) indicated that Reynolds stress profiles of turbulent boundary layer flows over smooth and fully rough (k_s^+ = 2.3 ~ 26) collapse at outer region among them. Namely the wall similarity is satisfied for both smooth and relatively small-scaled rough turbulent boundary layers. In this study the profile of Reynolds stress ($u'v'$) over homogeneous roughness shows well agreement to the experiments by Schultz and Flack (2007), while that of urban-like large-scaled roughness does not collapse to their experimental data. This difference is due to the ratio δ/h. It suggests that the wall similarity hypothesis is not applicable to the flow over large δ/h roughness, such as urban surface condition. The influence of the large-scaled roughness on the turbulence structure of the boundary layer is very strong. Its range extends and reaches to the outer layer. It means that the urban canopy model based on RANS does not work well universally for the very large-scaled roughness flows. So, in order to examine turbulent structures of the urban boundary layer flow, it must be a better way to use the experimental or the numerical technique to treat directly urban surface configuration.

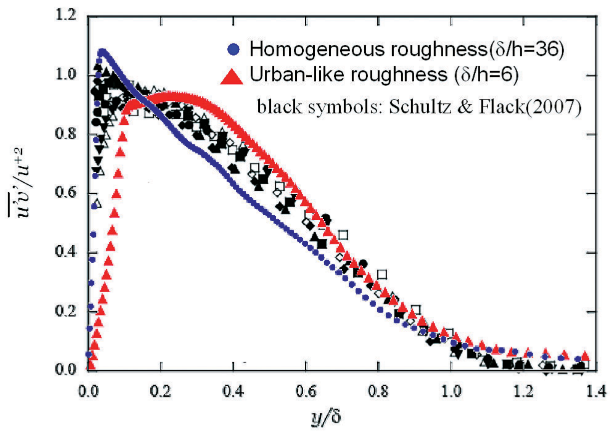

Fig. 8 Reynolds shear stress profiles over homogeneous roughness and urban-like roughness.

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

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 2008, modification of DNS code for parallel computing was made. It contains replacement of multi grid method and employment of pseudo spectrum method. Second order central differential scheme was changed to that of fourth order. Subliminal results were presented in the symposium. Application test of the drag reducing additives were performed in the Sapporo city hall with the cooperation of AIST, Sapporo city etc. It was revealed that 65% of pumping power was reduced by addition of surfactant into the water circuit of air conditional system. The achievement of this year is 70%.

References

[1] Kolmogorov A.N., "The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers," C R Acad. Sci URSS 30, (1941), 301–305.

[2] Saddoughi S.G., Veeravalli S.V., "Local isotropy in turbulent boundary layers at high Reynolds number," J Fluid Mech. 268, (1993), 333–372.

[3] Tsuji Y., "Large-scale Anisotropy Effect on Small-scale Statistics over Rough Wall Turbulent Boundary Layers," Phys Fluids 15, (2003), 3816–3828.

[4] McKeon B.J., Morrison J.F., "Asymptotic scaling in turbulent pipe flow," Phil Trans R Soc A 365, (2007), 771–787.

[5] Morishita K., Ishihara T., Kaneda Y., "Direct Numerical Simulation of Turbulent Channel Flow at High Reynolds Number," Proc of FCS2008 Nagoya Nov. 27–29, (2008). (to appear)

[6] Antinia R.A., Kim J, Browne L.W.B., "Some characteristics of small-scale turbulence in a turbulent duct flow," J Fluid Mech. 233, (1991), 369–388.

[7] Monin A.S., Yaglom A.M., Statistical Fluid Mechanics: Mechanics of Turbulence. Volume 2, MIT Press, Cambridge, (1975).

[8] Sreenivasan K.R., "On the universality of the Kolmogorov constant," Phys Fluids 7, (1995), 2778–2784.

[9] Kong, H., Choi, H. and Lee, J. S., "Direct numerical simulation of turbulent thermal boundary layers," Phys. Fluids, 12, (2000), 2666.

[10] Lund, T. S., Wu, X. and Squires, K. D., "Generation of turbulent inflow data for spatially-developing boundary layer simulations," J. Comput. Phys., 140 (2), (1998), 233–258.

[11] Seki Y., Kawamoto, N. and Kawamura, H., "Proposal of Turbulent Heat Flux Model with Consideration of Linearity and Its Application to Turbulent Channel Flow with Various Thermal Boundary Conditions," Turbulence, Heat and Mass Transfer 4, (2003), 569.

[12] Okuda Y. and Ohashi M., private communication, (2007).

[13] Schultz M. P. and Flack K. A., "The rough-wall turbulent boundary layer from the hydraulically smooth to the fully rough regime," J. Fluid Mech. Vol.580, (2007), 381–405.

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

プロジェクト責任者
金田　行雄　　名古屋大学　大学院工学研究科

著者
金田　行雄　　名古屋大学　大学院工学研究科
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
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

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。ひとつは平行平板間乱流であり、もうひとつは乱流熱境界層である。これらの大規模DNSは各々、壁乱流の対数領域における小スケール渦の普遍統計法則、及び、乱流熱境界層における外層の乱流構造と温度揺らぎの統計の関係を調べるためのものである。

我々はまた、応用計算として、地球シミュレータ上で、東京八重洲地区の地表被覆状態を再現した風の流れのLES解析を行ったほか、粗面乱流境界層におけるラフネスのスケール効果を明らかにした。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・改良し、予備的な計算を行ったほか、実規模のビル省エネ実験（札幌市役所における循環ポンプ動力の削減）に貢献した。

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, 非ニュートン流体, 抵抗低減