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LARGE EDDY SIMULATION OF COMPLEX TURBULENT FLOWS: PHYSICAL ASPECTS AND RESEARCH TRENDS*

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ABSTRACT: In the current paper, we have primarily addressed one powerful simulation tool developed during the last decades——Large Eddy Simulation (LES), which is most suitable for unsteady three-dimensional complex turbulent flows in industry and natural environment. The main point in LES is that the large-scale motion is resolved while the small-scale motion is modeled or, in geophysical terminology, parameterized. With a view to devising a subgrid-scale(SGS) model of high quality, we have highlighted analyzing physical aspects in scale interaction and energy transfer such as dissipation, backscatter, local and non-local interaction, anisotropy and resolution requirement. They are the factors responsible for where the advantages and disadvantages in existing SGS models come from. A case study on LES of turbulence in vegetative canopy is presented to illustrate that LES model is more based on physical arguments. Then, varieties of challenging complex turbulent flows in both industry and geophysical fields in the near future are presented. In conclusion, we may say with confidence that new century shall see the flourish in the research of turbulence with the aid of LES combined with other approaches.

KEY WORDS: LES, energy dissipation, backscatter, local and non-local interaction, SGS model

1 INTRODUCTION

It is the rule rather than the exception that most fluid flows in industry and natural environment are at least partly turbulent. Through joint great efforts by scientists in the mechanics and physics communities, the understanding of turbulence has been tremendously deepened during the last 100 years or so. For instance, we not only may describe the turbulence statistically, but also have the Kolmogorov scaling law based on his assumptions for locally isotopic turbulence, then leading to the universal energy spectrum in the inertial range. Furthermore, we now have learned that the turbulence bears twofold characteristics of both order and disorder, namely, there are coherent structures in seemingly random flow fields. Therefore, we may switch the evolution of turbulence by regulating these structures carrying most momentum and energy of the flow field in order to reduce drag, enhance

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diffusion or intensify mixing. Finally, we have succeeded in designing jet airliner by combining wind tunnel experiments and relatively mature turbulent modeling. However, we are still confronting enormous difficulties due to the limited power of nowadays' computers if all small-scale eddies are resolved to capture significant details of turbulent flows. Furthermore, the acquisition of instantaneous information of the full flow field remains beyond the capability of existing measurement techniques despite of astonishing technical achievements in this respect. This circumstance has hindered people to gain more penetrating insight into the essence of turbulence. Therefore, turbulence, the most significant unsolved problem in classical physics, as R. Feymann called, remains a challenging issue in the new century[1~4].

As an indispensable approach, the numerical simulation of turbulence has been substantially improved by introducing new concepts and ideas. During the last two decades, people have commonly recognized the role of LES as a powerful research tool. On the one hand, LES obtains three dimensional unsteady instantaneous flow fields to yield any statistical quantities instead of the Reynolds averaged ones without relying on a great many empirical constants. On the other hand, LES is more perspective to simulate the complex flows of practical engineering in the foreseeable future due to its moderate CPU time and storage memory demands. Initial applications are mainly focused on the geophysical fluid flows, in particular, the convective boundary layer (CBL)[5]. Recently, the scope of research has extended to many industrial flows which exhibit complicated features or include other physico-chemical processes such as compressibility, acoustics and combustion[6,7]. The research of turbulent flows via LES by Chinese scientists began in 1990s. Su & Kang[8] investigated the flow around a circular cylinder at sub-critical Reynolds number. And Yan et al.[9] examined turbulent round jet flows by stimulated small-scale model in 2000. Li & Xie[10] have simulated the turbulent flows in canopy to explore the terrestrial processes over land with vegetation coverage. Cui et al.[11] have studied the transportation of passive scalar and revealed the cause of underestimation in thermal fluxes by phenomenological turbulent modeling. By using dynamic SGS model, the oscillatory turbulent flow over a flat plate is simulated to reveal distinct behavior during accelerating and decelerating phases[12,13].

The crucial step for LES to succeed is to establish an appropriate SGS model in order to reflect the effects of the unresolved small eddies on the resolved large eddies. Of course, the quality of SGS models is obviously dependent on how much we know about the interaction between large and small eddy modes. The validation of SGS model is necessarily carried out with the aid of direct numerical simulation (DNS) or experimental measurements. We may directly compare the residual stress with DNS database, i.e. test a priori or compare the simulated results with DNS and experiments in the laboratory i.e. test a posteriori. Please note the latter tends to merge various effects including numerical errors. Since the establishment of SGS model is still a most tough task as yet, we attempt to concentrate on the physical aspects to elucidate mechanism implied for assessment of various SGS models in the current paper. The present article therefore is planned in the following way. Introducing fundamental concepts in turbulence and LES, we are concerned with the involved physical foundation: energy dissipation, backscatter, scale invariance, local and non-local triad interaction, anisotropy and resolution requirement. Then, we present an application of turbulence in forest canopy via LES to demonstrate how to establish physical models for practical complex turbulent flows. Finally, we have analyzed the research trends and proposed a few potential directions in this field.

2 PHYSICAL ASPECTS AND SGS MODELS IN LES

The so-called LES means that three-dimensional unsteady turbulent motion of large scales is presented, whereas the turbulent motion of small scales is modeled or, as scientists in meteorology and oceanography communities have named, parameterized. Hence, we may decomposition velocity vector into two components

$$U = \bar{U} + u' \tag{1}$$

where the former is the filtered quantity and the latter the subgrid-scale (SGS) one. Filtering defined as

$$\bar{U}(x,t) = \int G(r,x)U(r-x,t)\mathrm{d}r \tag{2}$$

is one kind of operation implying an average over space instead of ensemble one in RANS, where $G(r,x)$ indicates the normalized filter functions. The conventional filter functions are box function $H(\Delta/2 - r)/\Delta$, Gaussian function $(6/(\pi\Delta^2))^{1/2}\exp(-6r^2/\Delta^2)$ or sharp spectral function $\sin(\pi r/\Delta)/\pi r$. The box function is a spatial average in the neighbor of x with a width Δ. The sharp spectral function corresponds a box filter in the spectral space. And the Gaussian function seems a compromise between both of them. Then, the Navier-Stokes equation is reduced to

$$\frac{\bar{D}\bar{U}}{Dt} = -\frac{1}{\rho}\nabla\bar{p} + \nu\nabla^2\bar{U} - \nabla\cdot\tau_{ij}^r \tag{3}$$

where the residual stress tensor or SGS stress tensor τ_{ij}^r looks like

$$\tau_{ij}^r = \overline{U_iU_j} - \bar{U}_i\bar{U}_j \tag{4}$$

The main problem is how to close the equation by modeling the residual stress in terms of the filtered velocity components.

According to the relationship between the energy spectrum and the filtered one, the kinetic energy of the residual motions turns out

$$\langle k_\iota \rangle = \int_0^\infty (1 - G(k)^2)E(k)\mathrm{d}k \tag{5}$$

In the above expression $G(k)$ denotes the transfer function corresponding to the filter function. By the requirement, for instance, 80% of the energy that should be captured, we are able to estimate the maximal filter width Δ or minimal cutoff wave number k_c. Take the sharp spectral filter as an example, we have $k_cL_\varepsilon = (15/2C_K)^{3/2} = 37.73$ and $\Delta/l_{EI} = 6\pi/0.43k_cL_\varepsilon = 1.16$, where L_ε is the length scale defined as $L_\varepsilon = q^3/\varepsilon$, $q^2 = \overline{u_iu_j}$, $C_K = 1.5$ the Kolmogorov constant and $l_{EI} \approx 0.072L_\varepsilon$ the demarcation scale of energy containing and inertial ranges. If we attempt to capture additional 10% of the total energy, an increase in cutoff wave number k_c or decrease in filter width of factor $2^{3/2} = 2.83$ in each dimension is required[14]. Consequently, the spectral cutoff filter cleanly separates between modes with lower resolution requirement. Nevertheless, it causes non-local oscillation when filtering spatially local phenomenon. In contrast, the box filter exhibits better spatial localization, but it does not allow to separate large and small scales unambiguously[15].

2.1 Energy Dissipation and Eddy Viscosity Models

The earliest SGS model of dissipative eddy viscosity is due to Smagoringsky[16]. As we know, SGS stress tensor can be decomposed into isotropic and anisotropic components. The former determines the rate of global subgrid-scale dissipation, namely, the net energy cascade flux from the resolved to unresolved scales while the latter determines the mean shear stress and therefore the mean velocity profile[17]. Modeling dissipation and stress are two different tasks fulfilled by different models. It has been shown that modeling the former is absolutely of primarily significance. It seems that LES is able to reproduce characteristics of moderately complex turbulent flows such as mean velocity and rms velocity fluctuation even if they are mostly based on the variants of the Smagoringsky mode. Consequently, we would rather have a discussion on the eddy viscosity models at first.

To describe the energy cascade drain, Smagoringsky[16] assumed that SGS stress may be represented as

$$\tau_{ij} = -2\nu_T \bar{S}_{ij} \tag{6}$$

where

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \tag{7}$$

is the strain rate, ν_T the eddy viscosity defined as the product of the mixing length of grid size Δ and the velocity difference at this length scale

$$\nu_T = (C_S \Delta)^2 |\bar{S}| \tag{8}$$

where

$$|\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{1/2} \tag{9}$$

The determination of the Smagoringsky constant C_s ranging from 0.18~0.23 is considerably crucial for correct estimation of dissipation. The Lilly's theoretical value is 0.17, which is found overestimated and should be reduced to 0.10 for most practical flows. The presence of shear near the wall or in transitional flows diminishes the dissipation and the eddy viscosity is revised by applying the so-called Van Driest-type damping or intermittent function such as

$$\nu_T = (C_S \Delta)^2 [1 - \exp(-(y^+/A^+)^3]|\bar{S}| \tag{10}$$

where A^+ is set to the value of 25.

The dynamic model is motivated by the concept of optimization in dissipation estimation by adjusting Smagoringsky constant to account for non-equilibrium flows. This is performed dynamically by calculation of the energy content of the smallest resolved scale based on the Germano identity, implying that the resolved turbulent stress L_{ij} coming from the scale between the test filter with typical filter width $\hat{\Delta} = 2\Delta$ and the grid filter is the difference of subtest stress and subgrid stress. The coefficient C_{ev} required to minimize the error now is a function of $\boldsymbol{x}$ and t so as to minimize the error in dissipation as well.

2.2 Backscatter and Similarity Models

The eddy viscosity model described in the previous paragraph lays emphasis on the modeling of energy dissipation by mainly accounting for isotropic component albeit neglecting the anisotropic component. It is not surprising that such models fail to model turbulent stress etc. We usually compare the real (from DNS or experiments) and modeled stresses as highly fluctuating stochastic variables in a priori tests in terms of correlation coefficient $\rho(\tau^{\Delta}, \tau^{\Delta \mathrm{mod}})$. Typically, ρ merely ranges from $0 \sim 0.25$, exhibiting that there is hardly any correlation between them. The correlation of SGS force of $\nabla \cdot \boldsymbol{\tau}$ is slightly lager than 0.4, whereas the correlation of local SGS dissipation rate can be as high as $0.5 \sim 0.7$[13].

However, people are not very interested in so much detail as one realization, but more concerned with the statistical behavior of turbulent flows. Hence, we should further examine how the stress affects the mean dissipation. In the mean resolved kinetic energy equation

$$\frac{\partial k}{\partial t} + \langle \bar{u}_i \rangle \frac{\partial k}{\partial x_i} = -\frac{\partial A_i}{\partial x_i} - 2\nu \langle \bar{S}_{ij} \bar{S}_{ij} \rangle - \Pi^{\Delta} + \langle \bar{f}_i \bar{u}_i \rangle \tag{11}$$

in which $\Pi^{\Delta} = -\langle \tau_{ij}^{\Delta} \bar{S}_{ij} \rangle$ is highly intermittent SGS dissipation. Although Π^{Δ} on average is positive, its instantaneous value may be negative for a number of flows displaying backscatter[15]. Gong et al.[18] has decomposed the energy transfer into forward and backward part based on the DNS database of decaying turbulence with Reynolds number based on the Taylor scale $\lambda, R_{\lambda} = 113$. Hartel and Kleiser[19] have found that the buffer region in the vicinity of solid wall is the very place where SGS dissipation may be negative owing to larger inverse cascade energy transfer. Zhou[4] has analyzed in detail such triad interaction for energy transfer. All of them have identified the evidence that there do exist backscatter and cancellation of bi-directional transfer. Obviously, modeling of backscatter is beyond the capability of eddy viscosity models.

Accordingly, the similarity model was proposed by Bardina[20] to circumvent these limitations in the eddy viscosity models. The model is based on the assumption that the structure of velocity field below scale Δ is similar to that above scale Δ. On the one hand, $\boldsymbol{\tau} \sim (\varepsilon \Delta)^{2/3}$ according to the Kolmogorov assumption, that is, $\boldsymbol{\tau}^{\gamma\Delta}\gamma^{-2/3}$ is invariant when the scale changes from Δ to $\gamma\Delta$. On the other hand, Liu et al.'s experiment finding[21] that certain structure occurs simultaneously at different scale at nearly the same location further provides the evidence of scale invariance. Then, we may postulate that the subgrid-scale stress may be approximated by double filtering procedure. The filter function can be the same as the original one or different from it and the grid size can be $\gamma\Delta$ with $\gamma \geq 1$. For instance, Bardina[20] assumed $\gamma = 1$ and Liu[21] set $\gamma = 2$. People have considered the influences of these factors. To improve not enough dissipation, Bardina suggested a mixed model by adding a dissipative Smagoringsky term with an adjustable coefficient C_{sim}

$$\tau_{ij}^{\Delta} = C_{\mathrm{sim}} (\overline{\bar{u}_i \bar{u}_j} - \bar{\bar{u}}_i \bar{\bar{u}}_j) - 2(C_s \Delta)^2 |\bar{S}| \bar{S}_{ij} \tag{12}$$

Of course, the similarity model naturally includes energy backscatter effects and demonstrates close correlation between real and modeled results.

Recent study of the turbulent energy budget shows that backscatter in buffer region is essentially dependent on the wall-normal stress and the wall-normal gradient of large-scale streamwise velocity, which leads to an eddy viscosity ansatz based on new scales[19]

$$\nu_t = -C_c \nu \tau_{33} / u_\tau^2 \tag{13}$$

where $C_c = 6.42$ is a constant. With this eddy viscosity ansatz, we may obtain satisfactory results and extend it to high Reynolds number because no Reynolds number dependence is observed.

2.3 Local Interactions and Velocity Estimation Models

Domaradzki and Saiki[22] have suggested that the SGS stress may be calculated directly by its definition, in which the unknown velocity field however is estimated by the resolved one. As a matter of fact, to directly replace full velocity field by filtered one in Bardina's model[20] may, more or less, be regarded as one kind of velocity estimation.

For more accurate estimation, it is necessary to have a thorough analysis of the coupling between large and small-scale motions. Kerr et al.[23] has found that consideration of a limited range of wave number outside the resolved range may compare rather favorably with exact quantities in a priori test. Quantitatively, we may estimate local and non-local interaction by analyzing spectral eddy viscosity, which exhibits a strong cusp in the vicinity of cutoff wave number. Kraichnan's study[24] shows that 75% SGS energy transfer comes from the range of resolved scales $0.5k_c \sim k_c$ for high Reynolds flows, while this range is responsible for almost entire energy transfer for low Reynolds flows. DNS data analysis[25] further demonstrates that observed SGS energy transfer is attributed to the interaction of the resolved scales with a limited range of subgrid scales with wave numbers $k_c < k < 2k_c$. All of these arguments imply that the SGS energy transfer is dominated by local interaction among resolved and unresolved scales within the neighbor of cutoff wave number. The conclusion was also further confirmed by experiments[21]. Actually, Zhou[4] has provided a tool to distinguish local and non-local interaction by defining the following parameter for triad interaction $s(k,p,q) = \max(k,p,q)/\min(k,p,q)$, which can be considered as one sort of scale separation measurement. k, p and q construct a triad. Then, we may estimate local and non-local energy transfer by the following quantities

$$\Pi(k) = \sum_s \Pi(k,s) \tag{14}$$

with

$$\Pi(k,s) = \int_k^\infty T(k',s)\mathrm{d}k'$$

$$T(k,s) = \sum_{p,q|s} T(k,p,q)$$

People have also found that the ratio of the above two quantities is independent of k, i.e. $f(s) \sim \Pi(k,s)/\Pi(k)$, where $f(s)$ is nothing but the distribution function of energy transfer in terms of scale separation s. Therefore, the nonlinear dynamics of the resolved modes with wave number $k < k_c$ is almost governed by their interaction with a restricted range of modes with wave number not beyond $2k_c$.

Based on the foregoing argument, we may construct the SGS stress by

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\,\overline{u_j} \approx \overline{\tilde{u}_i \tilde{u}_j} - \overline{\tilde{u}}_i \overline{\tilde{u}}_j \tag{15}$$

where the approximate velocity field is estimated by filtering the resolved quantities with a grid width Δ so as to include SGS scale influences between and $\Delta/2$ and Δ. The simulation of channel turbulent flows displays the following advantages of the velocity estimation model: it has no adjustable constants; there is no need for any wall function; the comparison shows better correlation in stress components ($> 50\%$); the mean and rms of physical quantities are accurate enough; the results exhibit correct near-wall behaviors. The model captures conspicuous backscatter behavior by stable numerical approach[4,15,22]. In addition, the velocity estimation model also provides a paradigm for the nonlinear Galerkin method of long-term integrating evolution differential equation[26].

2.4 Resolution Requirements and Wall Models

In developing SGS models, we generally assume that the SGS turbulence is approximately locally isotropic. As a result, the simulation of free shear flows, isotropic turbulence and geophysical flows at high Reynolds number is relatively successful. In contrast, the application of LES in industrial flows remains very limited owing to the difficulties arising from the various complexities in this kind of flows such as moderate Reynolds number, more complicated geometry and solid wall[19]. In the near-wall region, the elongated turbulent structures becomes vertically finer so that the SGS turbulence appears obviously anisotropic and the numerical simulation based on coarse resolution is unable to capture significant coherent structures like streaks and burst.

Baggett et al.[17] have proposed a parameter to measure such anisotropy

$$\alpha = (A_{ij}A_{ij}/3)^{1/2} \tag{16}$$

with $A_{ij} = \tau_{ij}/\tau_{kk} - \delta_{ij}/3$, which ranges from 0 for isotropic flows to the maximum of 0.47 for a completely one-axial stress. He has analyzed two experimental flows: one is boundary layer flow in a strongly adverse pressure gradient and another is a circular jet, finding that they become essentially isotropic when $kL_\varepsilon > 50$ or $\Delta x = 2\pi/k \approx L_\varepsilon/10$, in which L_ε is the integral dissipation length defined previously. However, the flow is far from isotropic when the measurement location is very close to the wall, namely $y^+ \approx 60$. Zhou[4] has discussed the source of such anisotropy from long-range interaction of large and small scale modes.

Accordingly, people have recognized that we have to enhance the resolution of numerical simulation so that the energy of SGS scale modes occupy a negligible portion of total one or to devise a better SGS model capable of reflecting fundamental phenomena in the near-wall region. Basically, our strategy to handle these kinds of wall-bounded turbulent flows[17,19,27] is:

(a) To bridge the wall region by specifying the appropriate boundary conditions with the aid of wall models for integration in the core region flow. This approach avoids costly high resolution at the expense of missing the fine turbulent structure in the vicinity of solid boundary. It seems to be the unique feasible way to treat high Reynolds flows via LES.

(b) To use a refined mesh for higher resolution in the near-wall region by the domain decomposition method aiming at capturing at least the dominant turbulent structure there. Since about half the grid points belong to the near-wall region for channel flows at the moderate Reynolds number and the time step is also reduced by satisfying CFL condition, it requires more CPU time and storage memory demands although no further information there is further needed.

Baggett et al.[17] has made an estimation of the resolution requirement as follows. We have learned that the anisotropic modes are confined to eddies larger than a given fraction of integral scale L determined by geometric configuration involved, for instance, half of the width for channel flows. Nevertheless, the integral scale is linearly reduced as y, and eddies larger than $\Delta x \sim y$ remain anisotropic in the near-wall region. The number of anisotropic modes in a slab of thickness $\mathrm{d}y$ should be $\mathrm{d}N \sim L^2\mathrm{d}y/\Delta x^3$ and the total dimension is obtained by integration $N_T \sim \int_{y_0}^{\infty} L^2\mathrm{d}y/y^3 \sim L^2/y_0^2$, where y_0 is chosen as a distance proportional to a specified viscous wall units ν/u_τ. In this manner, the number of anisotropic modes or of dimensions is $N_T \sim (u_\tau L/\nu)^2 \sim Re_\tau^2$.

In reality, this estimation of "non-Kolmogorov modes" in the vicinity of wall illustrates that the cost of LES is only slightly less than that of DNS for wall-bounded turbulent flows. It seems that the way out for cost-saving is to stop at a certain distance from the wall outside the buffer layer where the flow is not scaled in viscous wall unit and to replace LES by a cheaper wall model in the inner region.

As far as the wall-model is concerned, we should mention Deardorff's initial contribution[28] early in 1970s. Thus far, there are three wall models available relating the wall stress and the horizontal velocity component at the first off-wall grid: equilibrium stress model, boundary layer equation model and stochastic estimation model[27]. The simulation of separated and reattached flows, however, is still a bottleneck in this respect[29]. Recently, Wang[30] has developed a wall model with dynamically adjustable eddy viscosity and reported that the model predicts the low-order velocity statistics and, in particular, the correct separation behavior at the trailing edge in good agreement with those by full LES simulation at less than 10% original cost.

3 A CASE STUDY

The investigation of turbulence over and within canopy is of significance due to the demand in understanding terrestrial processes for general circulation model(GCM) parameterization in climate prediction as well as flow field details in meteorology for agricultural production and environment protection. Previous research was based on the force-restore method and other models such as BATS and SIBS. Turbulent modeling and LES for planetary boundary layer was introduced in the last decades[5,31]. Based on previous research, we present a new model to simulate turbulence within and over vegetative canopy demonstrating how to construct a physical model for complex turbulent flows in this paragraph.

The governing equation system is the filtered Boussinesq equation considering buoyancy with additional source terms to model momentum and heat exchange due to canopy

$$F_i = C_d A V \bar{u}_i \tag{17}$$

$$Q(z) = Q(h)\exp(-\alpha F) \qquad F(z) = \int_z^h A\mathrm{d}z \tag{18}$$

where A is the density of leaf area, $F(z)$ is the leaf area index (LAI) between z and h, C_d is the drag coefficient, V is the module of velocity vector, Q is the distribution of radiation flux.

Since the Smagoringsky model is valid only for convective ABL far above the underlying surface, whereas structure-function model becomes more suitable by considering overestimation of dissipation due to intermittence and underdevelopment of small-scale motion in shear turbulence[32]. Then, we assume the eddy viscosity coefficient as

$$\nu_M = \beta\nu_{M1} + (1-\beta)\nu_{M2} \tag{19}$$

where

$$\nu_{M2} = 0.105 C_K^{-3/2} \Delta F(x,\Delta)^{1/2} \tag{20}$$

$$F(x,\Delta) = \frac{1}{6}\sum_{i=1}^{3}\left[|u(x)-u(x+\Delta x_i e_i)|^2 + |u(x)-u(x-\Delta x_i e_i)|^2\right] \tag{21}$$

ν_{M1} and ν_{M2} indicate eddy viscosities for convection or shear dominant regions respectively, β is a ratio ranging from 0 to 1 representing situation in the vicinity of or far from canopy top. F is the local structure function of filtered velocity field of the second order.

We have simulated a region of 192 m×192 m×64 m with 96 × 96 × 32 grids, and integrated 6 400 time step of 0.1 s. The computations are conducted on SGI Origin 2 000 parallel supercomputer at LASG, CAS for 11 h for each case. Strong and weak CBL with the Monin-Obukhov length –40 m, –700 m and LAI 2,5 (see Fig.1) have been calculated as examples[10]. In Figs.2~4, mean horizontal velocity profile, Reynolds stress and turbulent kinetic energy have been simulated and well compared with both observation and simulated results[33,34]. This model also exhibits smaller fraction of SGS energy than Patton's[35]. The organized structure of ramp pattern in temperature scalar field has been observed for strong convective ABL by Gao[36] (see Fig.5). About 15% of the tree height over the canopy,

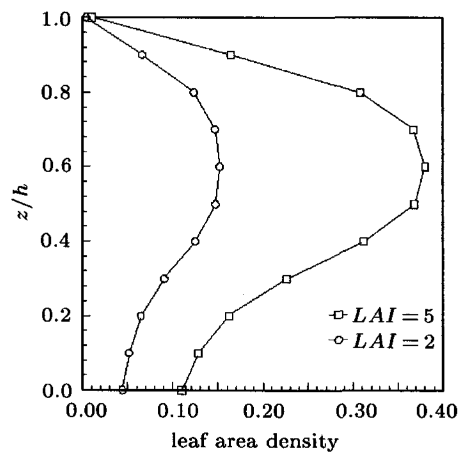

Fig.1 Vertical distribution of leaf area density, where LAI are 2 and 5, respectively

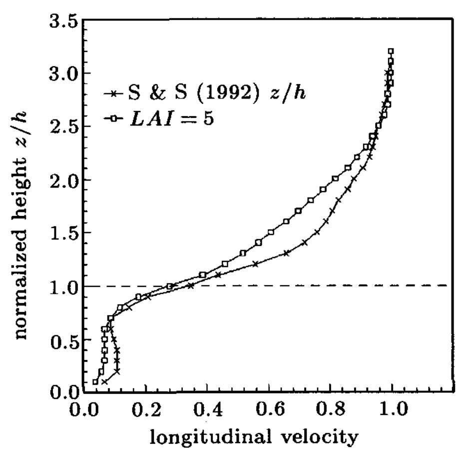

Fig.2 Vertical profile of the normalized horizontal average velocity compared with Shaw and Schumann's result in 1992 for the case with $LAI = 5$ and $L = -700$ m (weak convection)

we may find a slant front of width 3~6 m with drastic temperature variation separating warm and cold regions. This kind of turbulent structure caused by strong velocity shear is responsible for the exchange of warm and cold air in ejection and down sweeping process. In the simulation of turbulence within and above the vegetation canopy, we have also identified such structure for strong covective situation by this new model (see Fig.6).

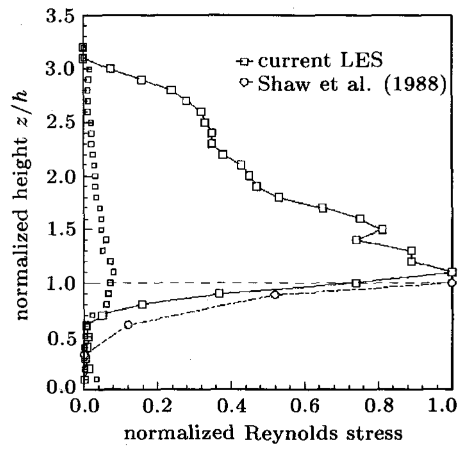

Fig.3 Vertical profile of the normalized Reynolds stress compared with Shaw's in 1988 for the case with $LAI = 5$ and $L = -700$ m (weak convection), where symbol small square indicates SGS stress

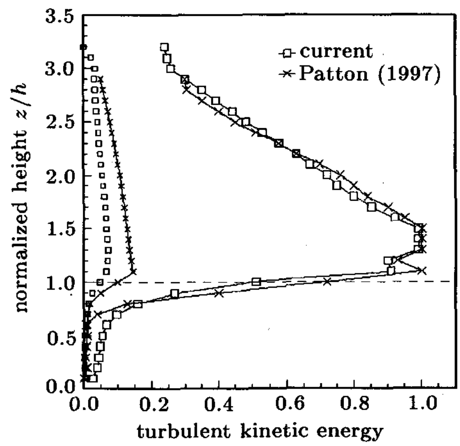

Fig.4 Vertical profile of the normalized total turbulent kinetic energy compared with Shaw and Patton's result in 1997 for the case with $LAI = 5$ and $L = -700$ m (weak convection), where symbol small square indicates SGS stress

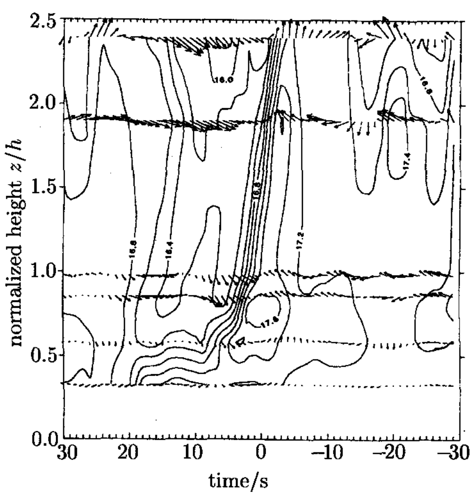

Fig.5 Vertical cross-section of temperature and fluctuation velocity observed by Gao in 1989

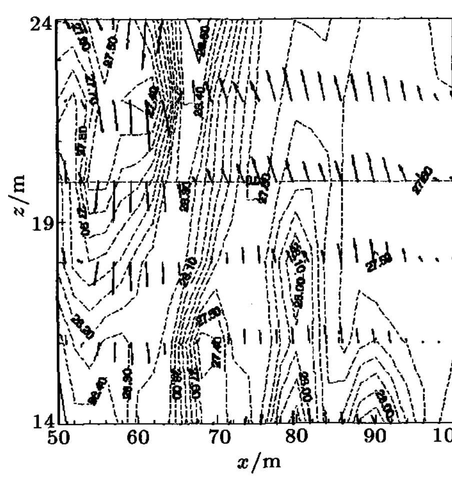

Fig.6 Simulated typical ramp of temperature field for strong convective boundary layer ($L = -40$ m) in and above the vegetation canopy

4 CONCLUDING REMARKS

Through persisting efforts for decades, people have come to the consensus that LES turns out a fairly promising tool for the numerical simulation of complex turbulent flows in engineering as well as in geophysical fields[3,6,7]. Although RANS remains a mature practical approach for routing engineering design, it is unable to undertake the task of simulating unsteady three-dimensional flows. On the other hand, DNS provides database of building-block flows for the validation of new turbulent modeling and SGS models in LES; it is still restricted by computer's power to the low Reynolds flows with simple geometry. LES, however, gets rid of these limitations in simple modeling and DNS at affordable cost.

Nevertheless, we are still facing challenges in this respect. As we have discussed in the previous paragraph, the simulation of wall-bounded turbulent flows requires the resolution as high as $Re_\tau^2 \sim Re_\delta^{1.76}$, which means a factor of 60 increase with a decade of Reynolds number increase and is merely slightly less than that for DNS. Despite the great progresses in LES study, the simulation of wall-bounded turbulent flows with enough resolution is still by far infeasible by present-day supercomputers.

To be more specific, we might as well to classify LES into several hierarchies of categories: VLES (very large eddy simulation) or URANS (unsteady RANS), LES, LES-NWM (with near-wall modeling) and LES-NWR (with near-wall resolution). Relying more upon physical model of high quality, the first and the third ones permit coarse resolution to save computer resources. In contrast, the second and, in particular, the fourth ones require much higher resolution to capture more than 80% turbulent energy at least. According to the prediction of Spalart[3], VLES, LES and LES-NWM get ready at present or in the near future, whereas, LES-NWS may take a couple of decades for handling complex industrial flows based on an estimation of computer technology progress at a conservative rate of a factor of 5 every 5 years.

Our target is to adapt LES as a design tool in industry such as an airliner or a car on an advanced supercomputer or as a research approach of building-block flows on desktop computers for improving available models and devising new concepts for turbulence control. To achieve this goal, we might as well make efforts in two directions. At first, we should have an in-depth analysis of the interaction and energy transfer between large and small-scale modes to establish an appropriate SGS and near-wall model. At the same time, we should develop high performance computing methods such as new grid generation, discrete schemes and massively parallel algorithms to enhance the efficiency of computation.

The simulation of homogeneous isotropic turbulence or free shear flows via LES is proved quite practical and exhibits a remarkable reduction in the computational cost as compared with DNS. The principal object of our research should be aiming at unsteady three-dimensional complex flows including some physical and chemical processes both in engineering and geophysical fields. The typical examples are transitional and relaminarizing flows, massively separated compressible flows, aerodynamic acoustics and non-equilibrium reacting flows. The geophysical turbulence research should serve as an approach of parameterization of small-scale phenomena in global or regional general circulation model or of micrometeorology and environment indices forecast. The complexities in this field come from stratification, rotation, radiation, clouds, heat and moisture transfer and other biological processes with different underlying surfaces such as vegetative canopy, complex terrain and wavy breakers[6,7].

In summary, we have every reason to say with confidence that the new century shall definitely see the flourish in the research of turbulence and its more extensive applications in industry design and environment prediction.

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