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THE POTENTIAL OF LARGE EDDY SIMULATION TECHNIQUES FOR MODELLING INDOOR AIR FLOWS

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ABSTRACT

Large eddy simulations (LES) were performed for flows relevant to or incurred in ventilation air motions with and without thermal effects. The emphasis was placed on the discussion of the possibility and potential of LES for modelling indoor air flows. Some prospective views were given on the capability and implementation of the LES approach. LES is a potential tool for providing detailed and accurate resolution of turbulent flow and heat transfer in analyses of indoor environment and building energy performance. In the foreseeable future, however, it will remain mainly as a complementary approach to statistical modelling and experiments owing to the limitation of computational costs.

KEYWORDS

Large eddy simulation (LES), Subgrid scale (SGS) model, Numerical simulation, Indoor air flow

INTRODUCTION

In Reynolds-Averaged Navier-Stokes (RANS) computations, the turbulence fluctuations are ruled out by a time-averaging process, leaving only the mean flow to be simulated. The statistical effect of turbulence on the mean flow is then fully modelled using the eddy viscosity or Reynolds stress models. Large eddy simulation is a modelling technique that accounts for turbulent flows, where the large, energy-carrying structures are computed directly and the effect of the small scales below the computational grid size is modelled through a subgrid-scale stress term. The large scales in LES are often distinguished from the small scales by using a spatial filtering process, which determines to what degree the large-scale eddy motions in a turbulent flow are explicitly resolved. The width of the spatial filter, which is usually related to the numerical mesh size, determines the largest size of the subgrid scales. In Direct Numerical Simulation (DNS), all the essential turbulence fluctuations are resolved from the largest to the smallest eddies, which consequently requires a sufficiently fine computational grid and is limited to low Reynolds number turbulent flows. LES is an intermediate approach between DNS and RANS. Still, the numerical grid resolution used in LES should be fine enough to resolve high wavenumber flow instabilities leading to large-scale eddy motions, whereupon the dynamically important eddies can be accurately computed and the effect of subgrid scale eddies on the large ones tends preferably to be isotropic and universal. As a result, the modelling of the effect of subgrid scales may be more amenable to successful simulations and may yield significantly smaller errors in the large-scale resolution than are incurred in RANS.

LES has been the subject of extensive studies in the past two decades. Nevertheless, studies of LES for modelling room air flows are rare. This work discusses the potential of LES techniques applied to indoor air flow modelling and briefly describes approaches to using LES. Along with some LES results, the capabilities of LES in producing flow and heat transfer quantities necessary for indoor environment analysis are discussed. It is not the intention of the present work to make an overall review of current LES approaches, but rather to outline the possibilities and potential of LES for indoor air flows in the authors' opinions. Comprehensive discussions on LES can instead be found in, e.g., Rogallo & Moin (1984) and Lesieur & Métais (1996).

MODELLING FORMULATION

LES is based on a spatial filtering operation. The filtered variable, denoted by an overbar, is defined as

$$\bar{f}(\mathbf{x},t) = \int_D f(\mathbf{x}-\mathbf{x}',t)G(\mathbf{x}')d\mathbf{x}', \tag{1}$$

where D is the entire flow domain and G is a low-pass filter function that smoothes the fluctuations on subgrid scales. Applying this filtering operation to the flow equations yields the governing equations for the large-scale motions:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i\bar{u}_j) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}, \tag{2}$$

and the filtered thermal energy equation is

$$\frac{\partial \bar{\theta}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_j\bar{\theta}) = \alpha\frac{\partial^2 \bar{\theta}}{\partial x_j \partial x_j} - \frac{\partial h_j}{\partial x_j}. \tag{3}$$

In Eqs (2) and (3), the SGS stress tensor, $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i\bar{u}_j$, and heat fluxes, $h_j = \overline{u_j\theta} - \bar{u}_j\bar{\theta}$, are the unknowns and must be modelled. Most SGS models assume a principal alignment between the SGS stress or flux and the resolved deformation tensor, $\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$, or the thermal gradient, $\frac{\partial \bar{\theta}}{\partial x_j}$, using the SGS eddy viscosity, ν_t. This gives

$$\tau_{ij} = -2\nu_t\bar{S}_{ij} + \frac{\delta_{ij}}{3}\tau_{kk}, \quad h_j = -\alpha_t\frac{\partial \bar{\theta}}{\partial x_j} = -\frac{\nu_t}{Pr_t}\frac{\partial \bar{\theta}}{\partial x_j}, \tag{4}$$

where α_t is the SGS eddy diffusivity and Pr_t is the SGS Prandtl number. The modelling then becomes a task to formulate the SGS viscosity/diffusivity, which has usually been cast into a relation of $\nu_t \propto {L_{sgs}}^2/\mathcal{T}_{sgs}$. The SGS length scale, L_{sgs}, is often related to the mesh size, Δ, and the time scale, $\mathcal{T}_{sgs}$, is constructed from the resolved large scales. In the famous Smagorinsky model, $\mathcal{T}_{sgs} = 1/|\bar{S}|$ with $|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$. This suggests that $\nu_t = C\Delta^2/\mathcal{T} = C\Delta^2|\bar{S}|$ and thus $\alpha_t = C_t\Delta^2/\mathcal{T} = C\Delta^2|\bar{S}|/Pr_t$. There are also other models that derive the SGS time scale from the SGS kinetic energy, k_{sgs}, through $\mathcal{T}_{sgs} \propto L_{sgs}/\sqrt{k_{sgs}}$. This approach consequently involves an additional equation for k_{sgs} (thus termed the one-equation SGS model). The modelled k_{sgs} equation can be written as

$$\frac{\partial k_{sgs}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_j k_{sgs}) = \frac{\partial}{\partial x_j}\left(C_{k0}\Delta\, k_{sgs}^{\frac{1}{2}}\frac{\partial k_{sgs}}{\partial x_j}\right) - 2C_{k1}\Delta k_{sgs}^{\frac{1}{2}}\bar{S}_{ij}\bar{S}_{ij} - C_{k2}\frac{k_{sgs}^{\frac{3}{2}}}{\Delta}. \tag{5}$$

Details on the implementation of such models can be found in, e.g., Davidson (1997) . Many other SGS models have also been developed, see e.g. Peng (1998) for a literature trace and Rogallo & Moin (1984) and Lesieur & Métais (1996) for reviews.

For thermal flows, such as in rooms with displacement ventilation, where the thermal buoyancy plays a significant role in turbulence evolution, the assumption of local subgrid-scale equilibrium (SGS shear production *vs* SGS dissipation) inherent in the Smagorinsky model can be argued to include the buoyant production. This will in turn yield a $\mathcal{T}_{sgs}$ formulation associated explicitly with a buoyancy-related term. To avoid giving non-real solutions and to account for a part of the energy backscatter caused by thermal stratification, Peng and Davidson (1998) proposed an improved buoyant SGS model as

$$\nu_t = C\frac{\Delta^2}{\mathcal{T}} = C\Delta^2\left(|\bar{S}| - \frac{g\beta}{Pr_t|\bar{S}|}\frac{\partial\bar{\theta}}{\partial x_j}\delta_{2j}\right), \quad \alpha_t = \frac{C}{Pr_t}\Delta^2\left(|\bar{S}| - \frac{g\beta}{Pr_t|\bar{S}|}\frac{\partial\bar{\theta}}{\partial x_j}\delta_{2j}\right). \qquad (6)$$

It is obvious that, for isothermal flows, this model returns to the conventional Smagorinsky model.

The SGS models often include one or more model coefficients (C's and Pr_t in the above expressions). A wide range of values has been employed in applications: the coefficients are flow-dependent. Moreover, some SGS models hold an incorrect near-wall asymptotic property, which would play a negative role in handling near-wall turbulence and would be a denominator of accuracy in simulations of, e.g., convective heat transfer over building enclosure surfaces. To overcome these and other drawbacks preserved in these base models, the Germano-Lilly dynamic procedure (Germano *et al.*, 1991, Lilly, 1992) has commonly been used to determine the model coefficient as a function of time and space. It is here termed a *dynamic procedure* rather than a dynamic model because the Germano approach provides the most powerful means to date and makes the LES more universal than ever for dealing with different flows, while the employment of this procedure needs to be based on a large eddy simulation performed using the aforementioned or other SGS base models. The philosophy of this procedure is that the small scales in the resolved eddies are assumed to be the most active part interacting with the subgrid scales. An additional test filtering operation is thus applied to the resolved scales to obtain the effect of small-scale eddies therein and, subsequently, is used to compute the SGS model coefficient. Note that the model coefficient determined by the dynamic procedure may in many cases be ill-conditioned with singularity problems and/or by having locally and temporally unphysical values. A number of methods have been proposed to remedy such problems. One usual way is to make a spatial averaging on the coefficient in the directions of flow homogeneity. For flows with no homogeneous direction, e.g. many room ventilation flows, local averaging may be used.

The numerical methods used are of significant importance for a successful LES. The governing equations can be discretised using any methods as used in RANS computations, e.g. finite difference, finite volume and finite element methods. Very commonly in LES for fundamental flows, the spectral method has been used owing to its high numerical accuracy. This method is much less flexible for geometrically complex flows, however, whereas finite volume (or finite difference) methods have so far been the most popular approaches. To resolve large-scale turbulence fluctuations, the grid resolution needs to be sufficiently fine, particularly near the wall, to account for the flow structures inherent in large-scale motions, e.g. streaks in the near-wall viscous sublayer. High-order numerical schemes, together with fine grid resolution, are always preferable in order to reach accurate LES, but are not necessary as such as are adopted in DNS. This may be justified by the numerical error associated with the schemes, which should be substantially smaller than the SGS contribution. Moreover, SGS stresses are dissipative in nature, and special care should then be taken in using dissipative, high-order upwind-biased schemes that may significantly affect the spectrum of the resolved structures. Instead, non-dissipative schemes such as central differencing are mostly used. In applications for relatively complex flows, second-order schemes have commonly been employed in both spatial and temporal discretisations.

APPLICATION EXAMPLES

Indoor air flows are often characterized by turbulence and, in many cases, in combination with a number of local flow features, such as mixing and separating, wall jet, thermal plume and stratification, vortex shedding, local laminar and transitional flows, and local relaminarisation. The modelling approach in most room air flow simulations has so far been two-equation eddy viscosity models (some have used Reynolds stress models). To deal with the local flow features as such, the RANS approach may be an awkward method. By contrast, LES is able to yield more affluent and accurate information on turbulence than RANS by resolving the flow structures and their evolution in time and space. It is thus expected to be more powerful and universal than RANS models in handling different flow phenomena such as those existing in room air motions.

Three examples are presented below to demonstrate the capability of LES. It should be pointed out that most ventilation flows are much more complex than the flows considered. Nonetheless, these flows are viewed as essential ingredients extracted from complex ventilation flows and cast in relatively simple, isolated configurations for more efficient and comprehensive studies. These flow features, alone or together, often play an essential role in the creation and control of indoor air flows, such as thermal buoyancy and stratification, natural convection boundary layer, mixing and separation. They are thus relevant to practical room air motions created by mixing, displacement and natural ventilation systems.

Figure 1 shows a LES based on Eq. (6) for the Reayleigh-Bénard (RB) convection flow ($Ra = 3.8 \times 10^5$) arising between two 6×6 planes with a heated floor and a cooled ceiling. This configuration is somewhat similar to a displacement ventilation system with cooled ceiling panels. The air motions are different, however, because this flow is driven purely by thermal buoyancy. The mean flow is statistically stationary but has very active turbulent fluctuations, which, particularly near the floor, are often necessary factors in evaluating thermal comfort. It is obvious that two-equation RANS models are incapable of handling this type of flow in which the turbulence fluctuations are ruled out by time averaging. Fig. 1 a) and b) show the time-averaged (denoted $\langle\rangle$) temperature and its fluctuation in comparison with the DNS data. Fig. 1 c) and d) illustrate the instantaneous flow field and the contour of vertical velocity, $\bar{v}$ (at the mid-depth xy-plane, only the left side is shown). Fig. 1 d) shows that the cold air (dashed lines) descends and the hot air (solid lines) rises alternatingly, causing large-scale coherent structures.

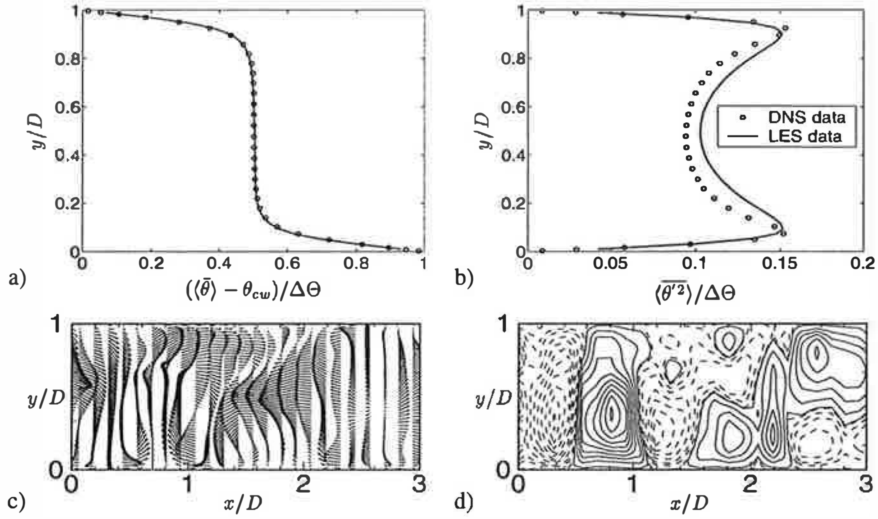

FIGURE 1: Rayleigh-Bénard convection. a). Mean temperature θ_{cw} is the temperature on the cooled ceiling and $\Delta\Theta$ the temperature difference from the heated floor); b). Temperature fluctuation; c). Instantaneous flow field; d). Contour of instantaneous vertical velocity: solid lines positive and dashed lines negative.

Figure 2 shows a LES for a buoyancy-driven flow arising in a closed square cavity ($H/W = 1$) with two opposite sidewalls differentially heated. This configuration is similar to rooms with one facet exposed to the outdoor cold/hot climate, causing natural convection flow along the room enclosure surfaces. The buoyant velocity scale, $U_0 = \sqrt{g\beta\Delta\Theta H}$, is about unity and $Ra = 1.58 \times 10^9$. The results shown are in rather good agreement with the experiment (Tian, 1997) .

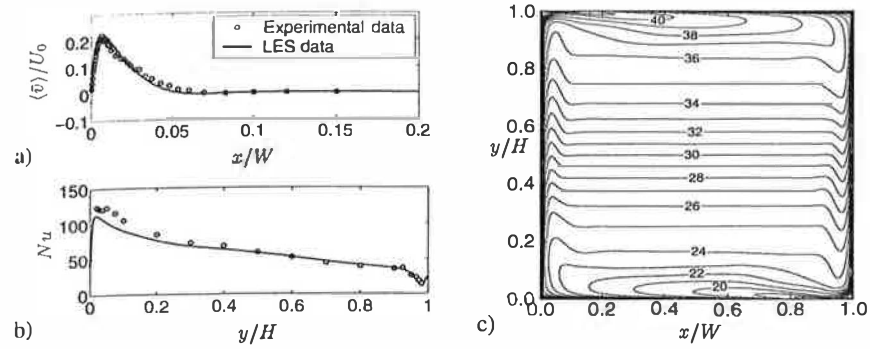

FIGURE 2: Buoyant cavity flow. a). Mean vertical velocity at $y/H = 0.5$; b). Heat transfer (Nusselt number, Nu) along the hot wall; c). Contour of mean temperature.

Figure 3 shows some LES results for a mixing ventilation flow in a room with dimensions of length $(L) \times$ height $(H) \times$ depth $(D) = 9 \times 3 \times 3$, in which the air is supplied through a slot under the ceiling and is exhausted above the floor on the opposite wall. The Reynolds number based on the inflow parameters is about 5000. A dynamic one-equation SGS model (Davidson, 1997) was used with wall functions (not along the ceiling). The LES does not show an improvement for the mean flow predictions as compared with the standard $k - \varepsilon$ model and is even worse in the near-floor region (Fig. 3 a)). This is probably due to the use of the log-law wall function, which is unsuitable for instantaneous flows, and to the relatively coarse grid used. The resolution for the turbulence quantities is reasonable, however, as shown in Fig. 3 b). Since the SGS model accounts only for the small scale eddies, the SGS eddy viscosity should be much smaller than the entire turbulent eddy viscosity obtained from a RANS model. Figure 3 c) shows that the SGS ν_t is two orders lower in magnitude than the RANS ν_t in the near-ceiling wall jet.

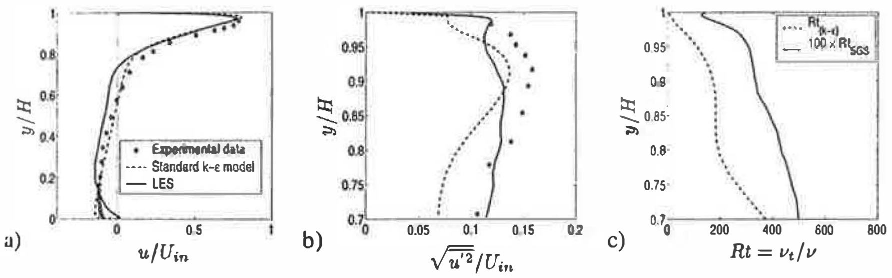

FIGURE 3: Mixing ventilation flow. a). Mean velocity at $x = H$; b). Turbulence intensity in the wall jet at $x = H$; c). Ratio of SGS/RANS eddy viscosity to molecular viscosity, $Rt = \nu_t/\nu$, in the wall jet at $x = H$.

SOME PROSPECTIVE VIEWS

Over the past twenty years the LES technique has matured considerably with significant advancements in developing new SGS models and numerical schemes. The rapid development of digital computers has also greatly facilitated the implementation of LES to complex flows of industrial and/or academic interest. At present, however, LES is viewed mainly as a complementary approach to RANS modelling and experiments and is used to improve the confidence of RANS modelling for indoor air flows.

Air movement in rooms is usually characterized by low velocities and a low turbulence level for comfort indoor environments. This makes LES possible and affordable for relatively complex room air flows. The general advantages of LES over RANS have been mentioned by many other authors elsewhere. For LES of indoor air flows, specifically, the following aspects are outlined here. **a)** Dynamic LES modelling should be more universal than any existing RANS models and usually provide more accurate predictions for indoor air flows created by and controlled with different ventilation systems; **b)** LES can provide relatively accurate measures, as a complementary approach to experiments, to develop, calibrate and validate RANS modelling of indoor air flows where no measured data are available and running measurements is too costly or may even be impossible; **c)** LES can provide quantities that are needed to evaluate indoor air quality and thermal comfort, while RANS models are incapable of providing them or inaccurate in their rendering of these quantities. For example, although little attention has been paid to thermal fluctuation for its influence on thermal comfort, it seems plausible (at least to the present authors) to argue that this quantity plays a significant role in thermal sensation of room occupants. Moreover, in studies of indoor air quality involving dispersion and deposition of indoor airborne pollutants, LES allows a much more accurate accounting of particle-turbulence interactions than does RANS upon a more powerful parameterisation of the turbulence.

In CFD simulations, higher accuracy and more profound physical insight are usually compromised by excessively costly computational resources. The same is ture for LES. While it is viewed as a potential and viable technique, LES is not at this time sufficiently ready for practical indoor air flow analyses, mainly owing to restrictions in computer power. Furthermore, more robust approaches are needed to improve the computational efficiency and accuracy. For indoor air flow analyses, special effort needs to be made on two primary aspects:

- Near-wall treatment. LES resolves instantaneous large-scale motions. The use of the log-law wall function, derived from local-equilibrium assumption for mean flows, is questionable in LES. To relax the requirement on near-wall grid refinement (in all three directions to capture structures such as low- and high-speed streaks), proper wall treatment is needed for efficient LES.
- Inflow boundary conditions. LES requires transient boundary conditions for instantaneous, filtered flow and thermal quantities. For ventilation flows, where the air is often supplied through diffusers, the inflow condition in LES must rely heavily on empirical formulation. Models/approaches to describe the inflow condition are needed in practical LES applications.

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