BUILD SIMUL (2018) 11: 821–870
https://doi.org/10.1007/s12273-018-0459-3

Review Article

LES over RANS in building simulation for outdoor and indoor applications: A foregone conclusion?

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Abstract

Large Eddy Simulation (LES) undeniably has the potential to provide more accurate and more reliable results than simulations based on the Reynolds-averaged Navier-Stokes (RANS) approach. However, LES entails a higher simulation complexity and a much higher computational cost. In spite of some claims made in the past decades that LES would render RANS obsolete, RANS remains widely used in both research and engineering practice. This paper attempts to answer the questions why this is the case and whether this is justified, from the viewpoint of building simulation, both for outdoor and indoor applications. First, the governing equations and a brief overview of the history of LES and RANS are presented. Next, relevant highlights from some previous position papers on LES versus RANS are provided. Given their importance, the availability or unavailability of best practice guidelines is outlined. Subsequently, why RANS is still frequently used and whether this is justified or not is illustrated by examples for five application areas in building simulation: pedestrian-level wind comfort, near-field pollutant dispersion, urban thermal environment, natural ventilation of buildings and indoor airflow. It is shown that the answers vary depending on the application area but also depending on other—less obvious—parameters such as the building configuration under study. Finally, a discussion and conclusions including perspectives on the future of LES and RANS in building simulation are provided.

Keywords

computational fluid dynamics (CFD),
position paper,
urban physics,
building physics,
fluid mechanics

Article History

Received: 10 June 2018
Revised: 20 June 2018
Accepted: 21 June 2018

Indoor/Outdoor Airflow and Air Quality

1 Introduction

CFD can be defined as *"the art of replacing the integrals or the partial derivatives (as the case may be) in the Navier-Stokes equations by discretized algebraic forms, which in turn are solved to obtain numbers for the flow field values at discrete points in time and/or space"* (Anderson 1995).

The application of CFD in the field of building simulation is particularly challenging. For wind flow around buildings, this can be attributed to the specific difficulties associated with the flow field around bluff bodies with sharp edges, many of which are not encountered in CFD computations for simple flows such as channel flow and simple shear flow (e.g. Ferziger 1990; Leschziner 1990, 1993; Stathopoulos 1997; Murakami 1998). Murakami (1998) meticulously outlined the main difficulties in CFD applied to wind flow around buildings: (1) the high Reynolds numbers in these applications, necessitating high grid resolutions, especially in near-wall regions as well as accurate wall functions; (2) the complex nature of the 3D flow field with impingement, separation and vortex shedding; (3) the numerical difficulties associated with flow at sharp corners and consequences for discretization schemes; and (4) the inflow (and outflow) boundary conditions, which are particularly challenging for LES. These difficulties were directly linked to limitations in physical modeling and in computational requirements at those times, but many of those limitations are still to some extent present today. For indoor airflow, the challenges are represented by (1) the potentially large variations in turbulence levels with can include low-Reynolds effects and relaminarization of the flow; (2) the wide range of spatial scales from the length scale of the room to the details of inlet and outlet openings

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necessitating large numbers of cells and (3) the surface boundary conditions for the energy equation which may inhibit the use of wall functions (Sørensen and Nielsen 2003). Additional challenges can be simultaneous heat flows (e.g. heat conduction through the building enclosure, heat gains from heated objects indoors, solar radiation through the building fenestration), phase changes (e.g. water condensation and evaporation), chemical reactions (e.g. combustion in case of a fire), and mechanical movements (e.g. fans and occupant movements) (Chen and Srebric 2001).

While many CFD approaches exist, a view at the vast literature in building simulation indicates that the two most popular approaches by far are Large Eddy Simulation (LES) and Reynolds-averaged Navier-Stokes simulations (RANS). The use of Unsteady RANS (URANS) in building simulation for stationary (statistically steady) problems is rather limited, although valuable achievements have been reported (e.g. Rossi and Iaccarino 2013; Tominaga 2015; Tominaga and Stathopoulos 2017). URANS is being used frequently though for problems in building simulation that are not stationary, e.g. with time-varying boundary conditions (e.g. Toparlar et al. 2015; Gao et al. 2018). Also the use of hybrid LES-URANS approaches in building simulation is rather limited. Hybrid LES-URANS consists of combining LES and URANS for reasons of computational economy, where URANS is applied in the near-wall region and LES outside this region. LES and URANS however are fundamentally different approaches with very different requirements in terms of grid topology. While in relatively simple flows such as channel flow and simple shear flow it is feasible to define a clear boundary between the regions where URANS and LES are applied and hence also the boundary between the two different grid topologies, in the very complex flow fields around buildings or inside buildings characterized by impingement, separation and—for outdoor flows—vortex shedding, this is far from straightforward.

LES and RANS are complementary to other, more traditional methods in building engineering, such as full-scale on-site or laboratory experimentation and reduced-scale laboratory testing. The latter includes atmospheric boundary layer wind tunnel testing (e.g. Penwarden and Wise 1975; Cook 1975; Isyumov and Davenport 1975; Wiren 1975; Castro and Robins 1977; Robins and Castro 1977a,b; Tieleman et al. 1978; Isyumov 1978; Murakami et al. 1979; Britter and Hunt 1979; Beranek and van Koten 1979a,b; Irwin 1981; Huber and Snyder 1982; Stathopoulos 1984; Simiu and Scanlan 1986; Stathopoulos and Storms 1986; Schatzmann et al. 1987; Kawamura et al. 1988; Livesey et al. 1990; Surry 1991; Richards and Hoxey 1992; Kato et al. 1992; Lam 1992; Uematsu et al. 1992; Niemann 1993; Wu and Stathopoulos 1994, 1997; Visser and Cleijne 1994; To and Lam 1995; Sasaki et al. 1997; Meroney et al. 1999; Blocken et al. 2008a; Salizzoni et al. 2009; Tsang et al. 2012; Conan et al. 2012; Tominaga and Blocken 2015, 2016; Ricci et al. 2017a), water channel measurements (e.g. Princevac 2010; Pournazeri et al. 2012; Cruz-Salas et al. 2014; Neophytou et al. 2014; Karra et al. 2017) or water tank experiments (e.g. Linden et al. 1990, 1999; Hunt and Linden 1999; Bolster and Linden 2007; Livermore and Woods 2007; Yu et al. 2007; Tapsoba et al. 2007; Kang and Lee 2008; Morsing et al. 2008; Chen 2009; Etheridge 2011; Thomas et al. 2011; van Hooff et al. 2012a,b; Partridge and Linden 2013; Khayrullina et al. 2017). Each approach has its specific advantages and disadvantages. The main advantages of CFD are that it can provide detailed information on the relevant flow variables in the whole calculation domain ("whole-flow field data"), under well-controlled conditions and without similarity constraints. However, the accuracy and reliability of CFD simulations are of concern and solution verification and validation studies are imperative. This requires high-quality full-scale or reduced-scale measurements, which in turn should satisfy important quality criteria. Therefore, experiments remain indispensable. In addition, the results of LES and RANS simulations can be very sensitive to the many computational parameters that have to be set by the user. For a typical simulation, the user has to select the target variables, the computational geometry, the computational domain, the computational grid, the turbulence model, the boundary conditions, the near-wall treatment, the discretization schemes, the convergence criteria, etc. This raises the need for best practice guidelines for CFD applications, both for LES and RANS.

LES undeniably has the potential to provide more accurate and more reliable results than RANS simulations. However, LES entails a higher simulation complexity and a much higher computational cost. In spite of some claims made in the past decades that LES would render RANS obsolete, RANS remains widely used in both research and engineering practice, in building simulation and beyond. This paper attempts to answer the questions why this is the case and whether this is justified, from the viewpoint of building simulation. Throughout the past decades, many valuable position papers on LES versus RANS have been published. Concerning building simulation for outdoor application, a peak of published position papers was reached about 20 years ago. Now, 20 years later and at the occasion of the 10th birthday of the international journal "*Building Simulation*", the time seems right to provide a retrospective and an update on the status of LES versus RANS in this field.

At the beginning of this paper, I issue a number of important disclaimers. First, this is a position paper, not a review paper, and no attempt is made to be complete. The building simulation community is a very large and very productive community with many researchers and practitioners involved in either LES or RANS simulations, or both. Many have provided very important contributions but in the interest of brevity, only a few can be mentioned and cited in this paper. Several of the application examples in the final stages of this paper will be taken from the author's own work, simply because of the availability of all the data and information about all the specifics of the simulations. The author apologizes to all colleagues whose very valuable work is not explicitly mentioned in this paper. Second, this paper focuses mainly on steady RANS and LES, it only briefly addresses URANS and it does not consider hybrid LES-URANS and other approaches for the reasons mentioned above. Third, this paper focuses only on five application areas: pedestrian-level wind comfort around buildings, near-field pollutant dispersion around buildings, urban thermal environment, natural ventilation of buildings and indoor airflow, although some comments concerning other application areas are provided as well. The reason for this focus is the expertise of the author, which is mainly situated in urban physics and environmental wind engineering and—albeit to a much lesser extent—in indoor airflow. Fourth, as an arbitrary choice, natural ventilation will be addressed as part of the outdoor applications, while evidently it would fit equally well with the indoor applications. Fifth, while building simulation in its widest sense encompasses a very wide range of spatial scales (Fig. 1), this paper only focuses on applications at the meteorological microscale and the building scale.

The paper is structured as follows. Section 2 presents the RANS and LES equations and options for closure. In Section 3, a brief history of RANS and LES is provided. Section 4 provides relevant highlights from some previous position papers on RANS and LES. Given their importance, the availability or unavailability of best practice guidelines is outlined in Section 5. In Section 6, the performance of RANS and LES for the five application areas mentioned above is demonstrated by a series of examples. Finally, Section 7 contains discussion and conclusions including some future perspectives.

2 Governing equations and closure

"How can it be that mathematics, being after all a product of human thought independent of experience, is so admirably adapted to the objects of reality?" [1]

2.1 Governing equations

The governing equations are the conversation of mass (continuity) and Newton's second law. While strictly the term Navier-Stokes (NS) equations only covers Newton's second law, in CFD it is generally used to refer to the entire set of conservation equations. The instantaneous three-dimensional NS equations for a confined, incompressible, viscous flow of a Newtonian fluid, in Cartesian co-ordinates and in partial differential equation form are:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1a}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2\nu s_{ij}) \tag{1b}$$

These equations can be supplemented with the energy equation. If it is assumed that the fluid has a constant specific heat, this equation is a convection-diffusion equation for the temperature:

$$\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial x_j}(\theta u_j) = \frac{\partial}{\partial x_j}\left(\frac{k}{\rho c_p}\frac{\partial \theta}{\partial x_j}\right) \tag{1c}$$

The equation for mass transfer (e.g. vapor or pollutants) has the same form:

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x_j}(c u_j) = \frac{\partial}{\partial x_j}\left(D\frac{\partial c}{\partial x_j}\right) \tag{1d}$$

The vectors u_i and x_i are instantaneous velocity and position, p is the instantaneous pressure, θ the instantaneous temperature, c the instantaneous concentration, t the time, ρ the density, ν the kinematic molecular viscosity, c_p the

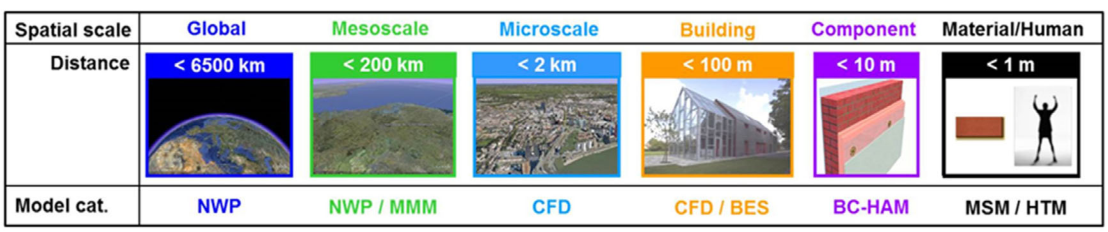

Fig. 1 Schematic representation of the spatial scales relevant to building simulation, including their typical maximum horizontal length scales and associated model categories. NWP = Numerical Weather Prediction; MMM = Mesoscale Meteorological Model; CFD = Computational Fluid Dynamics; BES = Building Energy Simulation; BC-HAM = Building Component – Heat, Air, Moisture transfer; MSM = Material Science Model; HTM = Human Thermophysiology Model

[1] Albert Einstein (1879–1955).

specific heat capacity, k the thermal conductivity, D the molecular diffusion coefficient or molecular diffusivity and s_{ij} the strain-rate tensor:

$$s_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{1e}$$

Additional terms can be added to these equations, e.g. the gravitational acceleration term and the buoyancy term. Directly solving the NS equations for the flows in building simulation is generally prohibitively expensive. This is attributed to the fact that these flows are generally characterized by complex geometries and boundary conditions, potentially in combination with high Reynolds numbers. Furthermore, direct numerical simulations (DNS) for engineering problems might also be unnecessary, since often only a limited number of average or integral parameters are required (Ferziger 1990). Therefore, approximate forms of the NS equations are solved. Two main categories employed in building simulations are RANS and LES.

2.2 Approximate forms of the governing equations

2.2.1 Reynolds-averaged Navier-Stokes

The basis of the RANS equations is the application of the Reynolds decomposition, which consists of expressing the solution variables as they appear in the instantaneous NS equations (Eqs. 1a–e) as the sum of a mean (ensemble-averaged or time-averaged) and a fluctuating component:

$$u_i = \overline{u}_i + u_i' \,;\quad p = \overline{p} + p' \,;\quad \theta = \overline{\theta} + \theta' \,;\quad c = \overline{c} + c' \tag{2}$$

where $\overline{u}_i$, $\overline{p}$, $\overline{\theta}$ and $\overline{c}$ are the mean and u_i' , p' , θ' and c' the fluctuating components (around the mean). Inserting Eqs. (2) in Eqs. (1a–e) and taking an ensemble-average or time-average of the resulting equations yields the RANS equations:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{3a}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu \overline{s}_{ij}\right) - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) \tag{3b}$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\theta}\,\overline{u}_j\right) = \frac{\partial}{\partial x_j}\left(\frac{k}{\rho c_{\mathrm{p}}}\frac{\partial \overline{\theta}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\overline{\theta' u_j'}\right) \tag{3c}$$

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{c}\,\overline{u}_j\right) = \frac{\partial}{\partial x_j}\left(D\frac{\partial \overline{c}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\overline{c' u_j'}\right) \tag{3d}$$

$$\overline{s}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{3e}$$

where $\overline{s}_{ij}$ is the mean strain-rate tensor. With the RANS equations, only the mean flow is solved while all scales of the turbulence are modeled (i.e. approximated). This is schematically depicted in Fig. 2. The averaging process generates additional independent unknowns. For the momentum equations, these are called the Reynolds stresses and for the temperature and concentration equations, they are called the turbulent heat and mass fluxes. These stresses and fluxes represent the influence of turbulence on the mean flow and on the mean temperature and mean concentration field, respectively. As a result the RANS equations do not form a closed set. Therefore additional information is required and approximations have to be made to achieve closure. This is performed by means of a turbulence model.

A distinction can be made between first-order closure and second-order closure models. For the Reynolds stresses, first-order closure is performed with the Boussinesq or eddy-viscosity hypothesis. This hypothesis is based on the analogy with momentum transfer by the molecular motion in gasses, which is described by a molecular viscosity. Similarly, the Boussinesq hypothesis relates the Reynolds stresses to the gradients in the mean flow by means of a turbulent or eddy viscosity ν_{t}:

$$-\overline{u_i' u_j'} = 2\nu_{\mathrm{t}}\overline{s}_{ij} - \frac{2}{3}k\delta_{ij} \tag{4}$$

where k is the turbulent kinetic energy, i.e. the kinetic

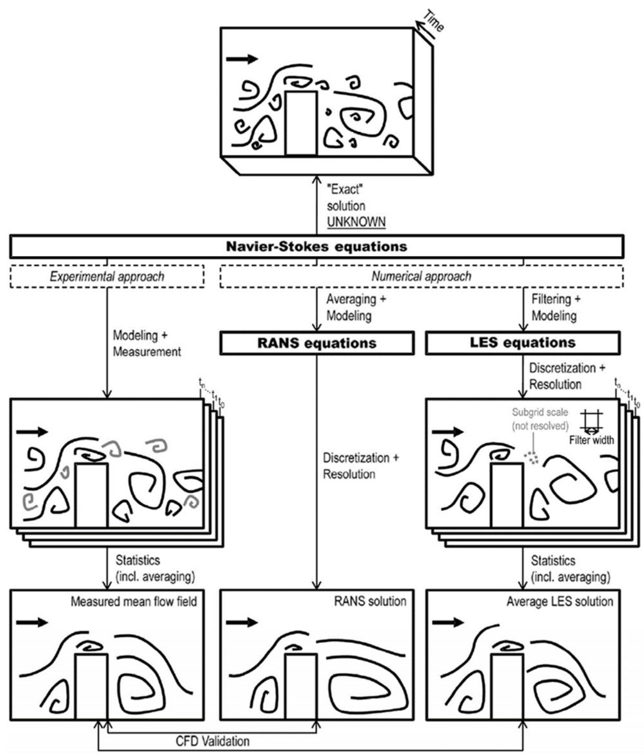

Fig. 2 Schematic representation of flow around a building as captured by experiments, RANS and LES simulations (courtesy of P. Gousseau)

energy associated with the fluctuations in the flow, and δ_{ij} is the Kronecker delta:

$$k = \frac{1}{2}\overline{u_i' u_i'} \tag{5}$$

$$\delta_{ij} = \begin{cases} 1 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases} \tag{6}$$

As opposed to the laminar or molecular viscosity, the turbulent viscosity is not a property of the fluid but a property of the flow. Turbulence models that are based on the Boussinesq hypothesis are called eddy-viscosity models (EVM). A wide range of EVM turbulence models exist that provide different ways to estimate the turbulent viscosity. Some that are widely used in building simulation are the one-equation Spalart-Allmaras model (Spalart and Allmaras 1992), the standard k-ε model (Jones and Launder 1972) and its many modified versions, such as the Renormalization Group (RNG) k-ε model (Yakhot and Orszag 1986) and the realizable k-ε model (Shih et al. 1995), the standard k-ω model (Wilcox 2004) and the k-ω shear stress transport (SST) model (Menter 1997). Second-order closure, also termed second-moment closure or Reynolds stress modeling (RSM), does not employ the Boussinesq hypothesis. Instead, it adopts a more comprehensive approach which consists of computing the Reynolds stresses from their respective transport equations (e.g. Launder et al. 1975). Although RSM is more comprehensive, applications in building simulation have not shown a consistent superior performance of RSM as compared to EVM (e.g. Ferziger 1990; Murakami 1997, 1998; Nielsen et al. 2007). It is generally accepted that no RANS turbulence model is universally valid and verification and validation studies are required to assess the performance of a given turbulence model for a given problem (e.g. Ferziger 1990, 1993; Ferziger and Peric 1996; Shah and Ferziger 1997; Gosman 1999).

Similar to the Boussinesq hypothesis that is based on the analogy with molecular motion, for the temperature and concentration equations, the standard gradient diffusion assumption can be employed. This assumption expresses the turbulent heat flux and the turbulent mass flux as a function of the temperature and concentration gradients in the mean flow by means of a turbulent heat diffusivity $D_{\theta,\mathrm{t}}$ and a turbulent mass diffusivity $D_{\mathrm{c,t}}$. These diffusivities are generally related to the turbulent momentum diffusivity by the turbulent Prandtl number Pr_t and the turbulent Schmidt number Sc_t, respectively:

$$Pr_\mathrm{t} = \frac{\nu_\mathrm{t}}{D_{\theta,\mathrm{t}}} \tag{7}$$

$$Sc_\mathrm{t} = \frac{\nu_\mathrm{t}}{D_{\mathrm{c,t}}} \tag{8}$$

Like ν_t, $D_{\theta,\mathrm{t}}$ and $D_{\mathrm{c,t}}$ are not properties of the fluid but of the flow. They are generally a function of the type of flow pattern and the location in this flow pattern. The same holds for Pr_t and Sc_t. Nevertheless, often constant values are used for Pr_t and Sc_t in RANS CFD simulations. This constitutes an important simplification and can give rise to serious errors. Many studies have shown the large impact of the choice of Sc_t on the resulting concentration fields (e.g. Tominaga and Stathopoulos 2007, 2009, 2010, 2013; Gousseau et al. 2011a; Gromke and Blocken 2015; Blocken et al. 2016a; Toja-Silva et al. 2017; Li et al. 2018; Kang et al. 2018). Second-order closure is also possible for the turbulent heat and mass fluxes, but this option is not often used in CFD for building simulation.

2.2.2 *Large Eddy Simulation*

In LES, a distinction is made between the large eddies in the flow that are mainly determined by the geometry of the problem under study and the smaller eddies that tend to be more universal. A filter is applied and scales smaller than the filter size Δ are removed from the variables. The following notation is used for a filtered variable (denoted by the tilde):

$$\tilde{\varphi}(x) = \int_D \varphi(x')G(x,x')\mathrm{d}x' \tag{9}$$

with D the fluid domain and G the filter function determining the scale of the resolved eddies. As a result, the smaller scales are not resolved but their effect on the resolved scales is modeled by means of a turbulence model. This is schematically depicted in Fig. 2. The solution variables can thus be split up into a filtered and a subfiltered component:

$$u_i = \tilde{u}_i + u_i'; \quad p = \tilde{p} + p'; \quad \theta = \tilde{\theta} + \theta'; \quad c = \tilde{c} + c' \tag{10}$$

where $\tilde{u}_i$ $\tilde{p}$, $\tilde{\theta}$ and $\tilde{c}$ represent the resolvable part and u_i', p', θ' and c' the unresolved part. The filtered continuity, momentum equation, temperature and concentration equations are obtained by substituting Eqs. (10) in the instantaneous NS equations and filtering these equations:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \tag{11a}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\tilde{u}_i\tilde{u}_j\right) = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu\tilde{s}_{ij}\right) - \frac{\partial \tau_{ij}}{\partial x_j} \tag{11b}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \frac{\partial}{\partial x_j}\left(\tilde{\theta}\tilde{u}_j\right) = \frac{\partial}{\partial x_j}\left(\frac{k}{\rho c_\mathrm{p}}\frac{\partial \tilde{\theta}}{\partial x_j}\right) + \frac{\partial q_{\mathrm{t},ij}}{\partial x_j} \tag{11c}$$

$$\frac{\partial \tilde{c}}{\partial t} + \frac{\partial}{\partial x_j}\left(\tilde{c}\tilde{u}_j\right) = \frac{\partial}{\partial x_j}\left(D\frac{\partial \tilde{c}}{\partial x_j}\right) + \frac{\partial q_{\mathrm{c},ij}}{\partial x_j} \tag{11d}$$

where $\tilde{s}_{ij}$ is the rate of strain tensor. Additional terms appear due to the filter operation, i.e. the subgrid-scale Reynolds stresses and the subgrid-scale heat and mass fluxes:

$$\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j \quad (12a)$$

$$q_{t,ij} = \tilde{\theta}\tilde{u}_j - \widetilde{\theta u_j} \quad (12b)$$

$$q_{c,ij} = \tilde{c}\tilde{u}_j - \widetilde{c u_j} \quad (12c)$$

As in the RANS approach, closure needs to be obtained. As the grid size is often used as the filter, the model used to provide closure is often called a subgrid-scale (SGS) model. SGS models usually adopt the Boussinesq hypothesis:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \tilde{s}_{ij} \quad (13)$$

with μ_t the SGS turbulent viscosity. The isotropic part of the SGS stresses τ_{kk} is not modeled but added to the filtered static pressure term. To obtain μ_t, different SGS models have been devised. The first type of SGS model was developed by Smagorinsky (1963) and is referred to as the Smagorinsky-Lilly SGS model, where the eddy viscosity is modeled as:

$$\mu_t = \rho(C_s\Delta)^2\sqrt{2\tilde{s}_{ij}\tilde{s}_{ij}} \quad (14)$$

with Δ the filter width and C_s the Smagorinsky constant. C_s usually has a value ranging from 0.1 to 0.2. Afterwards, several other models were developed including the Germano dynamic model (Germano et al. 1991) and its modified version by Lilly (1991).

3 Brief history of LES and RANS

"Historia vero testing temporum, lux veritatis, vita memoriae, magistra vitae" [2]

3.1 Early history of RANS

The concept of the Reynolds decomposition, on which the RANS approach is based, was first proposed by Osborne Reynolds in 1895 (Reynolds 1895). As mentioned in Section 2, application of the Reynolds decomposition and ensemble-averaging or time-averaging of the NS equations yields the RANS equations, in which the instantaneous flow variables have been replaced by the mean flow variables at the expense of adding additional terms to the equations, referred to as Reynolds stresses. These additional terms render the system of equations unclosed. The first attempt to address this so-called closure problem is attributed to Joseph Valentin Boussinesq (1877). In 1877, he introduced the concept of eddy viscosity and proposed to relate the Reynolds stresses to the gradients in the mean flow; the so-called Boussinesq or eddy-viscosity hypothesis. This hypothesis reduces the turbulence closure problem to calculating the eddy viscosity.

In 1904, when Ludwig Prandtl (Prandtl 1904) introduced the concept of the boundary layer, he additionally devised the concept of the mixing length based on the philosophy that for wall-bounded turbulent flows, the eddy viscosity should vary with distance from the wall. This provided the basis for the Prandtl's one-equation (turbulence) model. Later, many other turbulence models were developed. These can be categorized as linear EVMs, nonlinear EVMs and RSMs. In the linear EVMs, we distinguish between algebraic models, one-equation models such as the Prandtl's one-equation model and the Spalart-Allmaras model, and two-equation models such as the standard k-ε model, the realizable k-ε model, the RNG k-ε model, the k-ω model and the SST k-ω model. The adoption of RANS in the field of building simulation will be addressed in subsections 3.3 and 3.5.

3.2 Early history of LES

In 1922, long before the first digital computer was introduced, Lewis Fry Richardson (1881–1953) published his book "*Weather Prediction by Numerical Process*" (Richardson 1922), in which he presented his idea to predict the change of the atmospheric circulation by numerical integration of the NS equations in the rotating frame, the continuity equation and the first law of thermodynamics. With this approach, he attempted to forecast the weather during a single day (20 May 1910) by direct computation using data at a specific time (7 AM) to calculate the weather six hours later. This was done with nothing more than people performing calculations by hand, aided by slide rules and simple desk calculating machines. It generally took three months to predict the weather for the coming 24 hours. In the last chapter of his book, "The Speed and Organization of Computing", he envisioned the practical organization of this type of forecasting as a "Forecasting Factory", something like a large hall with many "computers", a term he actually used to refer to the people performing the calculations (Fig. 3):

"Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the

[2] "*History is the teacher and witness of times, sheds light upon reality, gives life to recollection and guidance to human existence*", from Cicero, De Oratore, II, 36. Marcus Tullius Cicero (106 BC – 43 BC), Roman philosopher, politician, lawyer, orator, political theorist, consul and constitutionalist.

upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little 'night signs' display the instantaneous values so that neighboring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map. From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns abeam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand."

He estimated he would need 64,000 people to race "the weather for the whole globe" (Richardson 1922). As stated by Hunt (1998) in his extensive review of Richardson's life, such a hall "would be more like a football stadium"—and actually a rather large one, completely filled with people doing hand calculations.

Although the reviewers of Richardson's book were impressed and seemed to realize the inherent value of this work (Ashford 1985), it also received negative criticism because of the sheer impracticality of the method and the rather catastrophic result of unrealistic pressure rise in the single trial forecast—which later only appeared to be due to insufficiently controlled initial conditions and the failure to apply smoothing techniques to the data to remove unphysical surges in pressure. Confronted with the impracticality of his approach, Richardson stated:

"Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances… But that is a dream."

The intrinsic potential of Richardson's astonishing idea only materialized with the advent of the digital computer. When von Neumann and Charney started to use the electronic digital computer called ENIAC (Electronic Numerical Integrator and Computer; Fig. 4) to calculate the weather, they used equations and methods very close to those described by Richardson in his book. Having obtained the first results of their efforts, Charney sent Richardson a copy of his paper (Charney et al. 1950) describing these results. Richardson replied in writing, congratulating Charney and his team and stating their work was "an enormous scientific advance on the single, and quite wrong result in which the calculations of Richardson (1922) ended" (Ashford 1985). Lynch (2008) states that "since the ENIAC was about five orders of magnitude faster than human computation, the Forecast Factory would have been comparable in processing power to this early machine." Indeed, the first calculations for a 24-hour forecast took about 24 hours on ENIAC (Lynch 2008). As nowadays weather forecasting is done on computers based on algorithms very similar to those by Richardson, one can state that "his dream has come true" (Kimura 2002; Lynch 2008). Since decades, the pioneering work of Richardson is universally recognized as the foundation of modern Numerical Weather Prediction (NWP).

What is now called LES emerged from the early days of NWP by the efforts of Smagorinsky, Lilly, Deardorff and others that followed in Richardson's footsteps (e.g. Smagorinsky 1963; Lilly 1962, 1964; Deardorff 1970a,b,c,d).

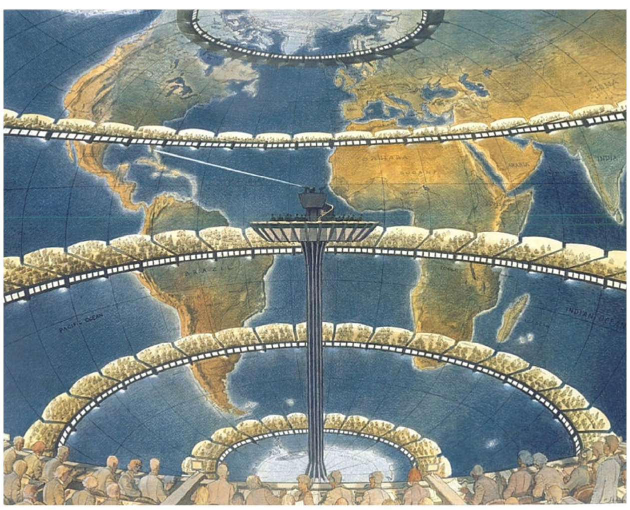

Fig. 3 Artist impression of the Forecast Factory (reproduced with permission ©François Schuiten)

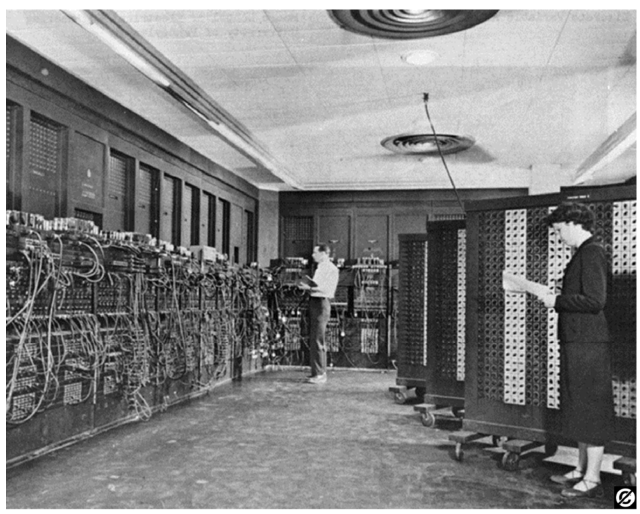

Fig. 4 The Electronic Numerical Integrator and Computer (ENIAC) in building 328 at the Ballistic Research Laboratory (BRL)

The philosophy of LES also has its roots in Richardson's concepts of eddy structure and eddy diffusion (Richardson 1926, 1929) and the subsequent development of self-similarity theory by Kolmogorov (1941). This theory implies that the larger eddies in the flow depend to a large extent on the geometry under study while the smaller scales tend to be more universal.

In the 1950s, in the beginning of his career, Smagorinsky worked with Charney and others to solve Charney's simplest equations using the ENIAC computer. In 1953, Smagorinsky was appointed at the U.S. Weather Bureau where in 1955 he became the director of the General Circulation Research Section. His ambition was to proceed to the final step of the von Neumann/Charney computer modeling program: a three-dimensional, global, primitive-equation general circulation model of the atmosphere. Smagorinsky was convinced that the increasing computational power would enable going beyond the simulation of the evolution of the atmosphere for a few days as common in weather forecasting. His ambition was to integrate the equations of motion, thermodynamics and radiative transfer for long enough time periods to simulate not only the weather but its actual statistics, i.e. the climate. In the 1970s, his collaborators provided the first simulations of the impact of increasing CO_2 concentrations in the atmosphere on the Earth's climate and they developed the first coupled atmosphere-ocean climate models. These successes laid the foundations for the current awareness and knowledge of global warming.

In his pursuit to extend forecasting past one or two days, Smagorinsky exploited new methods of NWP. In his pioneering paper in 1963 (Smagorinsky 1963), he extended early weather models to include variables such as wind, cloud cover, precipitation, atmospheric pressure and radiation emanating from the earth and sun. This required a method to account for atmospheric turbulence occurring on scales smaller than the model grid size but that are still important in the atmospheric energy cycle. This led to the introduction of one of the first successful approaches to LES, achieved in collaboration with his co-worker Douglas Lilly: the first order subgrid-scale closure called the Smagorinsky-Lilly model. This approach is still being used world-wide and has spread from meteorology to all fields of science and engineering involving fluid dynamics.

Lilly (1962) later employed this technique in 2D simulations of convection. In reviewing the meteorological development of LES, Lilly (2000) attributes the actual development and application of LES to James Deardorff, who initially worked on 2D direct numerical simulations of buoyant convection. As increasing computational resources became available, Deardorff initiated a series 3D numerical simulations using the Smagorinsky-Lilly eddy-viscosity formulations. In 1970, he published a first simulation of turbulent channel flow in a domain with 24×14 horizontal and 20 vertical grid points (Deardorff 1970a). Later, he focused on idealized neutral (Deardorff 1970b) and unstable (Deardorff 1970c, 1972) planetary boundary layers. Interestingly and to the best of our knowledge, although Deardorff fundamentally developed Large Eddy Simulation, he never used the term himself. According to Lilly (2000) this term originated in the Stanford-Ames turbulence group in 1973 and was first used in print by Leonard (1974).

Deardorff advocated the combination of LES with laboratory (water tank) experiments and field measurements because of the large potential synergy of these three approaches. This philosophy is strongly reflected in the field of building simulation, where LES and RANS simulations are routinely combined with either field measurements or laboratory tests, or both.

3.3 RANS in building simulation—outdoor

The first efforts to evaluate wind flow around buildings with various types of approximations to the NS equations were made in the 1970s. Yamada and Meroney (1972) studied 2D airflow over a square surface-mounted obstacle in a stratified atmosphere, both with CFD and in the wind tunnel. Hirt and Cook (1972) calculated 3D flow around structures and over rough terrain. Frost et al. (1974) numerically analyzed the 2D neutrally stratified wind flow over a semi-elliptical surface obstruction, used to represent an idealized building. These studies provided the basis for the steady RANS investigations that would follow soon after.

Indeed, in outdoor building simulation applications, steady RANS was first employed for the wind flow around generic isolated building configurations, often with a cubical shape, to analyze the mean velocity field and the mean surface pressure (e.g. Vasilic-Melling 1977; Summers et al. 1986; Paterson and Apelt 1986, 1989, 1990; Murakami et al. 1990a, 1992; Murakami and Mochida 1988, 1989; Baskaran and Stathopoulos 1989, 1992; Stathopoulos and Baskaran 1990; Murakami 1990a,b, 1993; Baetke et al. 1990; Fraser et al. 1990; Mochida et al. 1993; Stathopoulos and Zhou 1993) (Fig. 5). A number of these early RANS studies specifically focused on the sensitivity of the results to computational parameters such as the grid resolution (e.g. Murakami and Mochida 1989; Murakami 1990a,b; Fraser et al. 1990; Baskaran and Stathopoulos 1992), the boundary conditions (e.g. Murakami and Mochida 1989; Paterson and Apelt 1990; Baetke et al. 1990; Stathopoulos and Baskaran 1990; Baskaran and Stathopoulos 1992) and the turbulence model (e.g. Baskaran and Stathopoulos 1989; Murakami et al. 1992; Murakami 1993; Mochida et al. 2002). These early parametric studies laid the foundations for the best practice guidelines that would be compiled many years later

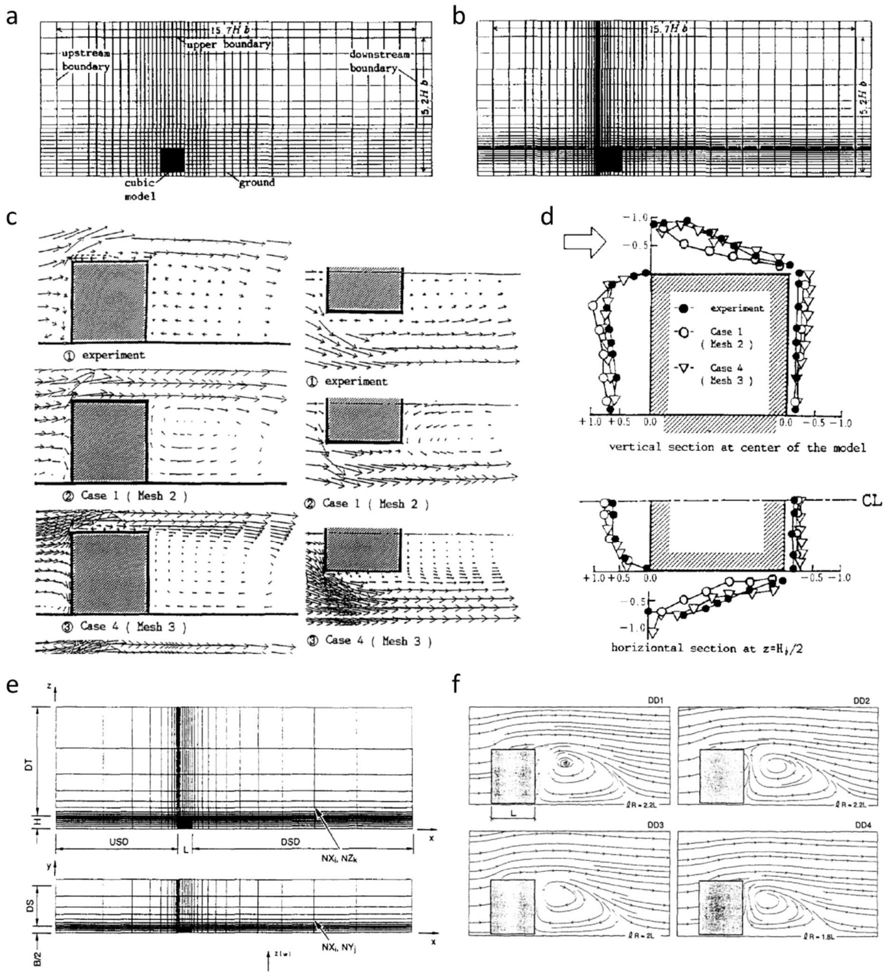

Fig. 5 Early RANS studies for wind flow around an isolated building. (a,b) Two different grid topologies (mesh 2 and mesh 3) in vertical centerplane (Murakami and Mochida 1988); (c) velocity vector field and (d) surface pressure coefficient from wind tunnel experiments and as obtained with the two grid topologies (Murakami and Mochida 1988); (e) grid topology in a vertical and a horizontal plane and (f) streamlines as obtained with computational domains of different size (Baskaran and Stathopoulos 1992) (all figures: reproduced with permission ©Elsevier)

and are nowadays intensively used in building simulation for outdoor applications.

The studies mentioned above are not all studies that were performed for isolated buildings. But starting from the 1990s, a gradual shift was made to studies for multiple-building configurations, which were supported by the foregoing studies and by the increasing availability of computational power (e.g. Murakami 1990a, 1997, Murakami et al. 1990b, Fraser et al. 1990, Stathopoulos and Baskaran 1996) (Figs. 6a–d). Since that time, more and more case studies—i.e. studies for actual buildings or urban areas—were performed with steady RANS in various application areas such as pedestrian-level wind conditions, wind comfort and wind danger (Figs. 6a–e) (e.g. Murakami and Mochida 1989; Murakami 1990a; Gadilhe et al. 1993; Takakura et al. 1993; Bottema 1993; Stathopoulous and Baskaran 1996; Murakami 1997; Westbury et al. 2002; Richards et al. 2002; Hirsh et al. 2002; Blocken et al. 2004, 2012; Yoshie et al. 2007; Mochida and Lun 2008; Tominaga et al. 2008a; Blocken and Carmeliet 2008; Blocken and Persoon 2009; Janssen et al. 2013; Montazeri et al. 2013; An et al. 2013; Yuan and Ng 2014; Iqbal and Chan 2016; Yasa 2016; Allegrini and Kubilay 2017; Ricci et al. 2017b; Du et al. 2018; Liu et al. 2017; 2018; Dhunny et al. 2018), urban thermal environment (Fig. 6f) (e.g. Ashie and Kono 2011; Tominaga et al. 2015; Toparlar et al. 2015, 2017, 2018; Gromke et al. 2015; Montazeri et al. 2017; Yang et al. 2017; Kang et al. 2017; Gao et al. 2018; Allegrini and Carmeliet 2018), urban ventilation and/or pollutant dispersion (Fig. 6g) (e.g. Hanna et al. 2006; Flaherty et al. 2007; Baik and Park 2009; Lateb et al. 2010, 2011; Gousseau et al. 2011a; Panagiotou et al. 2013; van Hooff and Blocken 2013; Blocken et al. 2016a; Antoniou et al. 2017; Jeanjean et al. 2017; Efthimiou et al. 2017; Juan et al. 2017; Toja-Silva et al. 2017; Garcia-Sánchez et al. 2017; Gao et al. 2018; Peng et al. 2018; Buccolieri et al. 2018)

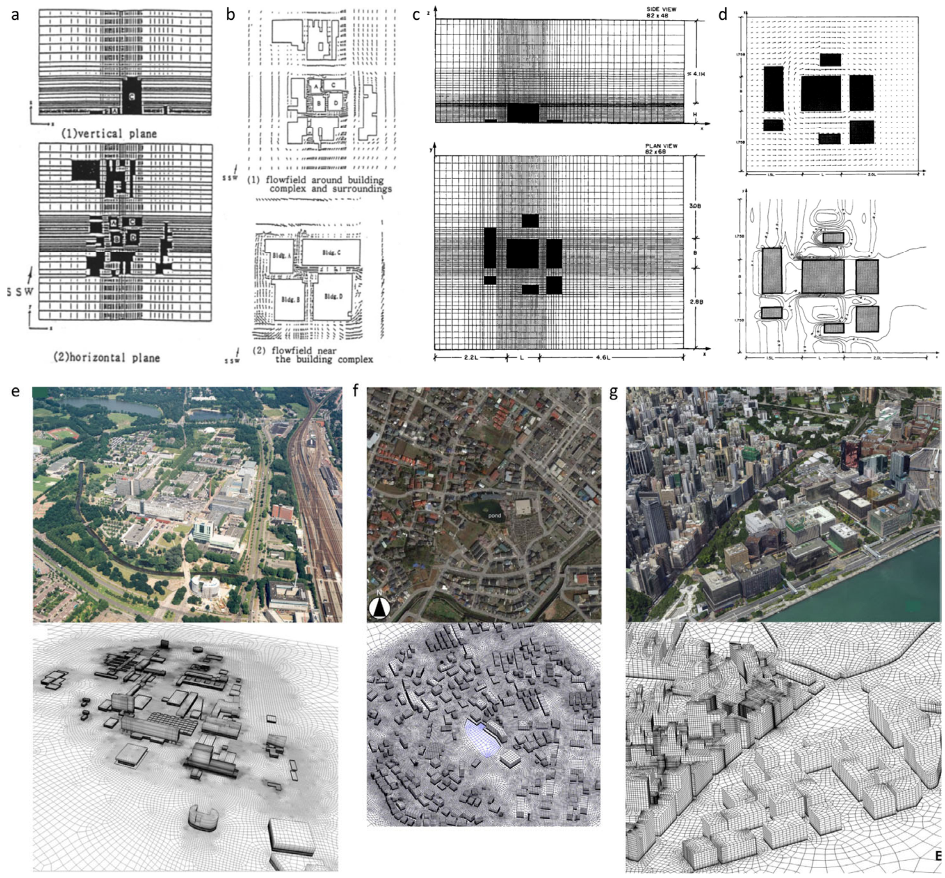

Fig. 6 RANS case studies for (a–d) pedestrian-level wind conditions around buildings; (a,b) by Murakami (1990b) for a building group in Tokyo, Japan; (c,d) by Stathopoulos and Baskaran (1996) for a building group in Montreal, Canada. (e) RANS case study for pedestrian wind comfort by Blocken et al. (2012) for the campus of Eindhoven University of Technology in the Netherlands; (f) RANS case study for urban thermal environment by Tominaga et al. (2015) for a neighborhood in Hadano, Japan; (g) RANS case study for urban ventilation by Peng et al. (2018) for part of Kowloon, Hong Kong (all figures: reproduced with permission ©Elsevier)

and natural ventilation of buildings (e.g. Mochida et al. 2005, 2006; Horan and Finn 2008; Norton et al. 2009; van Hooff and Blocken 2010a,b, 2013; Wu et al. 2012; Martins and da Graça 2016; Aydin and Mirzaei 2017).

3.4 LES in building simulation—outdoor

Early LES studies for wind flow around buildings were performed by Murakami et al. (1987, 1990a, 1992), Murakami (1990a,b, 1993), Hibi et al. (1993), Song and He (1993), Nicholls et al. (1993), Mochida et al. (1993) and others. In some cases the LES results were compared with wind tunnel measurements and intercomparison of results obtained with different grid systems, boundary conditions and/or Smagorinsky constants were made (e.g. Murakami et al. 1987; Murakami 1990a,b; Mochida et al. 1993; Selvam 1997; Tominaga et al. 1997). In other cases the LES results were used to analyze the deficiencies in the RANS modeling (e.g. Murakami et al. 1990a) (Figs. 7a,b). Kato et al. (1992) applied LES to investigate the mechanism of cross-ventilation of isolated generic building models with open windows (Figs. 7c–e). Hibi et al. (1993) performed LES simulations to determine the fluctuating pressure fields around buildings with wall openings in view of assessing the relation between building shape and wind-induced vibrations. Song and He (1993) computed the flow pattern around a tall building to analyze the large scale vortex structures and unsteady flow, while Nicholls et al. (1993) simulated microburst winds flowing around a building.

Several comparative LES-RANS studies were focused on demonstrating and explaining the deficiencies of the steady RANS approach, mainly with the standard k-ε model (Jones and Launder 1972), for wind flow around buildings. These include the stagnation point anomaly with overestimation of turbulent kinetic energy near the frontal corner (see Fig. 7b) and the resulting underestimation of the size of separation and recirculation regions on the roof and the side faces, and the underestimation of turbulent kinetic energy in the wake resulting in an overestimation of the size of the cavity zone and wake. These deficiencies are a direct result of the

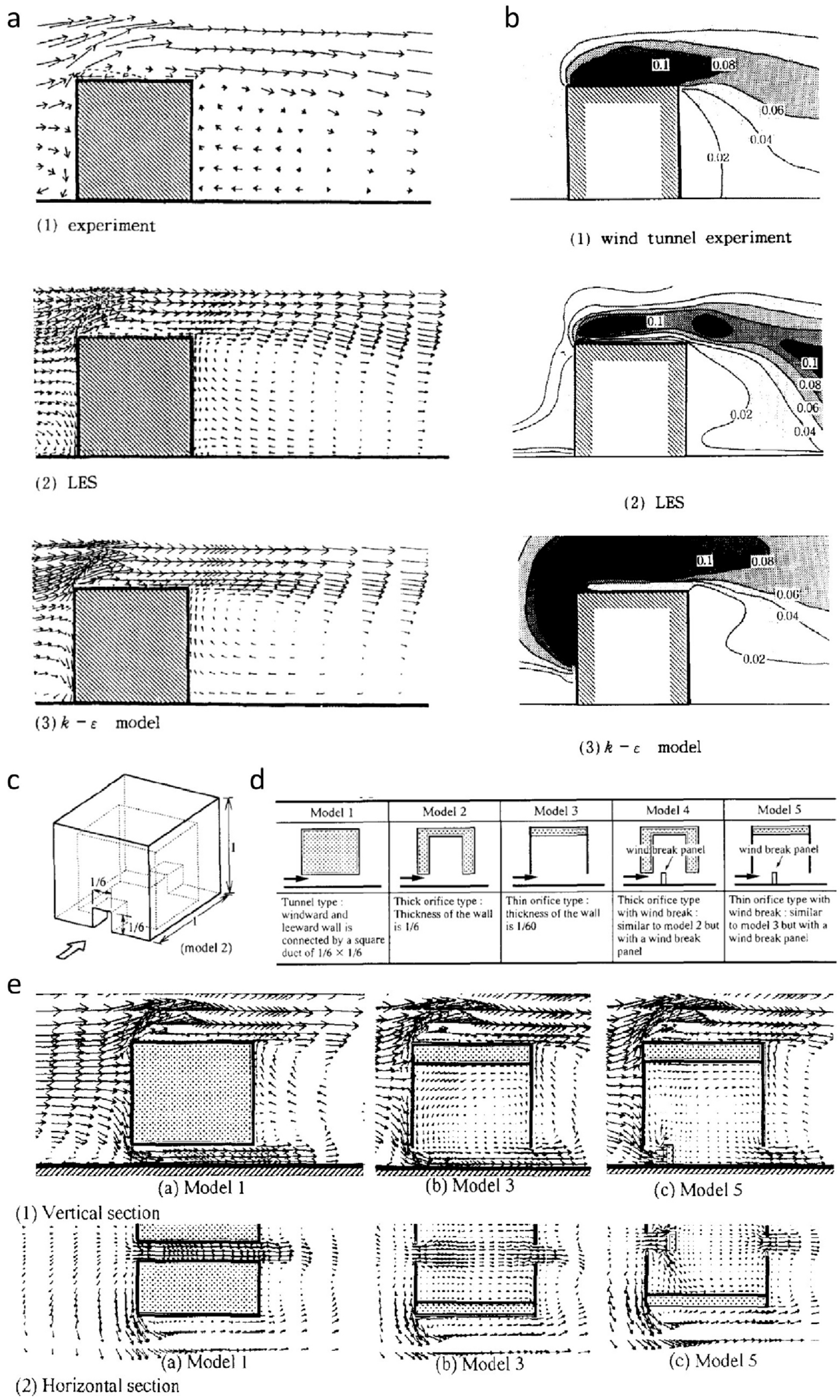

Fig. 7 (a,b) Early LES study for wind flow around an isolated cubic building: (a) mean velocity vector field and (b) turbulent kinetic energy in vertical centerplane by wind tunnel tests, LES and RANS with the standard *k*-*ε* model (Murakami et al. 1990a). (c,d,e) Early LES study for natural ventilation of an isolated cubic building by Kato et al. (1992): (c) building geometry; (d) different model opening configurations; (e) mean velocity vector field in vertical and horizontal cross-sections (all figures: reproduced with permission ©Elsevier)

RANS averaging and the eddy-viscosity hypothesis—more specifically, the isotropic nature of the eddy viscosity. As a partial solution towards this problem, various revised linear and non-linear k-ε models and also second-moment closure models were developed and tested. While improved performance for several parts of the flow field could be obtained (e.g. Baskaran and Stathopoulos 1989; Murakami et al. 1992; Murakami 1993; Wright et al. 2001; Mochida et al. 2002), the main limitation of steady RANS modeling remained: its incapability to model the inherently transient features of the flow field such as separation and recirculation downstream of windward edges and vortex shedding in the wake. These large-scale features can be explicitly resolved by LES. From the most early high-quality LES studies on, comparative LES-RANS-wind tunnel studies for wind flow around buildings have systematically illustrated the intrinsically superior performance of LES compared to RANS. Nevertheless, as will be discussed further, LES entails specific disadvantages that are not easy to overcome such as a higher simulation complexity and a much higher computational cost.

Examples of actual case studies with LES are some application studies of pedestrian-level wind conditions (e.g. He and Song 1999; Adamek et al. 2017; Jacob and Sagaut 2018), urban thermal environment (e.g. Liu et al. 2012), pollutant dispersion and/or urban ventilation (e.g. Hanna et al. 2006; Patnaik et al. 2007; Gousseau et al. 2011a, 2015; Liu et al. 2011; Nozu and Tamura 2012; Antoniou et al. 2017; Wang et al. 2018a,b) and natural ventilation of buildings (e.g. Jiang and Chen 2002) (Fig. 8). However, many examples

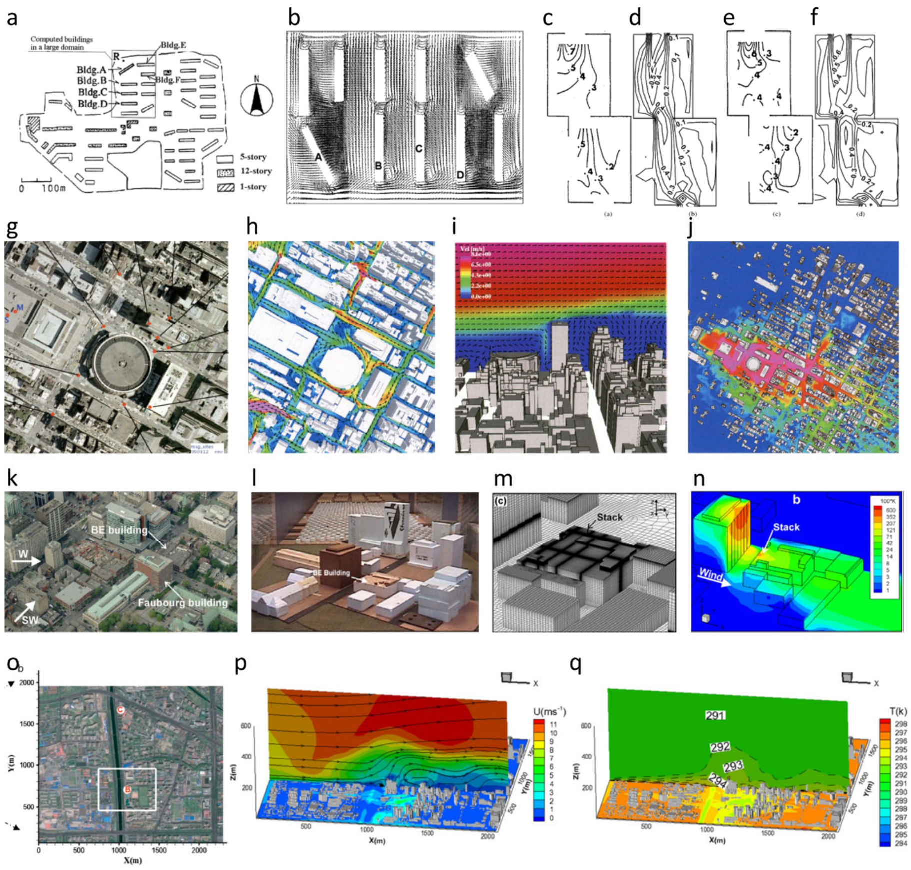

Fig. 8 (a–f) LES case study for natural ventilation of buildings by Jiang and Chen (2002) (reproduced with permission ©Elsevier): (a) top view of building site; (b) mean velocity vector field around the buildings at 3 m from the ground; (c–f) wind speed distribution inside apartment in building A as obtained from (c) wind tunnel test; (d) LES with fixed wind direction; (e) on-site measurement; (f) LES with varied wind direction. (g–j) LES case study for pollutant dispersion in downtown Manhattan by Hanna et al. (2006) (reproduced with permission ©American Meteorological Society (AMS)): (g) top view with position of measurement sensors; (h–j) LES results of (h) horizontal wind velocity vectors at z = 5 m; (i) wind velocity vectors in vertical plane; (j) tracer gas dispersion for WNW wind direction. (k–n) LES case study for pollutant dispersion in downtown Montreal by Gousseau et al. (2011a) (reproduced with permission ©Elsevier): (k) view of site; (l) corresponding wind tunnel model; (m) computational grid; (n) contours of dimensionless concentration coefficient on building surfaces. (o–q) LES case study for thermal environment in a district in Beijing, China by Liu et al. (2012) (reproduced with permission ©Elsevier): (o) LES computational domain; (p) LES wind field at ground level and in vertical plane; (q) same for LES temperature field

of RANS case studies mentioned in Section 3.3 versus only relatively few by LES demonstrate that the vast majority of CFD application studies in the past three decades were indeed performed with the steady RANS approach and this continues to be the case. Therefore it seems that in many aspects of building simulation, researchers and practicing engineers have employed the increasingly available computational power to perform RANS simulations for larger and more complex problems, rather than to make the switch from RANS to LES for less extensive problems.

3.5 RANS in building simulation—indoor

The first predictions of airflow in rooms were performed in the 1970s. Nielsen (1973, 1974a) was the first to compute air movement in buildings with CFD. Given the computational limitations at that time, he focused on 2D simulations of room airflow and employed a calculation procedure based on a stream function approach. He also performed comparisons of the computed velocity profiles with hot-wire measurements at different positions in the room. Nielsen (1974b) also simulated the humidity concentrations in cold stores using the advection-diffusion equation (see Eq. 3d). Later, Nielsen et al. (1978) solved the 2D RANS equations with the standard k-ε model for closure and compared the results with new laser-Doppler anemometry measurements (Figs. 9a,b) and with the previously obtained hot-wire data. In 1979, Nielsen et al. (1979) also analyzed buoyancy-assisted room ventilation flow with the 2D RANS equations supplemented with the energy equation (see Eq. 3c). Later, this team also collaborated

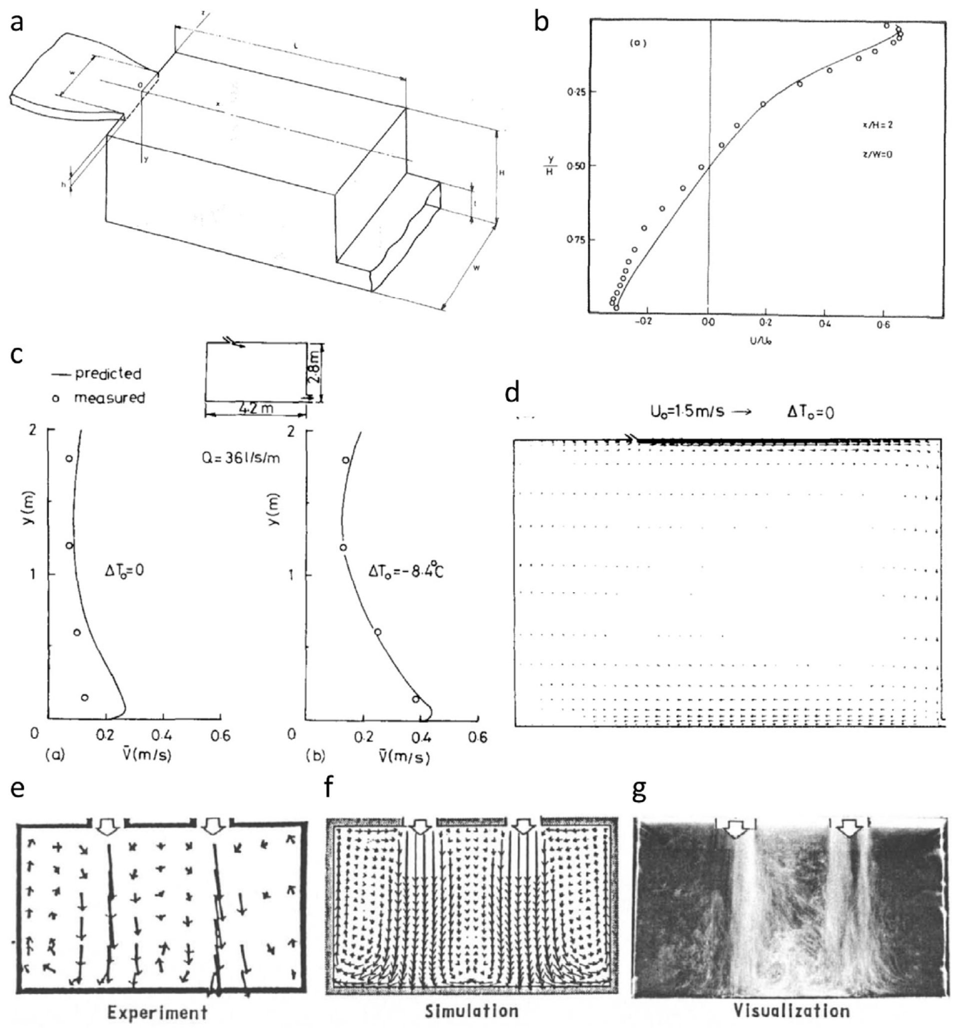

Fig. 9 Early RANS studies of indoor airflow. (a,b) 2D simulations and measurements by Nielsen (1976) (reproduced with permission from Peter V. Nielsen). (a) Test room with H = 89.3 mm; other dimensions correspond to L/H = 3.0; W/H =1.0; h/H = 0.056; t/H = 0.16; w/W = 1.0. (b) Comparison of simulations and measurements along vertical line in test room. (c,d) 2D simulations and measurements in a 4.2 by 2.8 m² room by Awbi (1989): (c) comparison of air speed along vertical line in test room; (d) velocity vector field for isothermal case in vertical plane. (e–g) Measurements, 3D simulations (velocity vector field) and visualization of indoor airflow in a test room by Murakami and Kato (1989) (Figs. c–g: reproduced with permission ©Elsevier)

with Gosman to extend the calculation procedure to 3D and perform 3D isothermal ventilation simulations (Gosman et al. 1980). These pioneering research efforts were followed by many other RANS studies. Awbi (1989) performed 2D RANS simulations of airflow and heat transfer in heated or cooled rooms and 3D RANS simulations of a wall jet over surface-mounted obstructions with the standard k-ε model for closure (Figs. 9c,d). Murakami and Kato (1989) conducted 3D RANS simulations with the standard k-ε model for a variety of room configurations including obstacles in the room (Figs. 9e–g). They also analyzed the spreading of a tracer gas inside the room and found favorable comparisons with dedicated experiments in 1/6 reduced-scale tests rooms. Other RANS CFD studies on indoor airflow were reported by Sakamoto and Matsuo (1980), Nomura et al. (1980), Timmons et al. (1980), Nielsen (1981), Holmes (1982), Broyd et al. (1983), Markatos and Pericleous (1984), Ishizu and Kaneki (1984), Reinartz and Renz (1984), Alamdari et al. (1984), Awbi and Setrak (1986), Waters (1986), Murakami et al. (1987), Whittle (1987), Jones (1990), Jones and O'Sullivan (1987), Jones and Reed (1988), Holmes and Whittle (1987), Lemaire (1989), Jones and Waters (1990, 1991), Holmes et al. (1990), Chen (1995, 1996) and others. Similar to early RANS studies for outdoor applications, also several early RANS studies for indoor airflow examined the influence of different computational parameters on the results (e.g. Nielsen et al. 1978; Murakami and Kato 1989; Chen 1995, 1996; Chen and Chao 1997; Nielsen 1998). These studies provided the basis for the best practice guideline documents for CFD for indoor airflow that would be compiled later.

Numerous CFD case studies were performed in the past decades using the 3D steady RANS equations, with applications focused on thermal comfort, ventilation efficiency and indoor air quality. These case studies employed a wide range of turbulence models.

3.6 LES in building simulation—indoor

To the best of our knowledge, the first LES simulation of room airflow was performed by Sakamoto and Matsuo (1980). They compared the simulation results in terms of mean velocity with measurements in a model room and found a good agreement both for the LES results but also for their RANS k-ε results. This made them conclude that the RANS approach is more practical given its shorter computational time (Figs. 10a–d). Later, Hibi et al. (1985) and Murakami et al. (1986) further examined the accuracy of LES for 3D recirculating flow. Other efforts in LES simulation of indoor airflow were made by Murakami et al. (1995), Davidson and Nielsen (1996), Emmerich and McGrattan (1998), Zhang and Chen (2000a,b) (Figs. 10e–g), and others. In their extensive report on how to verify, validate and report indoor environment modeling CFD analyses, Chen and Srebric (2001) indicated that only very few LES simulations were performed for indoor environment modeling applications. After 2000, this number increased substantially, albeit often related to the modeling of the indoor dispersion of particles (e.g. Tian et al. 2007; Chang et al. 2007; Lai and Chan 2007; Abdalla et al. 2007; Wang et al. 2012; Liu and Novoselac 2014; Karadimou and Markatos 2016).

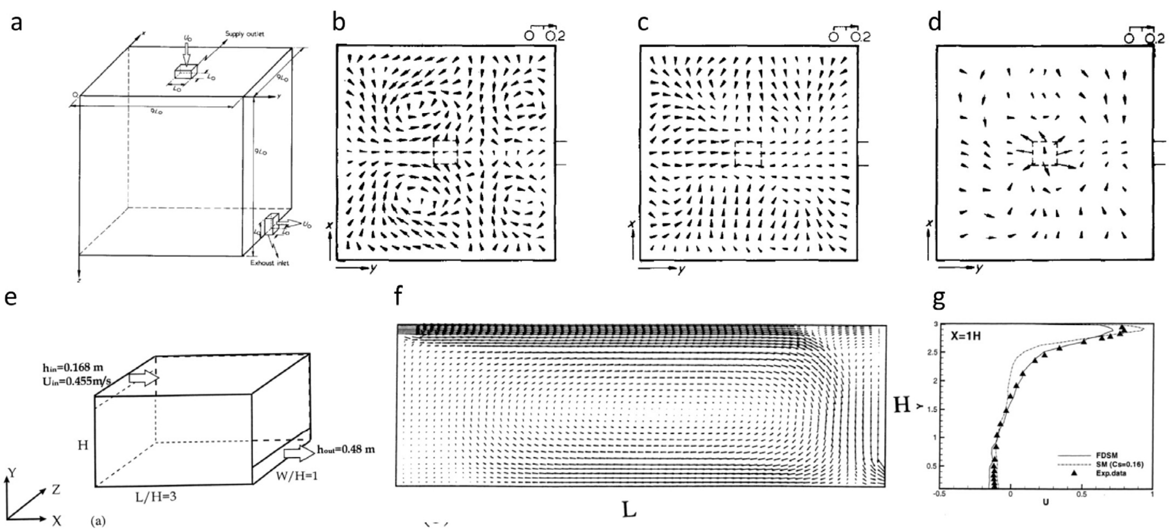

Fig. 10 Early LES studies of indoor airflow. (a–d) LES for 2 m cubic room by Sakamoto and Matsuo (1980): (a) room geometry; (b–d) velocity vectors in horizontal plane at midheight for (b) standard k-ε model; (c) LES; (d) experiments. (e–g) LES for forced convection in rectangular room by Zhang and Chen (2000a): (e) room geometry; (f) mean velocity vectors in vertical centerplane by filtered dynamic SGS model (FDSM); (g) comparison of LES results by standard Smagorinsky SGS model, FDSM and experiments in vertical centerplane at x/H = 1 (all figures: reproduced with permission ©Elsevier)

4 Previous review and position papers on LES versus RANS

"Great literature is simply language charged with meaning to the utmost possible degree." [3]

This section provides relevant highlights from some previous position papers on LES versus RANS. The intention is neither to be complete, nor to be balanced. Several of these opinions will be revisited at the end of this paper, after having assessed the performance of LES and RANS in the five application areas in section 5. The papers below are addressed in chronological order of appearance in their respective journals.

4.1 CFD for outdoor applications

In 1990, Joel H. Ferziger published the paper "Approaches to turbulent flow computation: applications to flow over obstacles" (Ferziger 1990), in which he specifically focused on RANS versus LES. A key argumentation in the paper is that the principal task of the wind engineer is to find a method that produces accurate values of the essential quantities at low cost. As a result, the method to be used may depend both on the required accuracy and on the problem. Indeed, Ferziger mentioned that while fields such as aerospace engineering will typically require a high accuracy (e.g. errors less than 5%), others, such as wind engineering, are generally less demanding (e.g. errors of more than 25% may be acceptable). Therefore he states that a model that is sufficiently accurate for one application may be totally unacceptable in another (Ferziger 1990).

Ferziger (1990) considered RANS and LES as two obviously imperfect approaches in view of practical engineering purposes. RANS models have the benefit of longer history and lower cost, but the existing turbulence models and wall models are often not sufficiently accurate for 3D separating and reattaching flows. LES on the other hand can address some of these issues, but the costs of LES are much higher and experience is limited. Ferziger (1990) reported that the fact that LES resolves more of the flow than RANS and the fact that therefore the calculation results can be rather insensitive to the quality of the SGS model has been advertised as one of the principal advantages of LES over RANS. However, he correctly argued that as the Reynolds number increases and/or the flow becomes more geometrically complex, more energy will be situated in the small scales of turbulence and the results will become more sensitive to the quality of the SGS model. This would require more accurate SGS models or the use of even finer computational grids. In this respect, Ferziger stated that "If it turns out that LES can be done on very coarse grids, it will be one of the few times that nature has been kind to us with regard to turbulent flows".

Although LES is potentially (sic) more accurate than RANS, Ferziger (1990) considered it to be too expensive to be a design tool. He concluded his paper by suggesting a research program that could lead to reliable methods in the next five to ten years. This program would employ high-quality experiments and carefully performed LES for producing accurate data and RANS for routine calculations.

In 1990, Shuzo Murakami published the paper "Computational wind engineering" (Murakami 1990a), in which he provided a detailed review of the state of the art in CFD for wind engineering applications. The range of CFD applications displayed in this early paper is impressive: from indoor turbulent flow fields over wind velocity patterns over isolated buildings and pressure coefficients on the surfaces of those buildings to the flow around an actual building complex including the flow details around individual balconies. Before outlining these applications, at the very start of the paper, Murakami stressed both the potential of the numerical approach but also the need for synergy between the numerical and the experimental approach in wind engineering. He considered it indispensable to examine the accuracy of the CFD simulations and to further develop the CFD approach by comparison with results from wind tunnel or field measurements. On the other hand, he expected that the increasing precision of CFD predictions would also increase the incentive for new research into experimental methods. Murakami (1990a) also correctly indicated that the graphical representation of the time-dependent flow fields by LES in the form of animations was a very useful tool in the analysis of the flows and that this provided information that in many cases was hard or even impossible to be obtained by experimental techniques.

In 1993, Michael A. Leschziner published the paper "Computational modelling of complex turbulent flow—expectations, reality and prospects" (Leschziner 1993). A key argument in this paper is that "CFD, whilst offering considerable predictive power and potential, is not yet sufficiently well established to be applied routinely to complex 3D flows, unless only a rough qualitative statement is being sought." This led him to several important statements. First, it is essential for a CFD user to possess considerable expertise, physical insight and experience, both to obtain meaningful solutions and to be able to appreciate the associated limitations. Second, CFD for general turbulent flow is unlikely ever to evolve to a "computational wind tunnel" or a "numerical wind tunnel". He referred to the rather radical view—expressed predominantly among the

[3] Ezra Weston Loomis Pound (1885–1972): American poet, critic, translator, publisher and major figure in the early modernist movement.

US aerodynamics fraternity—that the wind tunnel was destined to become a "convenient storage cabinet for computer output" (Leschziner 1993). He criticizes this rather narrow interpretation of CFD that could bear some truth for high-speed external aerodynamics and some turbomachinery applications, but not for wind engineering applications. Therefore he argued that wind tunnels are here to stay for many years to come and would continue to be the main vehicle for investigating realistic building design concepts (Leschziner 1993).

Concerning LES versus RANS, he stated that from the viewpoint of structural engineering, when peak wind pressures and peak wind loading need to be determined, LES is obviously the only alternative. For industrial applications in general, he expected that RANS methods would continue to play the main role for some years to come, but that there likely would be a continuous shift of focus towards LES. Nevertheless, he concluded that it is unlikely that LES will replace turbulence modeling (i.e. in the RANS framework) altogether and that "the need to arrive at acceptably accurate answers at minimum cost will probably secure at least a spacious niche within CFD for model-based algorithms", by which he again referred to the RANS framework (Leschziner 1993).

In 1997, Shuzo Murakami published the paper "Current status and future trends in computational wind engineering" (Murakami 1997). In this paper he outlined the specific difficulties pertaining to CFD in wind engineering, as well as the rapid growth of applications in this field, the new trends in RANS turbulence modeling and in LES SGS modeling. Based on a wide range of applications and comparisons with experimental data, he concluded that the different RANS turbulence models each have their advantages and disadvantages and that turbulence model selection should be based on the criteria of prediction accuracy and CPU time required. He indicated that selecting the best turbulence model for a given application is a knowledge-based learning process. Finally, he stated based on his many tests that LES with the dynamic SGS model provided the best results for many wind engineering applications, and that the rapid evolution of CPU hardware was expected to overcome the restriction of large CPU time, enabling wide application of LES to wind engineering problems in the near future.

In 1997, Shah and Ferziger (1997) published the paper "A fluid mechanician's view of wind engineering: Large eddy simulation of flow past a cubic obstacle" (Shah and Ferziger 1997). They provided results of LES simulations for the simple case of a surface-mounted cube in channel flow and stated that LES can accurately capture the effects of large-scale motions such as wind forces and their fluctuations. They correctly mentioned that the interest in LES had increased due to "the failure of RANS to do an adequate job, especially in cases in which information about the fluctuations is required". They indicated that the LES simulations they were presenting were expensive, and therefore, if high-quality results were required, it would not be possible at present to use LES as a design tool. They also argued that just the simple fact that one is using LES does not guarantee success. It is possible for LES to yield results that are incorrect qualitatively as well as quantitatively and that therefore, also in LES, the combination with experiments would remain necessary for a long time to come.

In 1997, Theodore Stathopoulos published the paper "Computational wind engineering: past achievements and future challenges" (Stathopoulos 1997). Because CFD in wind engineering involves complex 3D flows requiring solid knowledge of both turbulence theory and numerical analysis, he expressed his grave concern that "there are serious dangers inherent in the way that CFD is being increasingly used in industry often by people having little or no understanding of fluid dynamics or computational techniques." Concerning application areas, he indicated that where mean values of variables are involved such as mean wind speed and mean concentration, CFD approaches might be suitable "to provide some insight, valuable for preliminary design purposes", such as for the assessment of wind environmental conditions around buildings. For the prediction of pollutant concentrations however, the lack of success of several CFD exercises led him to conclude that "although CFD is definitely a good friend of wind engineering, it has not yet become a true ally". He concluded by arguing that "most practitioners are more concerned with obtaining results than with either the order of accuracy of their numerical schemes or the need to refine the grid until converged grid-independent solutions are obtained." And that the use of CFD in wind engineering was still in its infancy and had a very long way to go before it could become a design tool. His clear view was that it is unlikely that CFD for general turbulent flow would become a "computational wind tunnel", at least not in the foreseeable future, and that rather CFD and experiments should complement each other e.g. to reduce costs in the design process. These views were further addressed in a follow-up paper (Stathopoulos 2002).

In 1997, Wolfgang Rodi published the paper "Comparison of LES and RANS calculations of the flow around bluff bodies" (Rodi 1997). This paper provided very detailed comparisons of LES simulations with different SGS models and RANS simulations with different turbulence models versus high-quality experiments. Rodi (1997) also provided a clear view on the computational costs in terms of time: "on the SNI S600/20 vector computer the LES calculations (UKAHY4) took 160 h while the RANS two-layer model calculations took 6 h and the RANS calculations using wall functions only 15 min." The detailed comparisons in terms of accuracy but also in terms of cost made him conclude that RANS simulations would remain needed and applied for many years to come in engineering simulations of flow around buildings. But because LES is intrinsically more suitable and had displayed great potential for better simulation of these complicated flows, he advocated further development and testing, expecting that "with the recent advances in computing power LES will soon be ready and feasible for practical applications." (Rodi 1997).

In 1999, David Gosman published the paper "Developments in CFD for industrial and environmental applications in wind engineering" (Gosman 1999). He acknowledged the limitations of RANS simulations especially for flows around building-like obstacles and the unresolved issues in LES such as economical near-wall modeling and the specification of inlet boundary conditions. But his overall conclusion was that the level of accuracy that could be achieved could be acceptable for some purposes, and that this had caused CFD to be applied in a range of applications, such as pedestrian-level wind comfort, train-induced wind speed, wind on off-shore structures and indoor HVAC applications. He also mentioned the important fact that CFD as a methodology but also the codes themselves had improved substantially in terms of versatility, ease of use and speed (thanks also to hardware developments), which should help accelerating the uptake of this technology by industrial users—however, not without the required level of knowledge of flow physics to properly interpret and exploit the results.

In 1999, Castro and Graham published the paper "Numerical wind engineering: the way ahead" (Castro and Graham 1999) in which they convincingly denounced the concept of the "numerical wind tunnel" in the design process, for example for the assessment of wind loads and pollutant dispersion. In line with Stathopoulos (1997) they pointed to the significant dangers of using CFD without a sound understanding of the fluid mechanics of the problem under study, without awareness of the validation of the code for similar problems and a clear understanding of the sources of errors and uncertainties and the levels of accuracy required. They also stated that inadequate turbulence modeling could lead to a highly accurate solution to the modelled equations that differs significantly from the actual flow. But that this difference "is often of secondary importance compared with those which arise because of 'bad' choices (or even plain user mistakes) in all the other areas." (Castro and Graham 1999).

In 1999, Shuzo Murakami et al. published the paper "CFD analysis of wind climate from human scale to urban scale" (Murakami et al. 1999) in which they extended the earlier published large number of examples (see Murakami 1990a) by covering a very wide range of spatial scales but also physical processes from human body convection over convective, conductive and radiative heat transfer in street canyons to the urban heat island effect. They mentioned that they compared their CFD results with measurements whenever available. This statement referred to their very important point that in some cases, measurement data could not be obtained or would be very difficult to obtain. In such cases, Murakami correctly argued that "we do think that the comprehensive assessment based on the CFD method combining various factors seems to be the only approach for clarifying such complicated phenomena."

In 2004, Robert N. Meroney published the paper "wind tunnel and numerical simulation of pollution dispersion: a hybrid approach" (Meroney 2004), in which he advocated an intensive hybrid approach. As an example, he mentioned that fluid modeling (by which he meant wind tunnel testing) could initially provide data from which CFD turbulence models can be created, the CFD simulations can use these models to rapidly survey alternate solution strategies using simplified domain scenarios, and then wind tunnel testing can investigate in great detail design consequences, finally followed by CFD to extend the initial conclusions to a broader set of similar cases. Meroney (2004) also stressed the very strong need for a critical attitude towards all CFD but also wind tunnel results: "Good mental health in a fluid or CFD modeler is always indicated by the presence of a suspicious nature, cynicism and a "show me" attitude. These are not necessarily the best traits for a life mate or a best friend, but they are essential if the integrity of the modeling process is to be maintained."

In 2005, Kemal Hanjalic published the paper "Will RANS survive LES? A view of perspectives" (Hanjalic 2005). He observed that despite all their disadvantages, RANS simulations with first-order closure had remained the workhorses in industrial CFD applications because they are easy to use, economical and therefore suitable for design and optimization. Although there was a consensus among CFD experts that RANS had not lived up to the earlier expectations, LES was also not without disadvantages. While LES had been shown to be a very powerful method, the very large demands on grid resolution were the reasons for Hanjalic (2005) why LES application "is and will for long be limited to low-to-moderate Re and Ra numbers and relatively simple geometries." He correctly mentioned that "conventional LES on a too-coarse grid of wall bounded flows, especially in attached flows regions, can be very erroneous and inferior to even simple conventional RANS." Based on all these reasons, Hanjalic (2005) argued that "RANS will further play an important role, especially in industrial and environmental computations, and the further increase in the computing power will be used more to utilize advanced RANS models to shorten the design and marketing cycle rather than to yield the way to LES." Although he foresaw also further efforts in the improvement of LES modeling. Similar expectations were expressed by Pope (1999).

Several later papers provided additional very valuable views, generally—but not always—in line with previously expressed opinions. Baker (2007) indicated that he expected the use of RANS simulations to decrease over time, "although their relative simplicity and economy will ensure their continued use for many applications." He anticipated that CFD applications will become widespread in those area where velocities rather than surface pressures are needed, such as pedestrian-level wind (PLW) comfort assessment. And that this increase in the use of CFD might even lead to a reduction of atmospheric boundary layer wind tunnel facilities over the next decades. Yoshie et al. (2007), focusing on the CFD prediction of PLW conditions, admitted that LES could improve the prediction of wind velocity especially in wake regions as well as provide information about gusts. But they mentioned that before LES could be used in general-purpose applications for PLW conditions around buildings, a dramatic increase in computational speed would be needed, and that until that time, "we must be content with RANS type models currently in use." Tominaga and Stathopoulos (2013), in reviewing CFD techniques for modeling near-field pollutant dispersion, addressed both the significant potential of CFD but also the many challenges involved in this very complex application area. Meroney (2016) recalls the common presumptions over the past 50 years that CFD and experimental fluid dynamics (EFD) were mutually exclusive and competitive, as well as the often asked question "When can we get rid of our physical modeling facilities?" He argued that this question ignored the tremendous synergy of combining the best qualities of both CFD and EFD both in research and design, as this hybrid CFD-EFD approach can "expedite results, improve understanding of flow phenomena, and often reduce research costs and time." Also Tominaga and Stathopoulos (2016) correctly highlighted the current important consensus that both approaches should be complementary and employed to reduce the inaccuracy in the results of a single-approach method.

4.2 CFD for indoor applications

In 1992, P.J. Jones and G.E. Whittle published the paper "Computational fluid dynamics for building air flow prediction—Current status and capabilities" (Jones and Whittle 1992). Given the status of CFD at the time, this paper did not yet consider LES. They stated that the standard k-ε model is generally (but not universally) considered to be an appropriate turbulence model for (indoor) building simulation. But also that due to the limitations entailed by the assumption of isotropic turbulence, this model could prove inadequate, in which case an algebraic stress model or full RSM could be considered, however at the expense of increased computing time. As some major technical limitations and shortcoming in most CFD codes at that time, they listed the modeling of turbulence and the relative poor mesh generation methods and user interface. For the latter however they indicated that this was an area of fast development where substantial improvements were being made.

In 1997, Qingyan Chen published the paper "Computational Fluid Dynamics for HVAC: Successes and failures" (Chen 1997). He stressed the importance that CFD users should have a good knowledge of turbulent flows and numerical techniques to perform correct simulations. Based on his studies in turbulence model evaluation, he concluded that the predictions of first-order parameters such as mean velocities and temperatures by CFD are more accurate than those of second-order parameters such as turbulence intensities. He also mentioned that to date, LES had rarely been applied for actual engineering problems that involve high Reynolds number flow in complex geometries, because of the need for extensive computational power and the need for further development.

In 1998, Peter Nielsen published the paper "The selection of turbulence models for prediction of room airflow" (Nielsen 1998). From his comparison of turbulence modeling approaches, he concluded that a simple zero-equation model could be useful for provisional studies, a k-ε model could be used for stratified flows, a low-Reynolds number k-ε model was required for near-surface transport processes while LES could provide the most detailed information.

In 2001, Qingyan Chen and Jelena Srebric published the document "How to verify, validate and report indoor environment modeling CFD analysis" (Chen and Srebric 2001). In this extensive best practice document, they mentioned that only a few LES applications had been performed for indoor environment modeling because of the high computing costs but that it could become a powerful modeling tool in the near future.

Sørensen and Nielsen (2003) confirmed that LES can provide information beyond RANS models which allows for example a direct prediction of the turbulence intensity. However, they mentioned that the use of LES for predicting room airflow was very expensive and that the prediction accuracy of the average flow variables was not improved, at least not for fully developed flow, compared to results by a k-ε model (Davidson and Nielsen 1996). This observation was clearly different from that in wind flow around buildings which indicates that outdoor and indoor applications in building simulation should correctly be considered as different subfields, as done in the present paper. Nevertheless, Sørensen and Nielsen (2003) mentioned that LES could provide advantages in cases of non-fully developed turbulent flow. While they argued that with increasing computational power, LES would most likely become a useful and practicable tool for room airflow simulations in the future, at the time they recommended using RANS turbulence models for practical purposes.

In 2007, John Zhai et al. published the paper "Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: part 1 - Summary of prevalent turbulence models" (Zhai et al. 2007) in which they provided a review of available methods including LES and RANS. They indicated that for the design and study of air distributions in enclosed environments, the mean air parameters were generally more useful than the instantaneous turbulent flow parameters which justified the stronger interest in RANS simulations that could provide quick predictions rather than the more detailed but also more time-consuming LES simulations. LES was indeed considered more a research than a design tool.

In 2009, Qingyan Chen published the review paper "Ventilation performance prediction for buildings: A method overview and recent applications" (Chen 2009). Based on this review, he concluded that RANS models could perform well for one flow but poorly in another, and that LES could yield good results provided that a sufficiently fine grid resolution was applied. He correctly documented that LES is more popular for predicting particle distributions in ventilated spaces, because in this case more detailed information on the turbulent nature of the flow is required, which is provided by the LES simulations. Chen (2009) finally indicated that at the time of his publication, LES was still mainly used as a research tool and that its penetration in design applications would still take quite some time.

In 2011, Yuguo Li and Peter Nielsen published the paper "Commemorating 20 years of Indoor Air" (Li and Nielsen 2011). While this paper did not focus on LES versus RANS, it is mentioned here because it— very much like several leading papers in wind engineering (see Section 4.1)—indicated the continuing importance of experiments. They indicated that in spite of the continuously increasing capabilities for CFD simulations, "CFD has not become a replacement for experiment and theoretical analysis in ventilation research, rather it has become an increasingly important partner." These authors "believe that an effective scientific approach for ventilation studies is still to combine experiments, theory, and CFD. We argue that CFD verification and validation are becoming more crucial than ever as more complex ventilation problems are solved."

In 2015, Peter Nielsen published the paper "Fifty years of CFD for room air distribution" (Nielsen 2015) in which he looks back on the very field he successfully initiated himself in 1973. He concluded that in these years, the indoor environment community had embraced CFD as a useful tool for the airflow prediction in ventilated spaces. While it had been used for many years in research, now it was also routinely used in civil engineering practice for the design of large or complicated air distribution systems. Concerning LES versus RANS, he mentioned that room airflow is not always fully developed turbulent flow. As a result, a typical EVM like the k-ε model that is only valid for fully developed turbulent flow might not be a good option, and that indeed, for low-Reynolds number flow, LES simulations had shown a better agreement with experiments at specific locations. Nielsen (2015) also expected that the increasing computational resources would expand the use of LES in the future.

5 Best practice guidelines

"Abeunt studia in mores" [4]

5.1 General best practice guidelines

As mentioned earlier, the results of most CFD approaches, including LES and RANS, can be very sensitive to the wide range of parameters that has to be set by the user. To remove or at least limit and assess errors and uncertainties, verification and validation are imperative. Best practice guidelines (BPG) have been developed in an attempt to guide the scientific and engineering community towards removing or limiting and assessing errors and uncertainties with the aim of obtaining more accurate and reliable simulation results. A number of these guidelines have a generic character and are applicable to LES, RANS and other approaches. Examples are the guidelines and standards concerning verification and validation, as outlined in e.g. Roache et al. (1986), Freitas (1993), Roache (1994, 1997), the guidelines by the American Institute of Aeronautics and Astronautics (AIAA 1998), Oberkampf et al. (2004), Roy (2005), Roy and Oberkampf (2010), the guidelines by the American Society of Mechanical Engineers (ASME 2009), and others. These guidelines and standards underlie more specific guideline documents, such as the extensive BPG by the European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) published in 2000 by the Special Interest Group on Quality and Trust in Industrial CFD (Casey and Wintergerste 2000) and the ERCOFTAC BPG published in 2008 on CFD of dispersed multiphase flow (Sommerfeld et al. 2008). The former ERCOFTAC guidelines were focused on RANS simulations while the latter included a focus on DNS, LES and RANS. Although

[4] "*Practices passionately pursued become habits*"; Ovidius in Heroides 15.83. Publius Ovidius Naso (43 BC – 17 AD), Roman poet, one of the three canonical poets of Latin literature together with Virgilius and Horatius.

all of the aforementioned guidelines were not specifically intended for building simulation, almost all of them also apply to this field. Within the EC project ECORA, Menter et al. (2002) published BPG based on the ERCOFTAC guidelines but modified and extended specifically for CFD code validation. Generic best practice advice was also provided by Jakeman et al. (2006) in the article "Ten iterative steps in development and evaluation of environmental models", which were later on extended to development and evaluation of process-based biogeochemical models of estuaries by Robson et al. (2008) but also to CFD for environmental fluid mechanics (including building simulation) by Blocken and Gualtieri (2012). Although mainly focused on outdoor applications, they could also be applied to indoor applications.

5.2 Best practice guidelines for outdoor applications

Section 3.3 indicated that already since the start of the application of CFD for wind flow around bluff bodies in the late 70s and 80s, researchers had been testing the influence of different computational parameters on the results, which had provided a lot of valuable information. In addition, Schatzmann et al. (1997) provided an important contribution on validation with field and laboratory data. However, initially this information was dispersed over a large number of individual publications in different journals, conference proceedings and reports. Note that a part of this section is intentionally reproduced from (Blocken 2014).

Within the Network for Quality and Trust in the Industrial Application of CFD (QNET-CFD), the Thematic Area on Civil Construction and HVAC (Heating, Ventilating and Air-Conditioning) and the Thematic Area on the Environment presented some best practice advice for CFD simulations of wind flow and dispersion (Scaperdas and Gilham 2004; Bartzis et al. 2004).

In 2004, Franke et al. (2004) compiled a set of specific recommendations for the use of CFD in wind engineering from a detailed review of the literature, as part of the European COST Action C14: Impact of Wind and Storm on City Life and Built Environment (COST = European Cooperation in Science and Technology). Later, this contribution was extended into an extensive "Best Practice Guideline for the CFD simulation of flows in the urban environment" (Franke et al. 2007, 2011), in the framework of the COST Action 732: Quality Assurance and Improvement of Microscale Meteorological Models, managed by Schatzmann and Britter (http://www.mi.uni-hamburg.de/Home.484.0.html). Like the ERCOFTAC guidelines, also these BPG primarily focused on steady RANS simulations, although also some limited information on URANS, LES and hybrid URANS/LES was provided. When using CFD tools, whether they are academic/open source or commercial codes, it is also important that the code is well documented, and that basic verification tests and validation studies have been successfully performed and reported. A good description of how a microscale airflow and dispersion model has to be documented can be found in the Model Evaluation Guidance Document published in the COST Action 732 by Britter and Schatzmann (2007).

In Japan, working groups of the Architectural Institute of Japan (AIJ) conducted extensive cross-comparisons between CFD simulation results and high-quality wind tunnel measurements to support the development of guidelines for practical CFD applications. Part of these efforts were reported by Yoshie et al. (2007). In 2008, Tominaga et al. (2008a) published the "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings", and Tamura et al. (2008) provided the "AIJ guide for numerical prediction of wind loads on buildings". The guidelines by Tominaga et al. (2008a) focused on steady RANS simulations, while the guidelines by Tamura et al. (2008) also considered LES, given the importance of time-dependent analysis for wind loading of buildings and structures.

In addition to these general BPG, also some very specific guidelines were published. These include (1) consistent modeling of equilibrium atmospheric boundary layers in computational domains (e.g. Richards and Hoxey 1993; Blocken et al. 2007a,b; Hargreaves and Wright 2007; Franke et al. 2007; Di Sabatino et al. 2007; Gorlé et al. 2009; Yang et al. 2009; Parente et al. 2011; Richards and Norris 2011; Blocken 2015); (2) high-quality grid generation (e.g. Tucker and Mosquera 2001; van Hooff and Blocken 2010a) and (3) validation with field and laboratory data (e.g. Schatzmann et al. 1997; Schatzmann and Leitl 2011). Note that most of the efforts in the first two areas were focused on steady RANS simulations. In addition, Blocken et al. (2012) also provided a general decision framework for the analysis of PLW comfort and safety in urban areas.

The establishment of these guidelines has been an important step towards more accurate and reliable RANS CFD simulations for the outdoor built environment. Although several of the guideline documents mentioned above were developed with focus on PLW conditions (Franke et al. 2004; Tominaga et al. 2008a; Blocken et al. 2012), most of the information is also applicable to other topics in building simulation for the outdoor built environment.

In contrast to the fairly large number of efforts towards BPG for RANS for outdoor building simulation applications, such efforts for LES simulations are rather scarce. In the framework of the AIJ, Tamura et al. (2008) provided an initial guide for the numerical prediction of wind loads on buildings based on an earlier extensive cooperative project (Tamura et al. 1997). Gousseau et al. (2013) provided a detailed solution verification and validation study leading to guidelines for wind flow around an isolated high-rise building. Many studies compared LES and RANS simulation results, but more general or extensive BPG for LES in the field of outdoor building simulation are—to the best knowledge of the author—not yet available. However, LES entails a firmly increased simulation complexity compared to RANS and, as stated by Hanna (1989) "… as the model formulation increases in complexity, the likelihood of degrading the model's performance due to input data and model parameter uncertainty increases as well." The lack of such BPG for LES can be attributed to several reasons:

(1) The still rather limited use of LES for practical applications. The establishment of the RANS BPG has been an iterative process over several decades, incited and supported by successes and failures in a wide range of practical applications. Conversely, the lack of LES BPG is one of the reasons why LES is not applied more frequently—a vicious circle.

(2) The computational costs of LES are at least an order of magnitude larger than for RANS, and possibly at least two orders of magnitude larger when the necessary actions for solution verification and validation are to be included. But even without solution verification and validation, LES will often be too computationally demanding for many practical applications, even the less complicated ones such as PLW conditions (Yoshie et al. 2007). The establishment of BPG, which has to be based on many LES simulations in extensive sensitivity studies, will require a much higher computational cost and much more time and effort than the RANS BPG.

(3) Ironically, the lack of BPG in LES is undoubtedly delaying the development of further LES BPG. For RANS simulations, the establishment of the first series of BPG documents has incited continued efforts over the years and has led to the current situation in which the different outdoor applications in the field of building simulation are increasingly well covered by guidelines.

The lack of BPG for LES combined with the increased model complexity of LES can be held accountable, at least partly, for many poor quality LES simulations and can serve as background for the statements by Shah and Ferziger (1997) and Hanjalic (2005) mentioned in section 4. Shah and Ferziger (1997) indeed stated that it is possible for LES to yield results that are incorrect qualitatively as well as quantitatively, and Hanjalic (2005) mentioned that "conventional LES on a too-coarse grid of wall bounded flows, especially in attached flows regions, can be very erroneous and inferior to even simple conventional RANS."

5.3 Best practice guidelines for indoor applications

Section 3.4 indicated that already since the start of the application of CFD for indoor airflow in the 70s and 80s, researchers had been testing the influence of these parameters on the results, which had provided a lot of valuable information. Similar to the situation for outdoor building simulation applications, initially, this information was dispersed over a large number of individual publications in different journals, conference proceedings and reports. Later, several documents were compiled that serve as references on best practices in the field.

Chen (1997) described successes and failures in RANS CFD for HVAC applications. When testing eight popular eddy-viscosity and Reynolds-stress models for natural convection, forced and mixed convection and impinging jet flows in rooms, (Chen 1995, 1996) found that none of the models produces satisfactory results and that the difference between the computed turbulence level and the measured one can be more than 100%.

Chen and Srebric (2001) provided a very extensive BPG report on how to verify, validate and report environment modeling CFD analysis. The report is focused on RANS simulations, and includes basic flow and heat transfer, turbulence modeling, numerical methods, assessment of the CFD results and drawing conclusions from the CFD simulation results. It illustrates the CFD process step-by-step for two representative indoor environmental modeling applications, an office with mechanical displacement ventilation and an apartment building with natural ventilation.

Sørensen and Nielsen (2003) provided a paper focused on quality control of CFD simulations for indoor environments, with two main targets: (1) performing simulations with sufficient accuracy; and (2) reporting the simulations results in sufficient detail to allow readers to judge the quality. They addressed issues in turbulence modeling, specification of boundary conditions, numerical errors, and choices of differencing schemes and computational grids. While their paper was primarily focused on RANS simulations, their philosophy and discussions equally apply to LES and DNS.

Nielsen (2004) discussed the quality level of CFD and the involved schemes by the use of the Smith and Hutton problem on the mass fraction transport equation. He discusses the different aspects of boundary conditions in the indoor environment as, e.g., the simulation of Air Terminal Devices and the simulation of furnishings and occupants.

The REHVA Guidebook 10 (Nielsen et al. 2007) also provides a very extensive set of guidelines for CFD calculations for the analysis of air and pollution distribution in various spaces. However, it explicitly focuses on the RANS approach with first-order closure. Important advice has also been documented in the books by Etheridge and Sandberg (1996), Heiselberg et al. (1998), Awbi (2003, 2008) and others.

6 LES and RANS in building simulation applications

"The root of the matter is that the greatest stimulus of scientific discovery are its practical applications." [5]

In the past decades, a very large number of valuable application studies have been performed by either LES or RANS, or both. Without wanting to detract from the importance of any of these studies, in the interest of brevity, only very few are mentioned in this section.

6.1 Pedestrian-level wind conditions, wind comfort and wind safety

Past studies on PLW conditions have revealed the interesting observation that steady RANS CFD simulations— when performed according to best practices—can accurately predict the mean wind speed in high wind speed regions around buildings, while their performance in the low wind speed regions can be very poor (Yoshie et al. 2007; Blocken and Carmeliet 2008; Blocken et al. 2008b, 2011; Blocken et al. 2016b). A few examples are provided below.

Yoshie et al. (2007) compared CFD simulations and wind tunnel measurements for an isolated building with ratio L:W:H = 1:1:2 (Fig. 11a). The CFD simulations were performed with the steady RANS approach with the standard k-ε model and two revised k-ε models for closure: the Launder-Kato k-ε model (Kato and Launder 1993) and the RNG k-ε model (Yakhot and Orszag 1986). The comparison with the measurements in Figs. 11b–d shows that the amplification factor $K = U/U_0$ (ratio of local mean wind speed U to the mean wind speed U_0 at the same position without buildings present) is generally predicted within 10% in the regions where $U/U_0 > 1$. However, in the wake region behind the building, where $U/U_0 < 1$, large underestimations are obtained, locally by a factor 5 or more (Figs. 11b–d). These underestimations are due to the underestimation of turbulent kinetic energy in the wake, because steady RANS evidently cannot capture the vortex shedding (Murakami 1993; Yoshie et al. 2007; Tominaga et al. 2008b).

Blocken and Carmeliet (2008) obtained very similar conclusions when performing steady RANS CFD simulations with the realizable k-ε model (Shih et al. 1995) for groups of parallel shifted buildings. They compared the CFD results with the sand-erosion wind tunnel experiments by Beranek (1982). Figure 12 shows the very good agreement between CFD and wind tunnel results in the region of high K (about

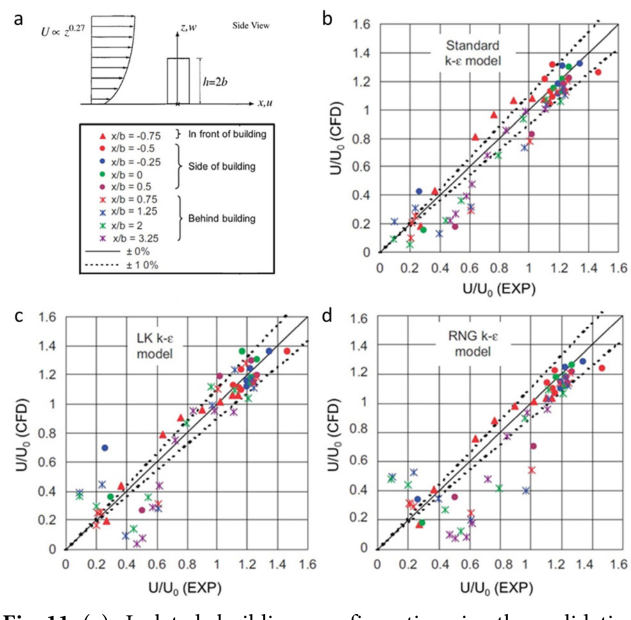

Fig. 11 (a) Isolated building configuration in the validation studies by Yoshie et al. (2007). (b–d) Comparison of CFD results and wind tunnel measurements of amplification factor $K = U/U_0$ around the building: (b) steady RANS with standard k-ε model; (c) steady RANS with LK k-ε model; (d) steady RANS with RNG k-ε model. The symbols refer to: Δ = front of building; o = side of building; x = behind building. The different colors refer to a variety of positions in front, beside and behind the building (Yoshie et al. 2007; reproduced with permission ©Elsevier)

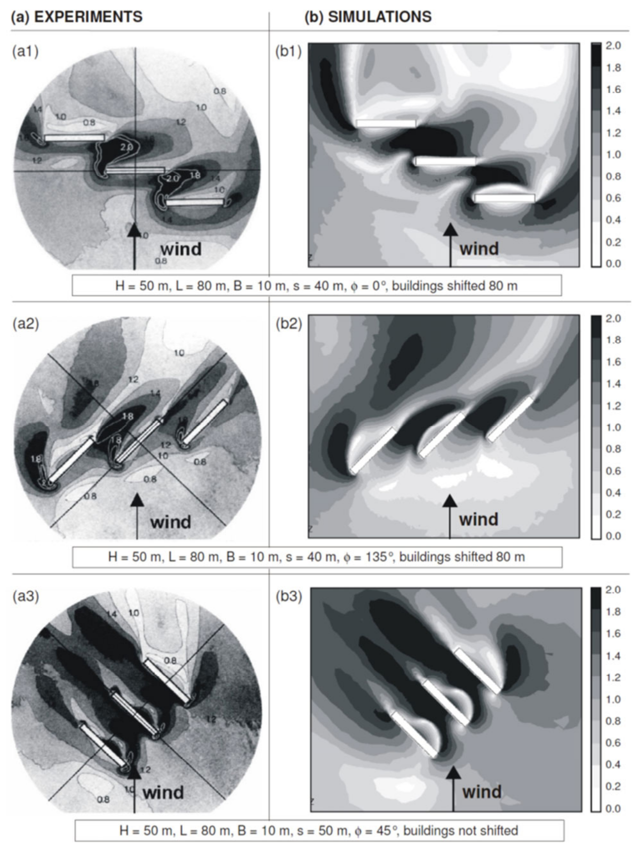

Fig. 12 Validation study for parallel building configurations by Blocken and Carmeliet (2008). (a) Top view of sand-erosion contour plots versus (b) top view of RANS CFD results of the amplification factor K. White contour lines in sand-erosion plots correspond to amplification factors of 1.8 and 2.0

[5] Lewis Fry Richardson (1908).

10% accuracy) and significant underestimations in the regions of lower K. Later studies also consistently showed a close agreement between steady RANS predictions of mean wind speed in the regions of high K (Yim et al. 2009; Blocken and Persoon 2009; Blocken et al. 2012; Janssen et al. 2013; An et al. 2013).

These observations that steady RANS CFD with first order-closure—when applied according to best practice — can provide accurate results (~10%) of mean wind speed in regions of high K (> 1) but poor to very poor results in regions of low K is very important towards the practical assessment of PLW comfort. Blocken et al. (2016b) hypothesized that the poor RANS performance in regions of low K would not necessarily compromise the accuracy of PLW comfort assessment, because the higher amplification factors provide the largest contribution to the discomfort exceedance probability in the comfort criterion. To check this hypothesis, they executed a complete wind comfort assessment for a simple case: an isolated high-rise building tower ($L \times B \times H$ = 40 m × 20 m × 70 m) on flat, level, uniformly rough terrain with aerodynamic roughness length z_0 = 0.25 m.

The wind comfort assessment study was performed according to the Dutch Wind Nuisance Standard NEN 8100 (NEN 2006a,b). A complete wind comfort assessment study involves a combination of three types of information/data: (1) statistical meteorological data; (2) aerodynamic information; and (3) a comfort criterion. The aerodynamic information, i.e. the PLW speed around the building, was provided by the sand erosion tests by Beranek and van Koten (1979a,b). Figure 13 shows the results for different wind directions. We focus on two critical points A and B: for wind direction 0°, point A is situated in the corner stream and point B in the standing vortex. The areas of the corner stream and the standing vortex exhibit the highest K and represent the most problematic areas for wind comfort. Note however that as the wind direction changes, these points are located in areas of higher or lower K. The meteorological data are provided by the Royal Dutch Meteorological Institute and are the 30-year statistical meteorological data of potential wind speed (U_{pot}) at Eindhoven airport. The potential wind speed is defined as the wind speed at 10 m height over a terrain with z_0 = 0.03 m. We consider twelve wind directions: 0°–330° in intervals of 30°. The comfort criterion is that by NEN 8100 with a threshold wind speed U_{THR} = 5 m/s and exceedance probabilities linked to different activities (Table 1). However,

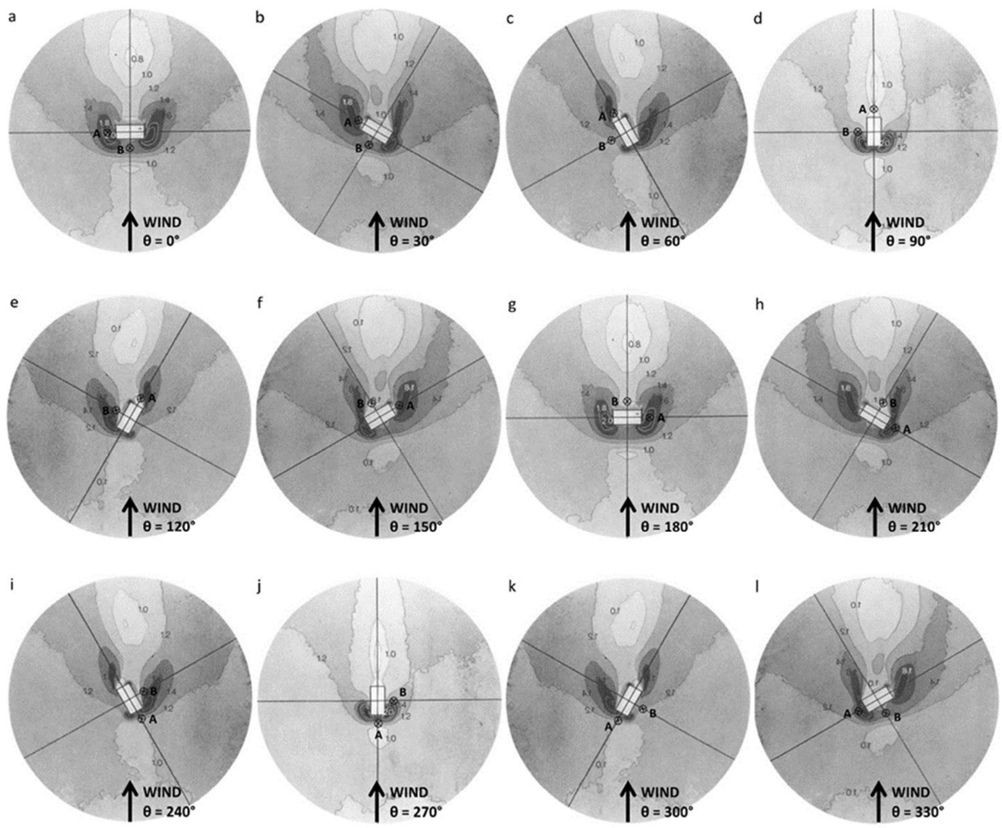

Fig. 13 Sand erosion contours of amplification factor K for an isolated building with dimensions $L \times B \times H$ = 40 m × 20 m × 70 m for 12 different wind directions. Indication of points A and B where wind comfort is evaluated (Blocken et al. 2016b; reproduced with permission ©Elsevier)

Table 1 Criteria for wind comfort according to NEN 8100 (2006a)

P (U_{THR} > 5 m/s) (in % hours per year)	Grade	Activity		
		Traversing	Strolling	Sitting
< 2.5	A	Good	Good	Good
2.5 – 5.0	B	Good	Good	Moderate
5.0 – 10	C	Good	Moderate	Poor
10 – 20	D	Moderate	Poor	Poor
> 20	E	Poor	Poor	Poor

also other threshold wind speed values are considered to extend the general character of this exercise. The exceedance probability P_θ of U_{pot} in relation to a threshold wind speed $U_{THR,10m}$ at 10 m height can be expressed by a Weibull distribution where the Weibull parameters A, c and k are fitted based on the 30-year meteorological data:

$$P_\theta = P_\theta(U_{pot} > U_{THR,10m}) = 100 \cdot A(\theta) \cdot \exp\left[-\left(\frac{U_{THR,10m}}{c(\theta)}\right)^{k(\theta)}\right] \tag{15}$$

For simplicity we assume that every wind direction has the same frequency occurrence and the same contribution to the wind statistics, and that the exceedance probability for a given threshold value and a given wind direction is 1/12th of the sum of the exceedance probabilities for all 12 wind directions:

$$\begin{aligned} P_\theta' &= P_\theta'(U_{pot} > U_{THR,10m}) \\ &= \frac{100}{12} \cdot \sum_{\theta=0°}^{330°} \left[A(\theta) \cdot \exp\left[-\left(\frac{U_{THR,10m}}{c(\theta)}\right)^{k(\theta)}\right]\right] \end{aligned} \tag{16}$$

The aerodynamic information is the product of two contributions: a terrain-related contribution (U_0/U_{pot}) and a design-related contribution ($K = U/U_0$). The design-related contribution is given by the local amplification factor K in Fig. 13. The terrain-related contribution is obtained by combining the expression of the vertical mean wind speed profile by the logarithmic law and the wind speed conversion using the blending height of 60 m (Verkaik 2006). Figure 14a shows the results in terms of the total exceedance probability $P = \Sigma 12 P_\theta'$ as a function of K with U_{THR} as a parameter. It indicates to which extent K values contribute to the total exceedance probability. It clearly shows that larger K values contribute more but that this is also governed by the choice of U_{THR}. Figure 14b shows the derivative of P to K with U_{THR} as parameter. It indicates the sensitivity of P to changes in K and hence the extent to which errors in K will propagate to errors in P.

To demonstrate the extent to which typically errors in K as obtained by RANS first-order closure simulations propagate to errors in P, two different sets of K values are considered. The first set corresponds to the values in Fig. 13. The second set is created from the first set by changes taking into account the error levels in Table 2. This yields the values of modified K (K_{mod}) in Table 3. The magnitude of the error levels is chosen based on Figs. 11b–d but assuming to some extent a worst-case scenario, i.e. all errors are underestimations, so there is no compensation of underestimations by overestimations as can be the case in reality as shown in Figs. 11b–d. Application of the total wind comfort procedure consists of combining Table 3 and Fig. 14a, which yields Fig. 15. The numerical values of the differences (i.e. errors) are given in Table 4. For all values of U_{THR}: In spite of the large errors imposed on especially the lower values of K, the errors in P remain rather limited. In reality however it is likely that errors by overestimations and underestimations of K will compensate each other, resulting in even lower total errors in P than in the present study. One could argue that the K errors will be larger in points other than A and B in less windy regions where K is lower, however note that the points with the highest K values are generally of most interest because they are the most important positions in terms of wind comfort.

Although LES is an intrinsically more accurate technique, this example study by Blocken et al. (2016b) supports the continued use of the faster and less expensive RANS approach for PLW studies. Extrapolating the statement by the late Joel H. Ferziger (Ferziger 1990), we argue that PLW comfort is one of the few topics in wind engineering where nature is kind to us concerning turbulent flows.

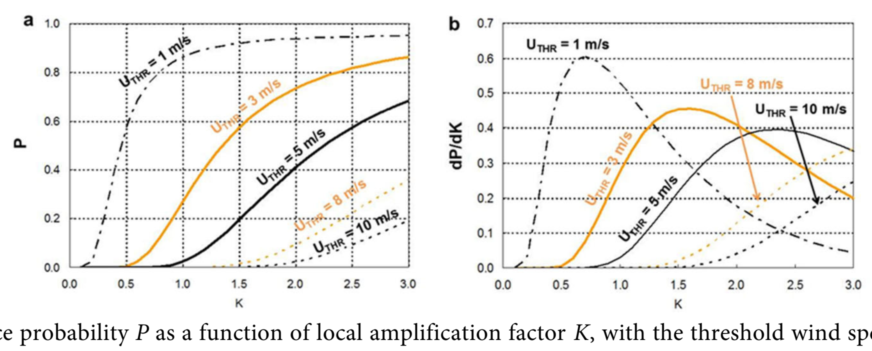

Fig. 14 (a) Exceedance probability P as a function of local amplification factor K, with the threshold wind speed U_{THR} as parameter. (b) Sensitivity dP/dK as a function of K with U_{THR} as a parameter (Blocken et al. 2016b; reproduced with permission ©Elsevier)

Table 2 Errors imposed on amplification factor K, yielding modified values K_{mod}

K	Error	K_{mod}
2.0	10%	1.8
1.9	10%	1.71
1.8	10%	1.62
1.7	10%	1.53
1.6	10%	1.44
1.5	10%	1.35
1.4	10%	1.26
1.3	10%	1.17
1.2	10%	1.08
1.1	10%	0.99
1.0	20%	0.8
0.9	20%	0.72
0.8	30%	0.56
0.7	30%	0.49
0.6	50%	0.3
0.5	50%	0.25
0.4	70%	0.12
0.3	70%	0.09
0.2	90%	0.02
0.1	90%	0.01

Table 3 Amplification factors K and K_{mod} for points A and B and all wind directions

	POINT A		POINT B	
	K	K_{mod}	K	K_{mod}
0°	2.00	1.80	1.50	1.35
30°	1.80	1.62	1.50	1.35
60°	1.50	1.35	1.20	1.08
90°	0.90	0.72	1.40	1.26
120°	1.20	1.08	1.40	1.26
150°	1.80	1.62	0.90	0.72
180°	2.00	1.80	1.00	0.80
210°	1.50	1.35	1.00	0.80
240°	1.20	1.08	1.50	1.35
270°	1.20	1.08	1.50	1.35
300°	1.20	1.08	1.20	1.08
330°	1.80	1.62	1.50	1.35

Table 4 Total exceedance probabilities for amplification factors K and K_{mod} for points A and B and for different values of U_{THR}

	U_{THR} = 1 m/s		U_{THR} = 3 m/s		U_{THR} = 5 m/s		U_{THR} = 8 m/s		U_{THR} = 10 m/s	
	A	B	A	B	A	B	A	B	A	B
$P(K)$	91.1	89.8	54.1	45.5	20.8	12.3	3.1	0.7	0.7	0.1
$P(K_{mod})$	89.5	87.3	47.1	36.2	15.2	7.6	1.6	0.3	0.2	0.0
Difference	1.6	2.5	6.9	9.3	5.6	4.7	1.5	0.5	0.4	0.0

6.2 Near-field pollutant dispersion around buildings

Near-field dispersion is defined as the dispersion in the immediate range (horizontal distance downwind up to 10 times the building height) of the building under study. A distinction is made here concerning dispersion around an isolated building and dispersion in a high-density urban area, as both configurations lead to different conclusions in terms of RANS performance.

6.2.1 *Generic isolated building*

Many CFD studies on pollutant dispersion for generic isolated buildings were based on the generic wind tunnel study of dispersion from a rooftop vent on an isolated cubic building by Li and Meroney (1983a,b) (Fig. 16a). CFD simulations for this configuration were reported by e.g. Li and Stathopoulos (1997), Blocken et al. (2008c), Tominaga and Stathopoulos (2009, 2010), Gousseau et al. (2011b,

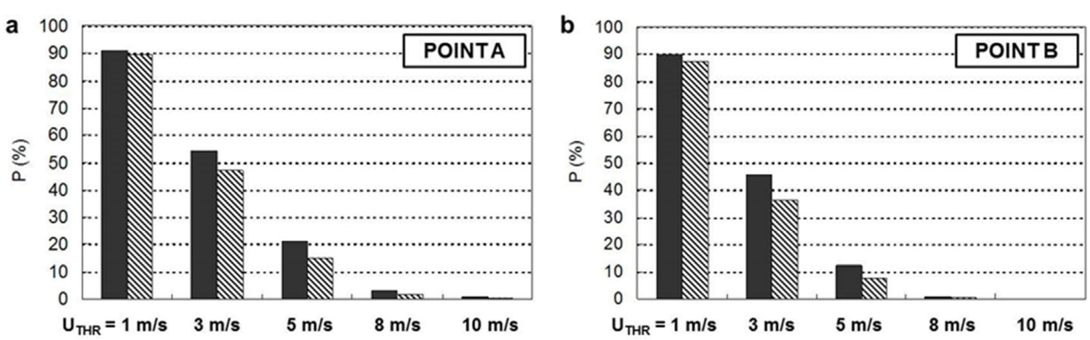

Fig. 15 Exceedance probability P (%) in (a) point A and (b) point B, for different values of the threshold wind speed U_{THR}. The solid bars and the hashed bars represent results from the two sets of amplification factors (Blocken et al. 2016b; reproduced with permission ©Elsevier)

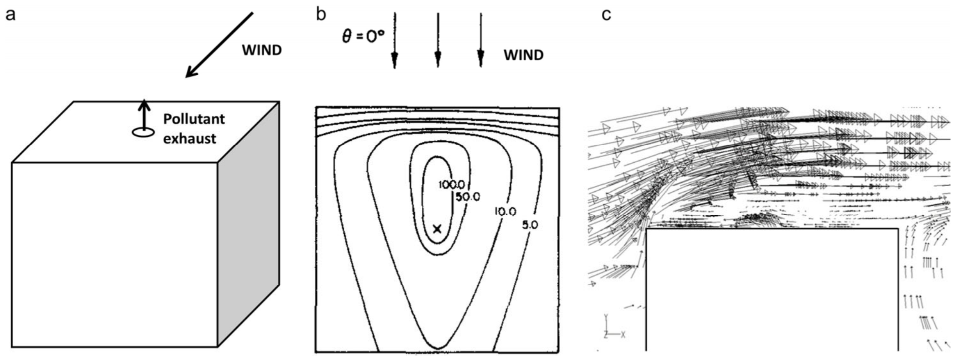

Fig. 16 (a) Isolated cubic building with rooftop vent; (b) contours of dimensionless concentration coefficient C^* on the roof of the building (Li and Meroney 1983a; reproduced with permission ©Elsevier); (c) mean velocity vector field in vertical centerplane through the cubic building (Blocken et al. 2008c)

2012) and Bazdidi-Tehrani et al. (2013). Below, the detailed simulations by Tominaga and Stathopoulos (2009, 2010) are provided in comparison to the wind tunnel experiments.

The reduced-scale building height is 0.05 m and the vent is located in the middle of the roof. The approach-flow is a neutrally stratified atmospheric boundary layer with power-law exponent 0.19, reduced-scale height 0.3 m, and mean wind speed 3.3 m/s at roof height. The longitudinal turbulence intensity is about 12% at roof height. The momentum ratio; i.e. the ratio of vertical exhaust velocity from the vent to the approach-flow wind speed at roof height is 0.19. Figure 16b shows the measured contours of the dimensionless concentration coefficient C^* on the roof. C^* is defined as:

$$C^* = \frac{CU_H LH}{Q} \times 10^{-6} \tag{17}$$

where C is the mean concentration in ppm, Q is the pollutant emission rate in m^3/s, H and L are obstacle height and length and U_H the mean wind speed at height H. Here, U_H is the approach-flow wind speed at roof height. Due to the low momentum ratio, the pollutant is trapped in the separation bubble above the roof and then transported inside this bubble towards the upwind roof edge, from which the pollutant is spread over the width of the roof and then convected downwind (Fig. 16c). Figure 17 displays the

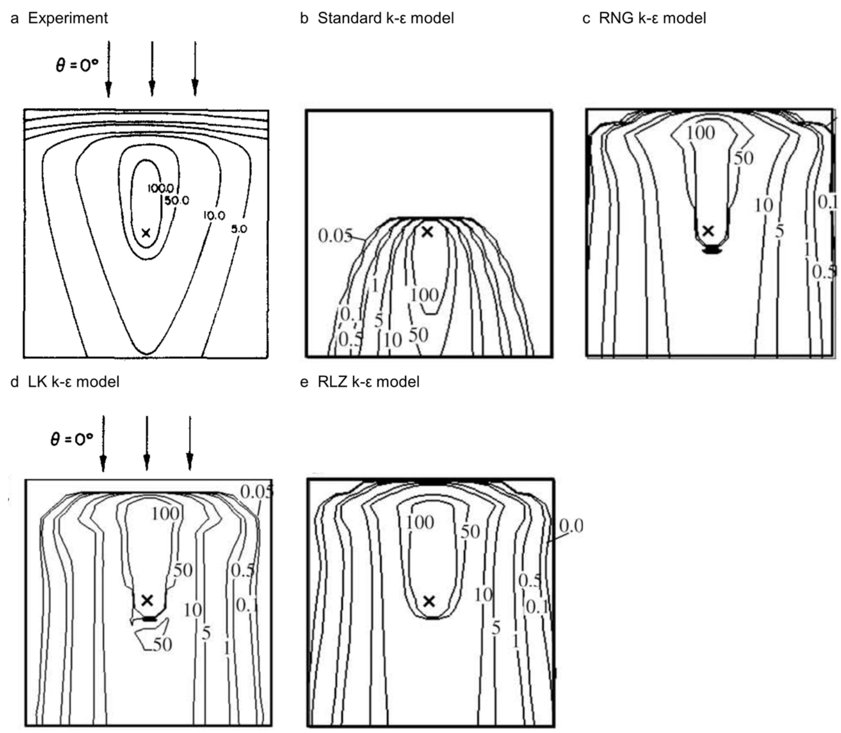

Fig. 17 Rooftop contours of dimensionless concentration coefficient C^*. (a) Experiment by Li and Meroney (1983a); (b–e) RANS CFD results by different turbulence models (Tominaga and Stathopoulos 2009) (all figures: reproduced with permission ©Elsevier)

RANS first-order closure simulations results by Tominaga and Stathopoulos (2009) on the building roof. While the standard k-ε model provides a very poor agreement with the experiments, the modified k-ε models provide a qualitatively better performance especially in terms of the upwind dispersion over the roof. However, deficiencies are noted for every simulation. Figures 17c and d show too much upwind dispersion and too low lateral dispersion. Figure 17e shows a somewhat better upwind dispersion but again a too low lateral dispersion.

A clearer view of the dispersion process that helps in understanding the deficiencies of the RANS modeling is shown in Fig. 18 as LES snapshots of contours of C^* at different time steps. These contours show that the pollutant exhausted from the rooftop vent is immediately convected upstream and the actually spread not along along part but along the entire upwind roof edge length, after which it is partly recirculated in the separation bubble and partly evacuated outside this bubble and moved into the wake region. As a result, indeed, the detailed LES simulations by Tominaga and Stathopoulos (2010) show a better agreement with the experiments, as shown in Fig. 19, not only for the roof top contours but also for the contours on the side and leeward facade. Figure 20 better highlights the different performance of the RANS RNG model versus LES by means of a semi-logarithmic diagram. Especially Fig. 20b that shows the lateral dispersion clearly illustrates the superior performance of LES compared to RANS RNG.

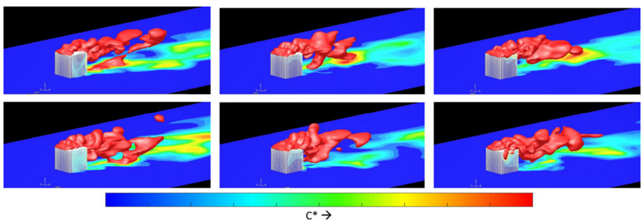

Fig. 18 LES simulation: snapshots of contours of dimensionless concentration coefficient C^*

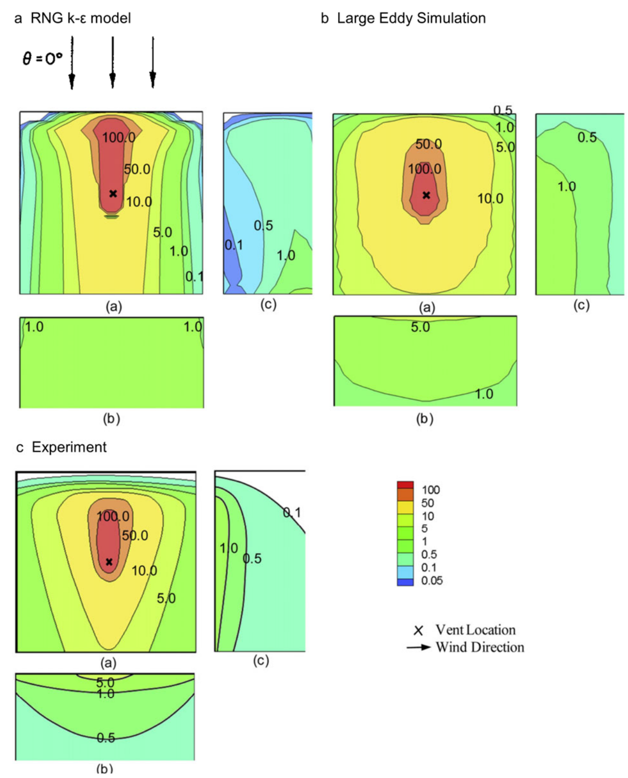

Fig. 19 Rooftop contours of dimensionless concentration coefficient C^*. (a) RANS CFD RNG k-ε results by Tominaga and Stathopoulos (2010); (b) LES CFD results by Tominaga and Stathopoulos (2010); (c) experimental results by Li and Meroney (1983a) (all figures: reproduced with permission ©Elsevier)

6.2.2 *Urban areas with high plan area density*

Two specific studies are addressed here: the study by Blocken et al. (2016a) on the generic urban area defined in the wind tunnel study by Garbero et al. (2010) and the study by Hanna et al. (2006) on the actual urban area of downtown Manhattan.

Garbero et al. (2010) reported wind tunnel experiments of the dispersion of passive tracer gas from a point source in regular arrays of rectangular building models (Fig. 21). Three different arrays were considered: array A with street width in both directions S_x and S_y equal to H; array B with $S_x = H$ and $S_y = 2H$; and array C with $S_x = 2H$ and $S_y = H$. The point source was positioned in the middle of the intersection between two perpendicular streets at height $z/H = 0.5$ (Fig. 21). A neutrally stratified turbulent boundary layer was generated with a height of about 0.8 m. The 1:400 reduced-scale building models had dimensions $L \times W \times H$ = 250 mm × 250 mm × 50 mm, corresponding to $L \times W \times H$ = 100 m × 100 m × 20 m in full scale. The model roofs were each covered with 14 staggered "nuts" of 5 mm height representing roof-top structures. The reference wind speed at boundary-layer height was 5 m/s resulting in an obstacle Reynolds number (based on obstacle height and wind speed at that height) of 6700. Concentration measurements were made at $z/H = 0.5$ and $z/H = 2$. The 3D steady RANS CFD simulations were performed with the realizable k-ε model (Shih et al. 1995) and the Eulerian advection-diffusion equation (Eq. 3d) with the standard gradient-diffusion hypothesis. Two different values of the turbulent Schmidt number Sc_t are used (0.3 and 0.7) in accordance with previous overview and review studies on gas dispersion (Tominaga and Stathopoulos 2007, 2013). The results are shown as simulated versus measured profiles of C^* at height $z/H = 0.5$ along horizontal lines in the lateral streets and as simulated contours of C^* (see insert figures) in a horizontal

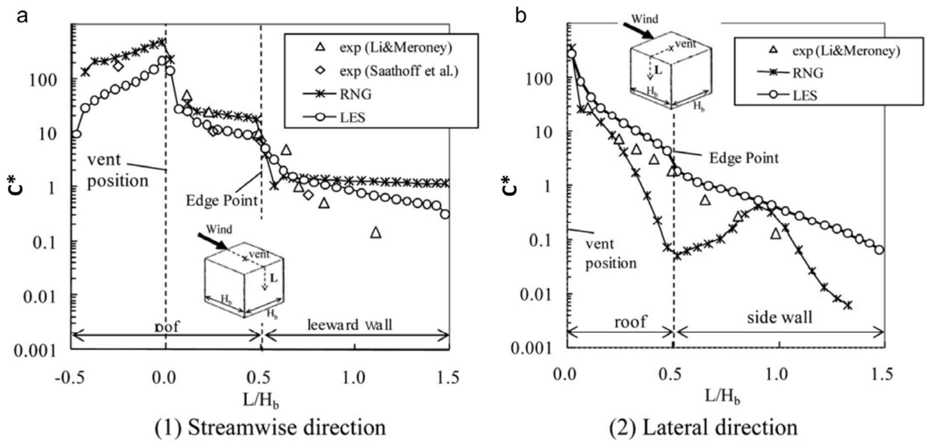

Fig. 20 Distribution of dimensionless concentration coefficient C^* along lines on roof and leeward/side wall (Tominaga and Stathopoulos 2010; reproduced with permission ©Elsevier)

Fig. 21 Wind tunnel set-up of building array with indication of source position (Garbero et al. 2010; reproduced with permission ©Springer)

plane at the same height (Figs. 22 to 24). The following main observations are made:

- Figure 22: the maximum concentrations are mostly reproduced within a factor 2 from the measurement values. The simulations with $Sc_t = 0.3$ (more turbulent diffusion) underestimate the street concentrations while those with $Sc_t = 0.7$ (less turbulent diffusion) overestimate the street concentrations, except in the first street downstream of the source. A higher turbulent diffusion causes more gas to leave the street canyons vertically and to be evacuated over the building array. For both Sc_t values, plume spreading is underpredicted.
- Figure 23: The simulations with $Sc_t = 0.3$ and 0.7 both underestimate the maximum concentrations. While for $Sc_t = 0.7$, the deviations are less than a factor 2, for $Sc_t = 0.3$, in the more downwind streets they can go up to a factor 4. Both Sc_t values provide an accurate reproduction of the extent of the lateral spread.
- Figure 24: The larger street with in the streamwise direction provides a very different dispersion pattern as in the previous cases. $Sc_t = 0.3$ underestimates the maximum C^* by a factor 2 up to 4, while $Sc_t = 0.7$ reproduces the maximum C^* within a factor 0.25. While both simulations cannot accurately reproduce the extent of the lateral spread, the predicted trend (skewness) in the 3rd and 5th street is good.

The fact that a variation in Sc_t sometimes yields a better accuracy is not surprising because the actual value of the Sc_t number depends on the type of flow pattern and on the location in this flow pattern. However, apart from the case with $S_x = 50$ mm, $S_y = 100$ mm (Fig. 23), the measured

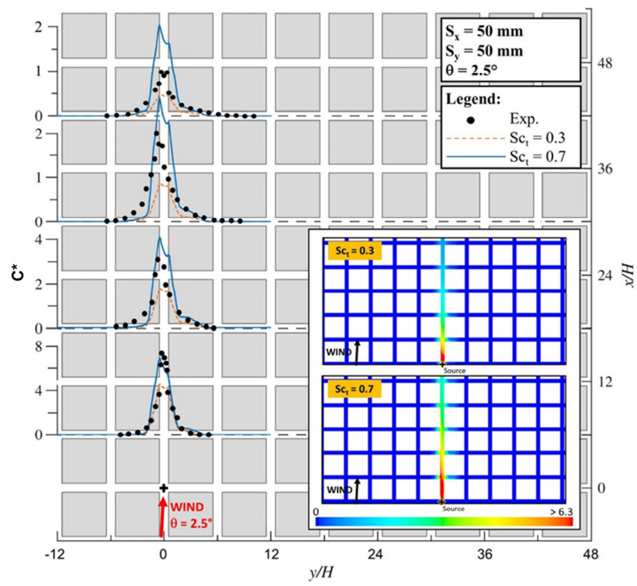

Fig. 22 Dimensionless concentration C^* by CFD RANS realizable k-ε simulations ($Sc_t = 0.3$ and 0.7) and wind tunnel measurements at height $z/H = 0.5$ for equally spaced buildings and wind direction $\theta = 2.5°$. Source is indicated by +. Inserts are contours of C^* at height $z/H = 0.5$ (Blocken et al. 2016a; reproduced with permission ©Elsevier)

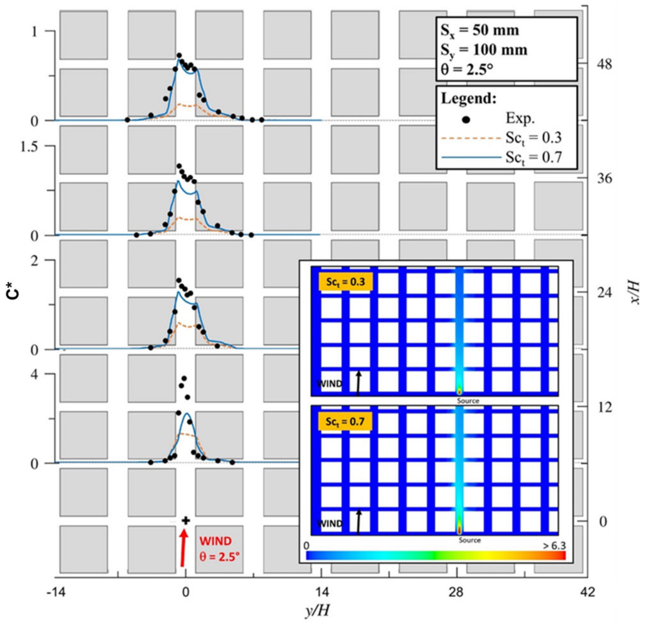

Fig. 23 Dimensionless concentration C^* by CFD RANS realizable k-ε simulations (Sc_t = 0.3 and 0.7) and wind tunnel measurements at height z/H = 0.5 for unequally spaced buildings (S_x = 50 mm, S_y = 100 mm) and wind direction θ = 2.5°. Source is indicated by +. Inserts are contours of C^* at height z/H = 0.5 (Blocken et al. 2016a; reproduced with permission ©Elsevier)

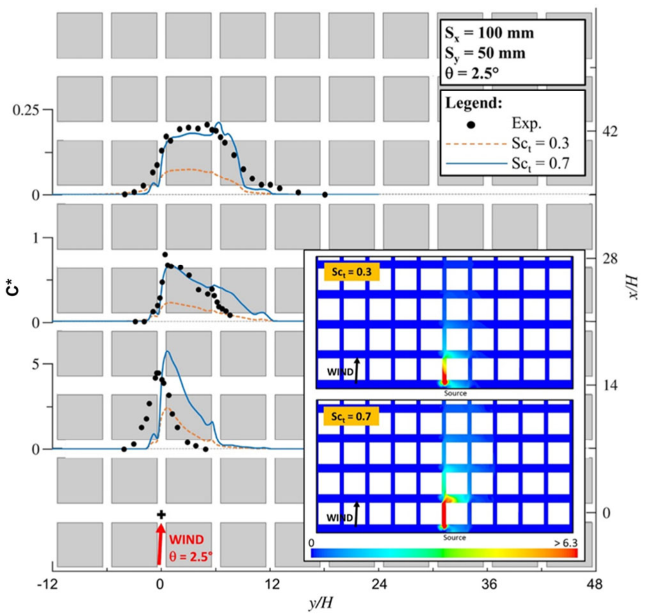

Fig. 24 Dimensionless concentration C^* by CFD RANS realizable k-ε simulations (Sc_t = 0.3 and 0.7) and wind-tunnel measurements at height z/H = 0.5 for unequally spaced buildings (S_x = 100 mm, S_y = 50 mm) and wind direction θ = 2.5°. Source is indicated by +. Inserts are contours of C^* at height z/H = 0.5 (Blocken et al. 2016a; reproduced with permission ©Elsevier)

concentrations are generally situated between the simulated concentrations by Sc_t = 0.3 and Sc_t = 0.7. Given the disagreements that are generally obtained between high-quality LES simulations and corresponding wind tunnel results, which can be much larger than a factor 2, the above-mentioned disagreements between RANS and experiments should be considered as acceptable.

The second study is near-field dispersion in the actual urban area of downtown Manhattan by Hanna et al. (2006). Figure 25 provides results of concentrations at pedestrian level at Madison Square Garden, obtained by two RANS k-ε models, one RANS non-linear eddy-viscosity model and an LES model with the Smagorinsky SGS model. While it is not clear whether the same colorbar range was used in every of these figures, the lack of which is attributed to security reasons, Hanna et al. (2006) do provide clear statements on the performance of the different models. They indicate that these tracer gas studies were not the main emphasis of the current paper, but that the results by the different models seem to agree quite well in that the tracer initially spreads a block or two upwind and laterally while it is still near street level, and then spreads downwind as a broad plume after mixing vertically to the building tops. Hanna et al. (2006) mention that their analysis of the time series of the modeled concentrations show the “hold up” of tracer material in the recirculating wake regions behind the buildings or in other areas with very low velocity. They state that the simulations by all applied models are qualitatively similar and that in fairly good agreement with the on-site observations at least concerning general patterns and flow magnitudes. Hanna et al. (2006) concluded that their preliminary CFD results show substantial promise for aiding in “increasing our understanding of wind flow and tracer dispersion in urban areas”.

6.3 Urban thermal environment

To the best of our knowledge no information is yet available in the publicly available literature that allows a clear comparison between RANS and LES for a study of the urban thermal environment. Therefore, the case study by RANS by Toparlar et al. (2015) is selected here. This study is conducted according to CFD best practice and allows conclusions on the potential of RANS CFD to be made.

The case study is the Bergpolder Zuid region in Rotterdam, located in the Noord district of the city (Fig. 26a). Figures 26b and c show the computational geometry and grid. The simulations are performed for five days during the July 2006 heat wave and the related meteorological input data are obtained from the Royal Dutch Meteorological Institute at the Rotterdam weather station. The 3D unsteady RANS equations were solved with the realizable k-ε turbulence model. Also conduction and radiation were modeled (see Toparlar et al. 2015 for details). The simulation results in

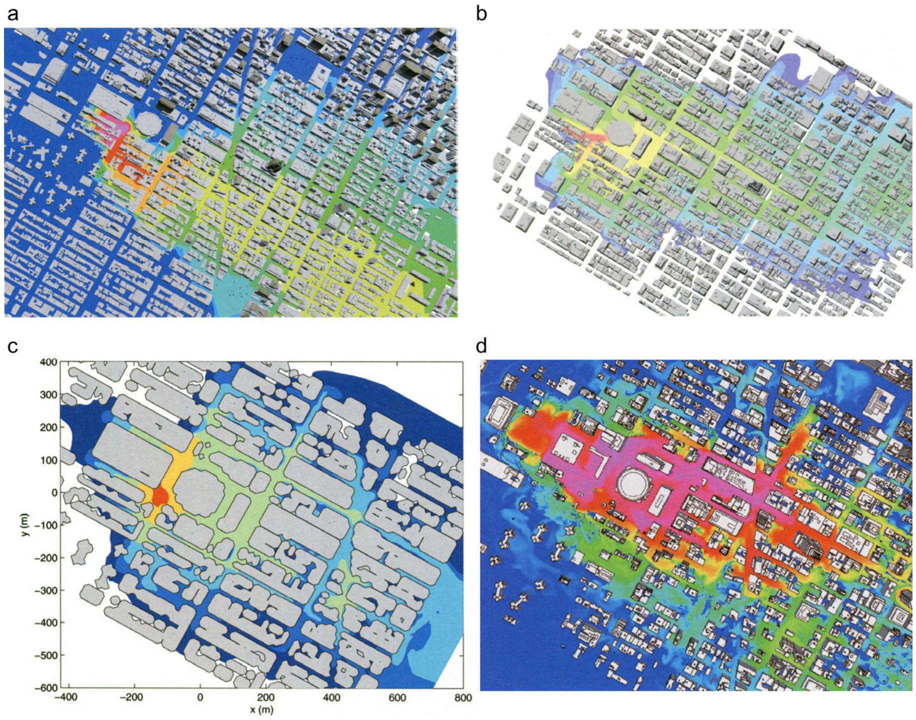

Fig. 25 Contours of simulated of tracer gas dispersion at pedestrian level for a point release near street level on the southwest side of Madison Square Garden, Manhattan, for WNW wind direction. This is one of the five source locations used during the MSG05 field experiment. (a,b) RANS k-ε; (c) RANS non-linear eddy viscosity model; (d) LES Smagorinsky-Lilly model (colorbar not provided in original article, but purple/red is high concentration, green to blue is low concentration) (Hanna et al. 2006; reproduced with permission ©American Meteorological Society (AMS))

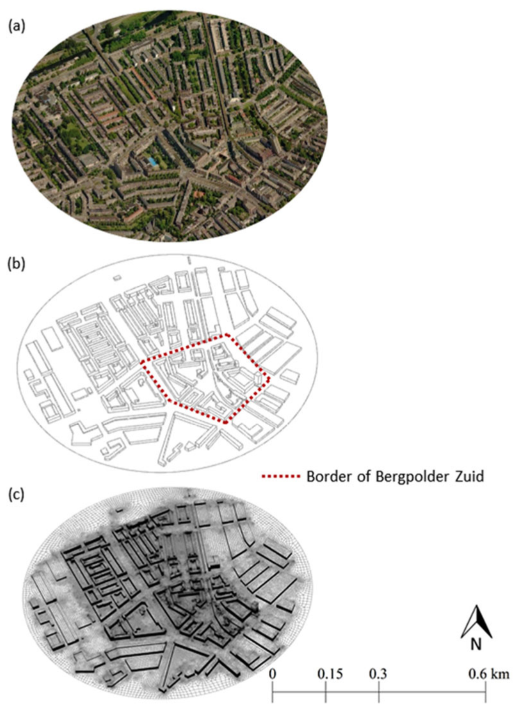

Fig. 26 (a) Aerial view of the Bergpolder region from south (source: Bing Maps); (b) corresponding computational geometry; (c) computational grid on the building surfaces and on part of the ground surface (6,610,456 cells) (Toparlar et al. 2015; reproduced with permission ©Elsevier)

terms of surface temperatures were compared with the experimental data by the NOAA-AVHHR satellite processed by Klok et al. (2012). Figure 27 shows a very good agreement, except during the hottest hours on day 4, which is likely to be attributed to the appearance of clouds that were not included in the CFD simulations. In general, the minimum, average and maximum deviations of surface temperature are 0.27% (19th of July, 18:38 h), 7.9% and 24.2% (16th of July, 8:13 h), respectively. The surface temperature amplitude is smaller in satellite imagery data than in the simulations. Overall, the agreement between the URANS simulations and the experiments is considered to be very good.

6.4 Natural ventilation of buildings

Most CFD research on natural ventilation focused on generic isolated buildings rather than on actual buildings or generic or actual building groups. Most of these studies were performed with the steady RANS approach and first-order closure. Some exceptions are the studies by Kato et al. (1992), Kurabuchi et al. (2000), Jiang and Chen (2002), Hu et al. (2005, 2008), Meroney (2009), Chu and Chiang (2013) and van Hooff et al. (2017), who used LES, and the studies by Wright and Hargreaves (2006) and Meroney (2009) who used Detached Eddy Simulation (DES).

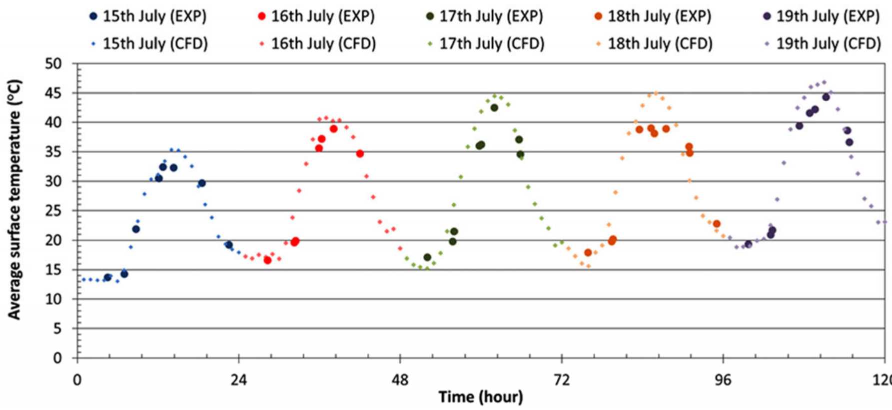

Fig. 27 Comparison of CFD simulation results and data from satellite images of average surface temperatures for five consecutive days (Toparlar et al. 2015; reproduced with permission ©Elsevier)

Jiang and Chen (2002) compared results from LES with the Smagorinsky SGS model with experimental data from Katayama et al. (1992), who performed on-site measurements and wind tunnel tests for both outdoor and indoor airflows on a building site (Figs. 8a–f). Jiang and Chen (2002) focused on the influence of wind direction fluctuations on the outdoor and indoor wind velocity patterns. This recognizes the fact that natural wind is indeed highly variable in both speed and direction, even though this situation cannot easily be generated in a wind tunnel. In a conventional wind tunnel as well as in a conventional RANS or LES CFD simulation, the inlet wind direction is fixed, i.e. stationary, which could introduce considerable errors. Jiang and Chen (2002) demonstrated that both the wind tunnel results and the LES results with fixed wind direction showed a deep, thin and high velocity core in the north room (upper room) of building A. On the other hand, the on-site measurements and the LES results with varied wind direction presented a shallower and wider high-speed region in both rooms, which was clearly more realistic. In both cases, a good agreement between LES and experiments was obtained.

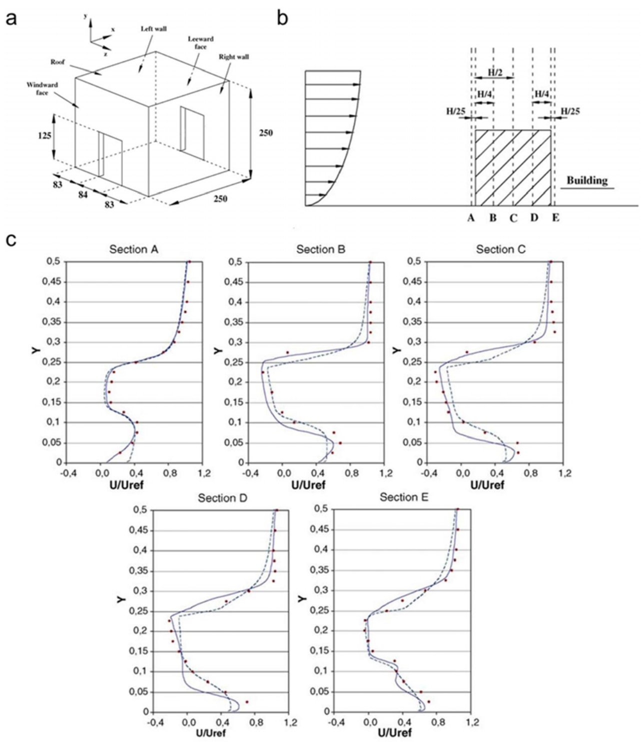

Fig. 28 (a) Building geometry with dimensions in mm (modified from Evola and Popov 2006); (b) sections A–E along which experimental and numerical results are compared; (c) vertical profiles of ratio of horizontal velocity component to reference wind speed: dots are wind tunnel results, solid lines are results from RNG k-ε model, dashed lines results from standard k-ε model. Dimensions on vertical axis in m (Evola and Popov 2006; reproduced with permission ©Elsevier)

Evola and Popov (2006) performed 3D steady RANS simulations with the standard and RNG k-ε model for the analysis of cross-ventilation of the isolated cubic building model previously studied by Jiang et al. (2003) (Fig. 28a), with the wind direction perpendicular to the ventilation openings. The comparison between CFD and wind tunnel mean velocity was performed along 5 vertical lines (Fig. 28b). Figure 28c shows that the RNG k-ε model outperformed the standard k-ε model at some locations while the opposite occurred at some other locations. However, comparing the ventilation rates by both RANS models with the LES results by Jiang et al. (2003), the deviation by the standard k-ε model and the RNG k-ε model was only 9% and 3%, respectively.

Meroney (2009) conducted an extensive turbulence model evaluation study for the generic isolated building that was experimentally analyzed by Karava et al. (2011) and Karava and Stathopoulos (2012). His study compared results from the steady RANS approach with the standard k-ε model, the realizable k-ε model, the RNG k-ε model, the standard k-ω model and the Reynolds Stress Model

(RSM), Detached-Eddy Simulation (DES) and Large-Eddy Simulation (LES). Meroney (2009) concluded that in spite of the clearly inherently transient nature of separation and reattachment, some of the steady RANS models showed a similar performance as the intrinsically superior LES or DES models.

Ramponi and Blocken (2012a,b) performed 3D steady RANS simulations for the same isolated building as studied by Karava et al. (2011), Karava and Stathopoulos (2012) and Meroney (2009) (Fig. 29a). The turbulence models included the standard k-ε model, the realizable k-ε model, the RNG k-ε model, the standard k-ω model, the SST k-ω model and the RSM. Also the impact of other computational parameters was investigated. The best agreement with the PIV wind tunnel measurements by Karava et al. (2011) was obtained by the SST k-ω model (Figs. 29b,c) followed by the RNG k-ε model. Apart from the area close to the ventilation openings,

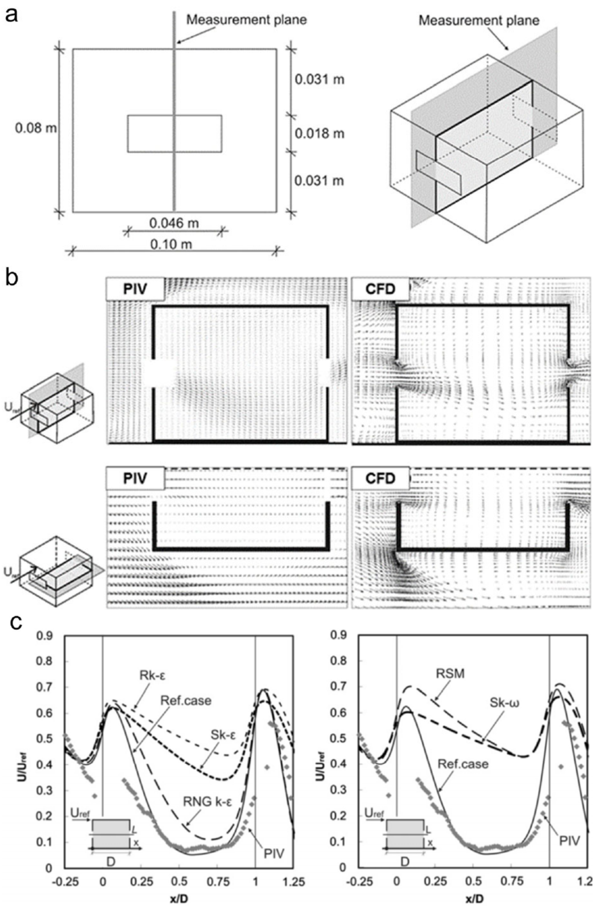

Fig. 29 (a) Building geometry and indication of vertical measurement plane; (b) comparison of PIV and CFD (SST k-ω) velocity vector fields in vertical centerplane and horizontal plane at mid-height through the openings; (c) comparison of streamwise mean wind speed ratio U/U_{ref} from PIV and RANS CFD with various turbulence models (note Ref.case = SST k-ω) along centerline through the openings (Ramponi and Blocken 2012a; reproduced with permission ©Elsevier)

where the accuracy of the PIV measurements suffered from reflections, the differences between measurements and simulations by the SST k-ω model are generally less than 20%, and less than 10% in the central part of the building.

The CFD study by van Hooff et al. (2017) based on the cross-ventilation wind tunnel experiments by Tominaga and Blocken (2015, 2016) indicated that the SST k-ω model, the RNG k-ε model and the RSM reproduced the experimentally observed direction of the incoming jet, but that all RANS models failed in reproducing the turbulent kinetic energy, which was too low especially above and below the jet. They attributed this to the fact that steady RANS does not capture the vertical flapping of the jet. Because LES does capture this transient feature (Fig. 30), this resulted in a better reproduction of all three measured parameters (mean velocity, turbulent kinetic energy, volume flow rate). Van Hooff et al. (2017) therefore concluded that the choice RANS vs. LES actually depends on which parameter is the target parameter, but that the use of LES entails an increase in computational demand with a factor of ≈80–100.

6.5 Indoor airflow

Many valuable studies on indoor airflow by either LES or RANS have been performed and these have contributed greatly to the present state of the art. A few selected studies that specifically focused on the performance of LES versus RANS are mentioned here.

Zhang et al. (2007) analyzed the capability of reproducing measured mean velocity, air temperature, Reynolds stresses and turbulent heat fluxes in a room by LES, DES and various RANS models: the indoor zero-equation model, three two-equation models (the RNG, low Reynolds k-ε number and k-ω SST models), the v^2-f model and a Reynolds-stress model (RSM). Four different cases were considered: natural convection in a tall cavity, forced convection in a model room with partitions, mixed convection in a square cavity, and strong buoyancy flow in a model fire room. They combined their results, including calculation time, in a clear overview table, reproduced here in Table 5, in which the performance of every approach/model to reproduce the experiments is given a label A to D, based on the relative error between prediction and measurement at measured points as a major criterion. If this value was less than 10% or more than 50% at most measured points, the rating A or D was given, respectively. Hence these labels point to the extremes. Label B was awarded to predictions with a relative error less than 20%–30% at most measured points, and rating C to the remaining predictions. Zhang et al. (2007) concluded that LES provided the most detailed flow features, while the computing time was much higher

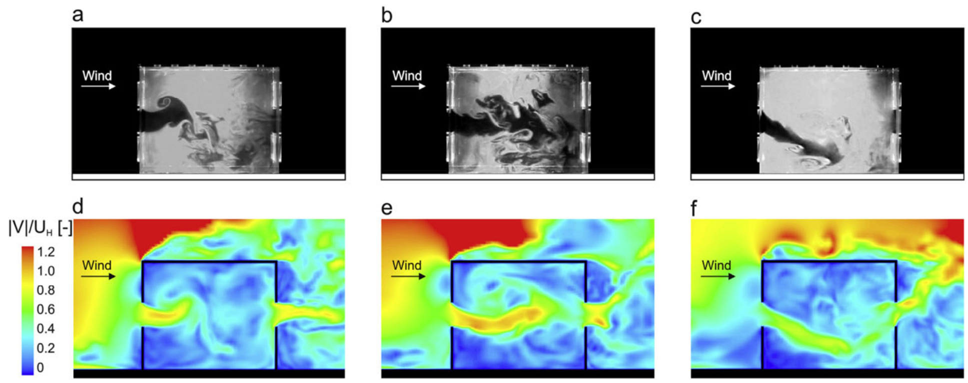

Fig. 30 Comparison of (a–c) instantaneous images from flow visualization (Tominaga and Blocken 2015) with (d–f) instantaneous images from LES simulation (van Hooff et al. 2017). The figures indicate the observation and prediction of jet flapping inside the enclosure. (a,d) Upwards directed jet (bended jet). (b,e) Horizontally directed jet with small downward bend after jet entry. (c,f) Downward directed jet (all figures: reproduced with permission ©Elsevier)

Table 5 Rated performance for the simulations for the four cases. A = good, B = acceptable, C = marginal, D = poor, n/a = not applicable, and n/c = not converged (Zhang et al. 2007)

Cases	Compared items	Turbulence models							
		0-eq.	RNG *k*-*ε*	SST *k*-*ω*	LRN-LS	v^2f-dav	RSM-IP	DES	LES
Natural convection	Mean temperature	B	A	A	C	A	A	C	A
	Mean velocity	D	B	A	B	A	B	D	B
	Turbulence	n/a	C	C	C	A	C	C	A
Forced convection	Mean velocity	C	A	C	A	A	B	C	A
	Turbulence	n/a	B	C	B	B	B	C	B
Mixed convection	Mean temperature	A	A	A	A	A	B	B	A
	Mean velocity	A	B	B	B	A	A	B	B
	Turbulence	n/a	A	D	B	A	A	B	B
Strong buoyancy flow	Mean temperature	A	A	A	A	A	n/c	n/a	B
	Mean velocity	B	A	A	A	A	n/c	n/a	A
	Turbulence	n/a	C	A	B	B	n/c	n/a	B
Computing time (unit)		1	2–4		4–8		10–20		10^2–10^3

than the RANS models and the accuracy may not always be the highest. Among the RANS models, the v^2f-dav and RNG *k*-*ε* models showed the best overall performance compared to the other models in terms of accuracy, computational efficiency and robustness. They recommended both models for indoor airflow simulations.

In a later study, Wang and Chen (2009) focused on reproducing specifically transitional flow regimes in an enclosure for three cases with gradually added flow features; jet, separations and thermal plumes. For these cases they analyzed the performance of the same models as Zhang et al. (2007). A test room of 2.44 m × 2.44 m × 2.44 m was used for this investigation with a linear (slot) diffuser located in the left wall near the ceiling along the whole width of the room and an exhaust slot along the whole width near the floor on the right wall. The slot Reynolds number was about 2,600 indicative of transitional flow. For these three cases and for the transitional flow, Wang and Chen (2009) again provided a clear overview table (Table 6) with ratings and concluded that some RANS models were good for the simple but not for the complicated flows, while LES was most accurate and stable.

7 Discussion, conclusions and perspectives

LES undeniably has the potential to provide more accurate and more reliable results than simulations based on the RANS approach. However, LES entails a higher simulation complexity and a much higher computational cost. In spite of some claims made in the past decades that LES would render RANS obsolete, RANS remains widely used in both research and engineering practice. This paper attempted to

Table 6 Rated performance for the simulations for the three cases (Wang and Chen 2009)

Cases	Item	Turbulence models							
		0-eq	LRN	RNG	SST	v^2f	RSM	LES-DSL	DES-SA
1	*U*	B	A	A	A	C	A	B	B
	TKE	N/A	A	A	C	B	A	B	B
2	*U*	A	B	B	C	A	A	A	B
	TKE	N/A	C	B	B	B	B	A	B
3	*U*	D	D	B	C	A	B	A	A
	TKE	N/A	C	B	B	B	B	A	B
	T	C	C	A	A	A	A	A	B
Overall grade		2.5	2.6	3.4	2.9	3.3	3.6	3.7	3.1

U: mean air veloccity, TKE: turbulence kinetic energy, *T*: mean air temperature.
A: good (4.0), B: acceptable (3.0), C: marginal (2.0), and D: unacceptable (1.0).

answer the questions why this is the case and whether this is justified, from the viewpoint of building simulation, for both outdoor and indoor applications. The answer to this and other questions is given in the following subsections.

7.1 Potential accuracy

LES is at least potentially more accurate and reliable than RANS because it resolves more of the flow. However, because of the higher simulation complexity it is easier to ruin a LES than a RANS simulation. As Hanna (1989) stated “as the model formulation increases in complexity, the likelihood of degrading the model’s performance due to input data and model parameter uncertainty increases as well.” LES, for example, requires much more care for grid generation, certainly for complex geometries and even more when the grid size is used as the filter.

Concerning building simulation for outdoor applications, also the atmospheric inflow boundary conditions and rough wall boundary conditions are much more challenging in LES. Several related pertinent statements were made. Ferziger (1990) stated that RANS models have the benefit of longer history while experience in LES is limited. Shah and Ferziger (1997) stated that just the simple fact that one is using LES does not guarantee success, as LES can yield results that are both qualitatively and quantitatively incorrect. Hanjalic (2005) stated that “conventional LES on a too-coarse grid of wall bounded flows, especially in attached flows regions, can be very erroneous and inferior to even simple conventional RANS.” Although these views were expressed quite a long time ago, all of them are still equally valid today.

Sørensen and Nielsen (2003) and Nielsen (2015) confirmed that LES could provide a direct prediction of the turbulence intensity but that for fully developed flow, the prediction accuracy of the average flow variables was not improved, while LES could provide advantages for non-fully developed turbulent flow. Chen (2009) concluded that RANS models could perform well for one flow but poorly in another but that LES could yield good results at sufficiently high grid resolutions. He correctly documented that LES is more popular for predicting particle distributions in ventilated spaces, because in this case more detailed information on the turbulent nature of the flow is required.

The problems of potentially inaccurate and unreliable LES simulations are co-determined or even aggravated by the lack of best practice guidelines (BPG) for LES, both for outdoor and indoor applications. And the fact that establishing such guidelines, in spite of the ever increasing computational power, is likely to take quite a lot longer for LES than RANS, given the much higher computational requirements for LES. So RANS models will keep having the benefit of more experience compared to LES for a long time – and it is not even certain that this will ever change.

7.2 Computational requirements

Even if LES would be performed according to best practice, still, the computational requirements remain much higher than for RANS. Concerning building simulation for outdoor applications, two groups of statements can be found in the literature, as clear from the overview of previous review and position papers in Section 4. The first group concerns positive statements that focus on the expectation that the rapid increase in computational resources would make LES more amenable for practical engineering problems. The second group of statements stresses the very large computational requirements by LES without expressing such positive expectation. Interestingly, these two different groups are not associated with clearly different periods in time.

In the first group, Ferziger (1990) considered LES too expensive to be a design tool. With the high grid requirements in mind, he stated “If it turns out that LES can be done on very coarse grids, it will be one of the few times that nature has been kind to us with regard to turbulent flows". Shah and Ferziger (1997) indicated that the LES simulations they were presenting were expensive, and therefore, if high-quality results were required, it would not be possible at present to use LES as a design tool. Hanjalic (2005) provided the rather uncommonly expressed view that "the further increase in the computing power will be used more to utilize advanced RANS models to shorten the design and marketing cycle rather than to yield the way to LES." Yoshie et al. (2007), focusing on PLW conditions, mentioned that the use of LES would require a dramatic increase in computational speed and that for now "we must be content with RANS type models currently in use."

In the second group, Leschziner (1993) expected there would likely be a continuous shift of focus towards LES. Murakami (1997) indicated that the rapid evolution of CPU hardware was expected to overcome the restriction of large CPU time, enabling wide application of LES to wind engineering problems in the near future. Rodi (1997) expected that "with the recent advances in computing power LES will soon be ready and feasible for practical applications."

As often in discussions between two prominent groups about complicated topics, these is some truth in both. Some of the above-cited authors, but not all, distinguish between research and design. Another distinction is that between the different application areas. While in research, indeed, the increasing computational resources have incited more focus on LES including applications, this is hardly the case in design. There are undoubtedly some exceptions but the vast majority of design and consultancy companies, when dealing with outdoor applications, resort to RANS simulation or to wind tunnel testing. Or both, but not to LES. At this moment, there are no clear indications that this is going to change drastically in the near future. Even for an application area such as wind pressures on building surfaces where peaks are important and for which RANS is generally considered not an option, LES is still very far from becoming standard practice in consultancy and design.

Concerning building simulation for indoor applications, Chen (1997) and Chen and Srebric (2001) correctly indicated that until that time, LES had rarely been applied for actual engineering problems because of the need to extensive computational power and the need for further development. In view of the increased computational power in the future, Sørensen and Nielsen (2003) stated LES would most likely become a useful and practicable tool for room airflow simulations in the future, but at the time they recommended using RANS turbulence models for practical purposes. Zhai et al. (2007) expressed a stronger interest in RANS simulations because of quick predictions rather than the more detailed but also more time-consuming LES simulations that were more considered as research than a design tool. Lately, Nielsen (2015) expressed his expectation that the increasing computational resources would expand the use of LES in the future.

7.3 Required accuracy

A criterion rather entangled with the two foregoing criteria is the required accuracy. Concerning building simulation for outdoor applications, Ferziger (1990) stated that the principal task of the wind engineer—by which he undoubtedly meant designer or consultant, not researcher—is to find a method that produces accurate values of the essential quantities at low cost. As a result, the method to be used may depend both on the required accuracy and on the problem. Indeed, for many practical applications, the accuracy presented by RANS—when applied according to best practice—can be considered as sufficient. It was demonstrated in Section 5 that this can be the case for PLW comfort where the areas of high wind speed are indeed of most importance, for near-field dispersion in urban areas with high plan area density, where the pollutant dispersion is largely governed by channeling in the narrow streets, for urban thermal environment at least when focusing on surface temperatures averaged over a sufficiently large area, and for building cross-ventilation (as single-sided ventilation is a much more challenging case). This view that RANS could provide "sufficiently accurate" results was also implicitly expressed by Leschziner (1993) stating that for industrial applications in general, RANS methods would continue to play the main role for some years to come and by Murakami (1997), indicating that RANS turbulence model selection should be based on the criteria of prediction accuracy (and CPU time) required. Hanjalic (2005) also confirmed the important role of RANS "especially in industrial and environmental computations". Gosman (1999), Yoshie et al. (2007) and Baker (2007) also referred to PLW comfort assessment as a suitable CFD (RANS) application.

Concerning building simulation for indoor applications, Chen (1997) found that the predictions of first-order parameters such as mean velocities and temperatures by RANS CFD were more accurate than those of second-order parameters such as turbulence intensities. Zhai et al. (2007) indicated that for the design and study of air distributions in enclosed environments, the mean air parameters were generally more useful than the instantaneous turbulent flow parameters which justified the stronger interest in RANS simulations. Nielsen (2015) indicated the superior performance of LES for non-fully developed turbulent flow.

7.4 The numerical wind tunnel

Although the analogy of the "numerical wind tunnel" appeals to the imagination, CFD experts in building simulation for the outdoor environment have consistently denounced this label, either explicitly or implicitly. Leschziner (1993) stated that CFD for general turbulent flow is unlikely ever to evolve to a "computational wind tunnel". He argued that wind tunnels are here to stay for many years to come and would continue to be the main vehicle for investigating realistic building design concepts. The clear view of Stathopoulos (1997) was that it is unlikely that CFD for general turbulent flow would become a "computational wind tunnel", at least not in the foreseeable future, and that rather CFD and experiments should complement each other. These views were further addressed in a follow-up paper (Stathopoulos 2002). Also Castro and Graham (1999) denounced the concept of the "numerical wind tunnel" in the design process, for example for the assessment of wind loads and pollutant dispersion. The same was done by Blocken (2014) in a more recent review paper. Indeed, while strictly atmospheric boundary layer wind tunnel testing could do without CFD, the opposite does not hold true, as validation remains needed. Also concerning CFD for the indoor environment, Li and Nielsen (2011) indicated that in spite of the continuously increasing capabilities for CFD simulations, "CFD has not become a replacement for experiment and theoretical analysis in ventilation research, rather it has become an increasingly important partner."

7.5 The hybrid approach: experiments—CFD

While it is well-known that CFD needs experiments for validation, the benefits of CFD for experimental testing might be less well-known. Nevertheless, this view was already present in the community since the very beginning.

Concerning building simulation for outdoor applications, in the 1970s, Deardorff advocated the combination of LES with laboratory (water tank) experiments and field measurements because of the large potential synergy of these three approaches. Murakami (1990a) stressed the synergy between CFD and experiments. He expected that the increasing precision of CFD predictions would also give rise to new research in experimental methods. Stathopoulos (1997) advocated using CFD and experiments to complement each other, for example for reducing costs in the design process. When Murakami et al. (1999) published an impressive range of practical applications in CFD from human scale to urban scale, they mentioned that they compared their CFD results with measurements whenever available. This statement referred to their very important point that in some cases, measurement data cannot be obtained or will be very difficult to obtain. In such cases, Murakami correctly argued that "we do think that the comprehensive assessment based on the CFD method combining various factors seems to be the only approach for clarifying such complicated phenomena." Indeed, a true synergy does not entail that both approaches are always equally important, but that, depending on the situation or application, one approach will be more applicable and hence leading, while the other one will provide support from the background. An example where CFD is more applicable and leading is the study of the urban heat island effect (Murakami et al. 1999), or, returning to the very origin of LES, numerical weather prediction as defined by Richardson (1922) and applied intensively and successfully up to the present day. Blocken (2014) listed some other applications where wind tunnel experiments would be very difficult or even impossible and where CFD could be used, such as natural ventilation through relatively small openings, where scaling down could change the nature of the flow in these openings from turbulent to laminar, wind flow and related processes in atmospheric boundary layers with stable and unstable stratification, multiphase flow problems such as the transport and deposition of sand, dust, rain, hail and snow, and meteorological phenomena such as tornadoes and downbursts. Meroney (2004) provided a compelling set of arguments for the hybrid approach between wind tunnel and CFD for pollution dispersion. In 2016, in the same hybrid framework, Meroney (2016) recalled the often asked question "When can we get rid of our physical modeling facilities?" He correctly stated that this question ignored the tremendous potential synergy of CFD and EFD both in research and design, as it can "expedite results, improve understanding of flow phenomena, and often reduce research costs and time." The same critical point was convincingly outlined by Tominaga and Stathopoulos (2016).

Concerning building simulation for indoor applications, Li and Nielsen (2011) compellingly argued that CFD had become a partner for experiment and theoretical analysis in ventilation research. They believed that "an effective scientific approach for ventilation studies is still to combine experiments, theory, and CFD."

In conclusion of this subsection, I provide this quote by Murakami (1990a) from the section of his paper where he focuses on the prediction of time-dependent flowfields by LES and visual animations of these results:

"Time-dependent flowfields given by LES and the techniques of visual animation based on them are very useful tools in turbulent flow analysis concerned with wind engineering and provide information hardly given by experimental techniques." This quote provided by one of the pioneers in the field provides a much better, more constructive and more appropriate view of the field of CFD—at least when applied according to best practice as done by many of us—than the rather tiresome and washed-out claims of non-CFD practitioners that CFD would stand for "Cheats, Frauds and Deceivers", or for other often-heard three-word combinations

that I do not wish to repeat here. This quote correctly indicates that in some cases, in terms of gaining understanding of the flow physics, there is no better way than high-quality LES and its visual animation. While techniques such as Particle Image Velocimetry (PIV) claim to have similar capabilities, the costs of time-resolved stereo PIV are much higher than those of LES, the time expense at least equally high and probably much higher, and for urban applications the views will easily be obstructed by laser-light shielding by the obstacles constituting the urban model.

7.6 No applications without basics

Although this should be self-evident, many submissions of papers to international journals, many presentations at conferences but also many consultancy CFD simulations and reports still display a major lack of basic understanding of fluid mechanics and numerical techniques, let alone knowledge of the CFD literature and the best practice guidelines in the field. This problem was apparently already present in the early 1990s, as authors explicitly mentioned and warned for these situations. Leschziner (1993) stated that first and foremost, it is essential for a CFD user to possess considerable expertise, physical insight and experience, both to obtain meaningful solutions and to be able to appreciate the associated limitations. Stathopoulos (1997) expressed his grave concern that "there are serious dangers inherent in the way that CFD is being increasingly used in industry often by people having little or no understanding of fluid dynamics or computational techniques." And that "most practitioners are more concerned with obtaining results than with either the order of accuracy of their numerical schemes or the need to refine the grid until converged grid-independent solutions are obtained." In line with Stathopoulos (1997), Castro and Graham (1999) pointed to the significant dangers of using CFD without a sound understanding of the fluid mechanics of the problem under study, without awareness of the validation of the code for similar problems and a clear understanding of the sources of errors and uncertainties and the levels of accuracy required. In addition, Meroney (2004) also stressed the very strong need for a critical attitude towards all CFD but also wind tunnel results with the vivid quote: "Good mental health in a fluid or CFD modeler is always indicated by the presence of a suspicious nature, cynicism and a 'show me' attitude. These are not necessarily the best traits for a life mate or a best friend, but they are essential if the integrity of the modeling process is to be maintained." The same critical concerns were expressed very clearly and repeatedly in the indoor airflow community. Chen (1997) and Chen and Srebric (2001) stressed the importance that CFD users should have a good knowledge of turbulent flows and numerical techniques to perform correct simulations.

7.7 User-friendly is good, but not too user-friendly

Regrettably progress in a field often raises new problems. Progress refers to – as stated by Gosman (1999) – the improvement of CFD codes in terms of versatility, ease of use and speed, which helps accelerating the uptake of this technology by industrial users. However, Gosman also correctly added that this should not occur "without the required level of knowledge of flow physics to properly interpret and exploit the results." Unfortunately, that is exactly what is occurring in many occasions these days, and this points directly to the problem in subsection 7.6. All the valid statements in subsection 7.6 constitute a warning against using CFD as a "black box". Nevertheless, several commercial software developers, not expert in CFD, have recently engaged in extending their design software with a so-called "very user-friendly" CFD module that can be "used" by even non-experienced CFD users. In other words: by users without the required level of knowledge of fluid mechanics and numerical techniques, the CFD literature in the field and the BPG documents. Other CFD software developers have made their code freely available however without a proper manual that provides insight on the numerical techniques embedded in it. This very practice shows that the alarming statements made 20 of 30 years ago (see subsection 7.6) are probably even more pertinent today than they were at that time.

7.8 Back to key question: why has LES not made RANS obsolete?

The key question in this paper was why LES has not rendered RANS obsolete as RANS remains widely used in both research and engineering practice and whether this is justified. The answers have been provided above: although LES is intrinsically superior, it entails a higher simulation complexity and a much larger computational cost, and because of that and the lack of BPG it can even yield results that are less accurate and less reliable that those by RANS. In addition, for several practical applications, it has been shown that RANS results can be sufficiently accurate. Paraphrasing the late prof. Joel H. Ferziger: "It turns out that in terms of practical applications in building simulation, there are quite a few application areas where nature is kind to us with regard to turbulent flows". Furthermore, switching from RANS to LES will not bring the fantasy of the "numerical wind tunnel" any closer to reality. Validation with wind tunnel or field experiments remains imperative.

Nevertheless, indeed, LES is intrinsically superior, and this is the reason why in research environments, the past decades have seen a gradually larger focus on LES. However, in design and consultancy, such a systematic shift in focus has not been observed. Even in research, RANS remains very popular for application areas such as PLW wind comfort, near-field pollutant dispersion in urban areas with high plan area density, urban thermal environment, natural ventilation of buildings and indoor airflow. The very many examples of RANS case studies that have appeared in the scientific literature in the past 20 years versus only relatively few by LES demonstrate that in many aspects of building simulation for outdoor and indoor applications, researchers and practicing engineers have employed the increasingly available computational power to perform RANS simulations for larger and more complex problems, rather than to make the switch from RANS to LES for less extensive problems.

Acknowledgements

"Cum omnibus virtutibus me adfectum esse cupio, tum nihil est quod malim quam me et esse gratum et videri. Haec enim est una virtus non solum maxima sed etiam mater virtutum omnium reliquarum" [1]

The author expresses his large appreciation to the many pioneers in Building Simulation, both for outdoor and indoor applications, who have built this field to the very successful research and engineering arena it is today, with worldwide networks, journals, conferences, projects and other activities. While only few of them could be cited in this incomplete paper, certainly all are implicitly included in this paragraph of this acknowledgment.

The author is greatly indebted to his four mentors in Building Physics and Building Simulation, in alphabetical order of last name: Prof. dr. ir. Jan Carmeliet, previously full professor at KU Leuven in Leuven, Flanders, Belgium and now Chair of Building Physics at ETH Zurich, Switzerland, Prof. dr. ir. Hugo Hens, emeritus full professor at KU Leuven, Leuven, Flanders, Belgium, Prof. dr. ir. Jan Hensen, full professor at Eindhoven University of Technology in Eindhoven, the Netherlands and Prof. dr. Ted Stathopoulos, full professor at Concordia University in Montreal, Canada. The author is also deeply indebted to his mentor in Applied Physics/Fluid Mechanics, Prof. dr. ir. GertJan van Heijst, full professor at the Department of Applied Physics at Eindhoven University of Technology.

The author is most grateful to Prof. dr. Xudong Yang, Editor-in-Chief of Building Simulation. The journal was inaugurated in 2008. The author was invited to join the editorial board in 2014. This special volume of the journal celebrates the 10-year anniversary of this journal. It takes a lot of patience, persistence, dedication and determination to start up a new journal and one could have wondered whether there was a need for yet another journal in the field of building engineering. The current success of this journal and the many excellent papers published in it show that the Editor-in-Chief and the publisher were very right to establish and consolidate this journal. In the past 10 years, Prof. Yang has made the journal what it is today: an indispensable and excellent key medium to disseminate the latest and most important findings in the wide field of building simulation that is respected and appreciated by all colleagues working in the field.

The author thanks the anonymous reviewers for their very valuable and constructive comments that have improved this paper.

"Αρχή πολιτείας απάσης νέων τροφά" [2]

The author expresses his gratitude to the senior researchers, PhD students and MSc students in his group in Urban Physics, Wind Engineering and Sports Aerodynamics at Eindhoven University of Technology in the Netherlands and at KU Leuven in Flanders, Belgium. The most rewarding and most enjoyable aspect of the job is the opportunity to work with and educate excellent young individuals. Special thanks therefore go to current senior researchers dr.ir. Twan van Hooff, dr.ir. Hamid Montazeri, dr. Alessio Ricci and dr. Yigit Can Altan. Special thanks also go to the PhD students Adelya Khayrullina, Katarina Kosutova, Raffaele Vasaturo, Samy Iousef, Fabio Malizia, Feiyu Geng, Olga Palusci, Antoniou Nestoras, Rahim Rezaeiha, Andreas Pfahl, Zhiyun Wang, Jo-Hendrik Thysen, Anto Moediartianto, Giacomo Alessi, Thijs van Druenen, Xing Zheng, Gerson Fernandes, Paul Mannion, Lili Xia, Yu-Hsuan Juan and Mutmainnah Sudirman. The same warm acknowledgment is given to PDEng students Rob Vervoort, Claudio Alanis Ruiz and Marlies Verbruggen. And to all previous postdocs and PhD students in the team.

Elsevier is acknowledged for the permission to reproduce a large number of figures from previous publications. The American Meteorological Society is acknowledged for the permission to reproduce a few figures from previous publications. We thank Peter Nielsen for the permission to reproduce some figures from his pioneering PhD thesis

[1] "*While I wish to be adorned with every virtue, yet there is nothing which I can esteem more highly than being and appearing grateful. For this one virtue is not only the greatest, but is also the mother of all the other virtues*". Source: Pro Plancio. Rome, 54 BC. Marcus Tullius Cicero (106 BC – 43 BC), Roman philosopher, politician, lawyer, orator, political theorist, consul and constitutionalist.

[2] "*The base of every state is the education of the youth*". Pythagoras of Samos (c. 570 BC – c. 495 BC), Greek philosopher and mathematician.

(Figs. 9a–b). We thank the Belgian artist François Schuiten for the permission to reproduce his drawing of the Forecast Factory (Fig. 3).

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