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INVITED REVIEW

Tackling complex turbulent flows with transient RANS

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Abstract

This article reviews some recent applications of the transient-Reynolds-averaged Navier–Stokes (T-RANS) approach in simulating complex turbulent flows dominated by externally imposed body forces, primarily by thermal buoyancy and the Lorentz force. The T-RANS aims at numerical resolving unsteady (semi-) deterministic vortical structures in flows with sufficiently strong internal forcing. With a well-tested RANS model to account for the unresolved ‘subscale’ motion, the T-RANS is considered as a tool for solving large-scale high Rayleigh and Reynolds numbers, which are inaccessible to the conventional large-eddy simulation (LES) or any other numerical simulation approach. First, a brief outline of the T-RANS rationale is presented and its potential illustrated in the simulation of Rayleigh–Bénard convection in an infinite domain for over a ten-decade range of Rayleigh numbers (10^6 – 2×10^{16}). The accurate prediction of heat transfer over a wide range of Rayleigh numbers provided sufficient credibility in the approach and its application to a variety of real-life flows dominated by body forces. This is illustrated by three examples of complex environmental and multi-physics phenomena: dynamics of a fuel-oil cooling inside a sunken tanker wreck, diurnal variations of air-movement and pollutant spreading over a mesoscale mountain city in a valley capped by a thermal inversion layer, and finally in the generation and self-sustenance of a magnetic field by a highly turbulent helical sodium movement. The simulated results agree well with the experimental data where available.

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1. Introduction

Despite the remarkable developments in direct numerical simulation (DNS) and large-eddy simulations (LES) over the past two decades, the classic Reynolds-averaged Navier–Stokes (RANS) method based on single-point turbulence closures remains the most widely used approach for the computation of complex industrial and environmental flows. In fact, for many real-life problems, as illustrated in this review, the RANS is the only viable option and it is likely to remain so for some time to come (see e.g. [Hanjalić 2005b](#)). However, the RANS approach has a number of known shortcomings, the major ones originating from its fundamental premise—the Reynolds decomposition and averaging of the governing transport equations. Thus, the conventional RANS provides only the time-, phase- or ensemble-averaged quantities, so that all information about the dynamics of turbulence structures are missing. While the spectral dynamics *per se* may not be of primary concern in industrial and environmental computations, the inability to return any information on structural dynamics can have serious drawbacks especially in flows dominated or governed by strong semi-deterministic vortical structures or other large coherent eddy formations. Such structures are usually created by large-scale instabilities caused by boundary conditions (i.e. vortex shedding behind bluff bodies) or by externally imposed or internally generated body forces (thermal or concentration buoyancy, rotation, electromagnetic fields, etc.). As a result, periodic or other unsteadiness of the flow as a whole or unsteady convection rolls and cells and other large-scale structures appear despite steady boundary and inflow conditions. It has long been recognized that such large, well-organized structures, which often have a (semi-) deterministic character, are the main carriers of momentum, heat and species so that their proper capturing is an important prerequisite for accurate predictions of turbulent transport phenomena. The complex dynamics of spatial and temporal structure reorganization, observed in many complex flows dominated by body forces, illustrate best why it is so difficult to derive a general turbulence model that will recover major turbulence features lost in the course of averaging, i.e. to design a mathematical model that will accurately account for all structural features and their effects on mean properties of interest for industrial and environmental computations.

The LES approach naturally accounts for the dynamics of large-scale eddies. The problem is that for accurate predictions of the wall-heat transfer and friction it is necessary to fully resolve the near-wall fine-scale streaky structures, what requires very fine numerical grid in all three coordinate directions (almost a DNS resolution), making such simulation very expensive and usually limited to relatively low values of Reynolds (forced convection) and Rayleigh (natural convection) numbers.

In pursuit of improvements in computational modelling, over the past decade there has been significant activities aimed at accounting for flow unsteadiness and large-scale vortical structures in complex flows. One line of development focuses on merging RANS and LES into a hybrid techniques ([Batten *et al* 2004](#), [Befeno and Schiestel 2007](#), [Davidson and Peng 2003](#), [De Langhe *et al* 2006](#), [Germano 2004](#), [Grinstein and Karniadakis 2002](#), [Hamba 2003](#), [Hanjalić 2005a, b](#), [Jouvray and Tucker 2005](#), [Keating 2006](#), [Kenjereš and Hanjalić 2006b](#), [Labourasse and Sagaut 2002](#), [Speziale 1998](#), [Temmerman *et al* 2005](#), [Tessicini *et al* 2006](#)). The goal is to combine the best features of both techniques in an integrated simulation approach. Since the aim is to relax the needs for a very fine mesh close to a solid wall, most efforts on RANS and LES hybridization have been directed towards using a unsteady RANS (U-RANS) in the near-wall region, while retaining the conventional LES in the bulk of the flow domain. Such *zonal* models still face the challenge of matching the two sets of different equations (Reynolds averaged in RANS and filtered in LES) at the interface of the RANS

and LES regions, which has to be defined explicitly or implicitly by some arbitrary control parameters, usually expressed in terms of the grid-cell size and a characteristic turbulence scale (Hanjalić 2005b). The grid requirement remains, however, still high, since the grid rationing is only achieved by relaxing the grid density in the streamwise and spanwise direction in the near-wall region.

Another approach that has recently gained in popularity follows the unsteady RANS rationale, but with modification of the RANS model in order to sensitize it to instabilities and thus to make it possible to capture some dynamics of large-scale vortical structures. This is done usually by decreasing the eddy viscosity (Girimaji 2006 and others, Schiestel and Dejoan 2005, Temmerman *et al* 2005). In such approaches, the true LES (or DNS) is regarded as the far-from-a-wall asymptote, usually not achieved anywhere in the flow. The advantage of such continuous ('seamless') methods (Hanjalić 2005b) is that no pre-specification of any interface is required, though in some approaches, where LES is eventually recovered far away from a solid wall, an implicit interface does appear. These methods also require a 'grid-detecting' parameter and empirical coefficient(s), which need to be tuned with reference to some known solutions from experiments, LES or DNS. An early version of such an approach is the semi-deterministic method (SDM) of Ha Minh (1993) and Ha Minh and Kourta (1994), who proposed to reduce the eddy viscosity simply by reducing the coefficient in the eddy-viscosity expression (e.g. C_μ from the conventional 0.09–0.06). This intervention made the RANS model more sensible to stronger internal instabilities, which in turn made it possible to capture unsteadiness and semi-deterministic structures in mildly separating flows for which conventional URANS would always return steady solutions. In order to interpret unsteady results, the instantaneous flow variables are decomposed into three parts: the time mean, semi-deterministic (coherent) and stochastic (turbulence) contributions. If interactions between the three scales of motion are neglected (assumed wide-scale separations), statistical moments will have three components: the mean (long-term averaged), large-scale coherent (semi-deterministic) structures and a stochastic contribution. The conventional RANS model should be here directly responsible only for the last (stochastic) part. The semi-deterministic contributions can be relatively easily captured by the numerical mesh and by using appropriate time steps. Then, these two contributions are added and compared with experimental and/or DNS data. In order to demonstrate the potential of such an approach, Ha Minh (1993) and Ha Minh and Kourta (1994) studied a two-dimensional back-step flow for which they succeeded in obtaining unsteady solutions in contrast to the conventional URANS which generate too strong turbulent viscosity that suppresses entirely all flow instabilities. The sum of the modelled and deterministic contributions returned improved turbulence moments and wall friction.

While all the above-mentioned (and other) hybrid RANS/LES and instability-sensitized RANS methods demonstrate a potential to reproduce internal unsteadiness and some spectral features of turbulence, their common shortcoming is in the inevitable introduction of new empirical parameters and functions that had to be tuned for specific flows considered (e.g. Hanjalić 2005b, Temmerman *et al* 2005). We argued, however, that for some flows with strong internal forcing, instabilities and large-scale structures can be reproduced with an adequate RANS model without any specific interventions on the model, provided, of course that computations are performed in time and in all three dimensions, (Hanjalić and Kenjereš 2001a,b, Kenjereš 1998, Kenjereš and Hanjalić 1999, 2000b, 2002a). Some prerequisites on the RANS model chosen are, however, warranted: the model should preferably be of a second-moment type (differential or algebraic), which are *per se* less dissipative than the eddy-viscosity models, and reproduce better turbulence anisotropy which plays an important role in the growth of instabilities. Moreover, because only large-scale semi-deterministic

structures are expected to be resolved, the model of the remaining (here termed ‘subscale’) motion is still expected to make a large (and close to a solid wall the major) contribution. Such an approach we call Transient RANS (T-RANS) rather than URANS to indicate that although we do not make any specific sensitizing modifications to the RANS, we do mean a specific RANS model that we developed and tested, which satisfies the above prerequisites. The RANS model remains, however, of the conventional type: when applied to steady computations, or unsteady but only in two dimensions, in flows even with a strong internal forcing, it returns usually the standard steady RANS solutions. This was clearly demonstrated in the numerical computation of the classical Rayleigh–Bénard convection—typical representative for turbulent thermal convection, where the initial temperature gradient and gravitational vectors are aligned but of the opposite sign, thus creating an unstable density stratification. Two-dimensional unsteady computations always produced steady solutions, whereas three-dimensional runs returned always unsteady dynamics of the convective roll-structures (Hanjalić and Kenjereš 2001a, Kenjereš and Hanjalić 2000b). Yet in both cases the heat transfer (in terms of Nusselt–Rayleigh number correlation for a large range of Ra numbers) were in good agreement both among themselves and with the available DNS (for low Ras) and experiments (for high Ras). Note that in this particular case, an algebraic version of the RANS model for the subscale turbulence contributions was applied with the ‘standard’ sets of the model functions and coefficients, tuned and validated in a range of buoyancy-driven flow test configurations. In the unsteady three-dimensional computations, the total second moments obtained by adding the semi-deterministic and stochastic (modelled) contributions gave excellent agreement with the DNS results, where available. In addition, the spatial and temporal dynamics of the coherent structures were well captured too. By using vortical-structure identification techniques based on the characteristic equation of the velocity gradient tensor, it was shown that T-RANS properly captured the largest structures whereas the smaller ones were filtered out. Good agreement with the available DNS, LES and experimental data for this and some other test cases, provided sufficient credibility in T-RANS as a suitable approach for modelling complex real-life flows dominated by body forces.

In the following paragraphs, we outline briefly the T-RANS rationale (for more details see (Hanjalić 2002, Hanjalić and Kenjereš 2001b, 2002, Kenjereš and Hanjalić 1999) and present results of the T-RANS application to three interesting examples of flows, two encountered in environmental engineering and the third dealing with an actual fundamental issue in physics research.

2. Mathematical framework

The governing fluid momentum, temperature, concentration and magnetic induction equations that fully describe fluid flow, heat- and species transfer, accounting for electromagnetic interactions can be written as

$$\begin{aligned} \frac{\partial \hat{U}_i}{\partial t} = \frac{\partial}{\partial x_j} \left[v \left(\frac{\partial \hat{U}_i}{\partial x_j} + \frac{\partial \hat{U}_j}{\partial x_i} \right) - \hat{U}_i \hat{U}_j \right] - \frac{1}{\rho} \frac{\partial \hat{p}}{\partial x_i} \\ - \underbrace{\beta g_i \left(\hat{T} - T_{\text{Ref}} \right) + \frac{1}{\rho \mu_0} \left(\hat{B}_j \frac{\partial \hat{B}_i}{\partial x_j} - \hat{B}_j \frac{\partial \hat{B}_j}{\partial x_i} \right)}_{F_i = F_i^B + F_i^L} \end{aligned} \quad (1)$$

$$\frac{\partial \hat{T}}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{v}{Pr} \frac{\partial \hat{T}}{\partial x_j} - \hat{T} \hat{U}_j \right), \quad \frac{\partial \hat{C}}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{v}{Sc} \frac{\partial \hat{C}}{\partial x_j} - \hat{C} \hat{U}_j \right), \quad (2)$$

$$\frac{\partial \hat{B}_i}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{1}{\mu_0 \sigma} \frac{\partial \hat{B}_i}{\partial x_j} - \hat{B}_i \hat{U}_j + \hat{U}_i \hat{B}_j \right), \quad (3)$$

where $\hat{U}_i$, $\hat{T}$, $\hat{C}$ and $\hat{B}_i$ are the velocity, temperature, concentration and magnetic field induction, respectively. The equation set is closed with the divergency free conditions for both velocity and magnetic fields, i.e. $\partial \hat{U}_j / \partial x_j = 0$ and $\partial \hat{B}_j / \partial x_j = 0$. It is assumed that the thermal buoyancy effects are imposed through the Boussinesq approximation ($F_i^B = -\beta g_i (\hat{T} - T_{\text{ref}})$) and the Lorentz force is calculated as $F_i^L = \hat{J} \times \hat{B} = 1/\mu_0 (\nabla \times \hat{B}) \times \hat{B}$. It can be seen that the momentum (equation 1) and magnetic induction (equation 3) equations are mutually dependent through the effects of the Lorentz force and convective terms. The same interdependency is present for the momentum and temperature equations. In contrast, the electromagnetic fields interact with both the temperature and concentration equations only indirectly through the velocity field. The ensemble-averaged form of the above presented system of equations can be written as (note: all instantaneous variables are decomposed into ensemble averaged and fluctuations, i.e. $\hat{U}_i = \langle U_i \rangle + u'_i$ further denoted as $U_i + u_i$, etc.)

$$\begin{aligned} \frac{\partial U_i}{\partial t} = \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - U_i U_j - (\tau_{ij}^u - \tau_{ij}^b) \right] - \frac{1}{\rho} \frac{\partial P}{\partial x_i} \\ - \beta g_i (T - T_{\text{ref}}) + \frac{1}{\rho \mu_0} \left(B_j \frac{\partial B_i}{\partial x_j} - B_j \frac{\partial B_j}{\partial x_i} \right), \end{aligned} \quad (4)$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{\nu}{Pr} \frac{\partial T}{\partial x_j} - T U_j - \tau_{\theta j} \right), \quad \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_j} \left(\frac{\nu}{Sc} \frac{\partial C}{\partial x_j} - C U_j - \tau_{cj} \right), \quad (5)$$

$$\frac{\partial B_i}{\partial t} = \frac{\partial}{\partial x_j} \left[\frac{1}{\mu_0 \sigma} \frac{\partial B_i}{\partial x_j} - B_i U_j + U_i B_j - (\tau_{ji}^{\text{bu}} - \tau_{ij}^{\text{bu}}) \right]. \quad (6)$$

The closure of the ensemble-averaged equations is achieved by models for the stochastic (subscale) turbulence second moments, i.e. $\tau_{ij}^u = \langle u_i u_j \rangle$, $\tau_{ij}^b = 1/\rho \mu_0 \langle b_i b_j \rangle$, $\tau_{\theta j} = \langle \theta u_j \rangle$, $\tau_{cj} = \langle c u_j \rangle$. The desirable modelling level would be a differential second-moment closure in which full transport equations would be solved for all these correlations. Obviously, such an approach will lead to very complex system of mutually interdependent nonlinear partial differential equations (note that in addition to the turbulent momentum, heat and concentration fluxes, in the magnetohydrodynamic (MHD) flows we may need to model magnetic stress and flux, $\tau_{ij}^b = 1/\rho \mu_0 \langle b_i b_j \rangle$ and $\tau_{ij}^{\text{bu}} = \langle u_i b_j \rangle$). These equations will again contain many terms that should be modelled (triple moments, correlations involving fluctuating pressure, derivatives of the fluctuating velocity and electromagnetic fields, and similar). The majority of these correlations can be obtained only from DNS, which for MHD flows are not yet available. In order to simplify the system of equations, instead of solving the full (differential) second-moment closure, we introduced algebraic models for the second moments. The main motivation behind this simplification lies in the fact that the turbulent transport by large-scale structures is now numerically resolved in time and space. On the other hand, the subscale turbulence contributions are primary dominant in the proximity of solid walls where the turbulence is highly anisotropic but convection is weak or negligible. By retaining all major production terms of the second moments and by assuming a reduced form of the weak equilibrium conditions ($D/Dt - \mathcal{D} = 0$, where D/Dt stands for the material derivative and $\mathcal{D}$ represents the total diffusion term) the algebraic expression for the second

moments can be obtained:

$$\begin{aligned}\tau_{ij} &= \langle u_i u_j \rangle = \frac{2}{3} k \delta_{ij} - \nu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + C_\theta \frac{k}{\varepsilon} \beta \left(g_i \tau_{\theta j} + g_j \tau_{\theta i} - \frac{2}{3} g_k \tau_{\theta k} \delta_{ij} \right), \\ \tau_{\theta i} &= \langle \theta u_i \rangle = -C_\theta \frac{k}{\varepsilon} \left(\tau_{ij} \frac{\partial T}{\partial x_j} + \xi \tau_{\theta j} \frac{\partial U_i}{\partial x_j} + \eta (\beta g_i \langle \theta^2 \rangle + \langle \theta f_i^L \rangle) + \varepsilon_{\theta i} \right), \\ \tau_{ci} &= \langle cu_i \rangle = -C_c \frac{k}{\varepsilon} \left(\tau_{ij} \frac{\partial C}{\partial x_j} + \xi \tau_{cj} \frac{\partial U_i}{\partial x_j} \right).\end{aligned}\quad (7)$$

In the derivation of the above algebraic expressions it is assumed that the species concentration behaves as a passive scalar in contrast to the temperature, but if not, the expression for τ_{ci} can be extended to account for body forces in the manner analogous to the expression for $\tau_{\theta i}$. Note that despite the fact that there is no direct interaction between temperature and magnetic induction, the fluctuating Lorentz force effects (f_i^L) are present in the expression for the subscale turbulent heat flux. The similar approach can be used for the derivations of the fluctuating magnetic induction contributions, τ_{ij}^b and τ_{ij}^{ub} . The problem is that the physical interpretation of such correlations is much more difficult than for their velocity-fluctuations counterparts. Beside, the DNS studies of the fully coupled velocity–magnetic field interactions are still in their initial development (mainly addressing initially homogeneous turbulence subjected to an external magnetic field) so that information providing such correlations are very scarce in the literature. In most applications, the initial magnetic field distribution is known and the turbulent fluctuations of the magnetic field can be neglected. Then a simple one-way coupled interactions can be considered: instead of solving the magnetic induction equations, a simple additional scalar equation for the electrical potential is solved (the so-called *inductionless* assumption). This was the approach that we followed in our early work (Hanjalić and Kenjereš 2001a, 2006, Kenjereš and Hanjalić 2000a, 2004, Kenjereš *et al* 2004). The system of the *ensemble-averaged* equations is finally closed by introducing three additional transport equations for the subscale turbulent kinetic energy (k), its dissipation rate (ε) and the temperature variance (θ^2), respectively:

$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial x_j} \left(\nu \frac{\partial k}{\partial x_j} + D_k^t - U_j k \right) - \tau_{ij}^u \frac{\partial U_i}{\partial x_j} - \varepsilon + P_k^B + P_k^L, \quad (8)$$

$$\frac{\partial \theta^2}{\partial t} = \frac{\partial}{\partial x_j} \left(\nu \frac{\partial \theta^2}{\partial x_j} + D_\theta^t - U_j \theta^2 \right) - 2 \tau_{\theta j} \frac{\partial T}{\partial x_j} - 2 \varepsilon_\theta, \quad (9)$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial x_j} \left(\nu \frac{\partial \varepsilon}{\partial x_j} + D_\varepsilon^t - U_j \varepsilon \right) - C_{\varepsilon 1} \tau_{ij}^u \frac{\partial U_i}{\partial x_j} \frac{\varepsilon}{k} - C_{\varepsilon 2} f_\varepsilon \frac{\varepsilon^2}{k} + P_\varepsilon^B + P_\varepsilon^L, \quad (10)$$

where

$$P_k^B = -\beta g_i \tau_{\theta i}, \quad P_\varepsilon^B = C_{\varepsilon 1} \frac{\varepsilon}{k} P_k^B, \quad P_k^L = -\frac{\sigma}{\rho} B_0^2 k \exp \left(-C_L \frac{\sigma}{\rho} \frac{k}{\varepsilon} \right), \quad P_\varepsilon^L = \frac{\varepsilon}{k} P_k^L$$

are the buoyancy and magnetic production of k and ε , respectively, and $B_0 = \sqrt{B_i^2}$. The turbulent diffusion terms are modelled by the simple gradient diffusion hypothesis, $D_\phi^t = (\nu_t / \sigma_\phi) (\partial \phi / \partial x_j)$, with $\phi = k, \varepsilon, \theta^2$. Instead of solving an additional equation for the dissipation rate of the temperature variance (ε_θ), the constant timescale ratio is assumed, i.e. $R = k \varepsilon_\theta / \varepsilon \theta^2 = \text{const}$. The turbulent viscosity is evaluated as: $\nu_t = C_\mu f_\mu k^2 / \varepsilon$, with $f_\mu = \exp[-3.4/(1 + Re_t/50)^2]$ and $f_\varepsilon = 1 - 0.3 \exp(Re_t^2)$ as the low- Re viscous damping

Table 1. Specification of the model coefficients.

$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_θ	C_c	C_L	C_μ	$C_{\varepsilon \theta i}$	σ_k	σ_ε	σ_θ	ξ	η	R
1.44	1.92	0.2	0.2	0.025	0.09	7×10^{-4}	1.	1.3	1	0.6	0.6	0.5

functions (defined in terms of the local turbulence Re number, $Re_t = k^2/\nu\varepsilon$). The viscous dissipation of the heat flux is calculated as

$$\varepsilon_{\theta i} = f_{\varepsilon \theta i} \frac{1 + Pr}{2\sqrt{PrR}} \frac{\varepsilon}{k} \tau_{\theta i}$$

with $f_{\varepsilon \theta i} = \exp[-C_{\varepsilon \theta i} Re_t(1 + Pr)]$ (Wörner and Grötzbach 1995). The model coefficients are listed in table 1.

3. Solution method

The discretized equations set (equations (4)–(9)) is solved using a multi-block structured finite-volume Navier–Stokes/Maxwell solver for three-dimensional non-orthogonal geometries. The Cartesian vector and tensor components in the collocated grid arrangements are applied for all variables. In order to prevent a decoupling between the velocity and pressure fields the Rhie–Chow interpolation is used in the pressure-correction equations. The corrected pressure and velocity fields are iteratively calculated by the SIMPLE algorithm. The diffusive terms are evaluated by the second-order central differencing scheme (CDS). Different second-order schemes for the convective terms have been used for different test cases: the second-order central (CDS) has been used in all LES, as well as for T-RANS of Rayleigh–Bénard convection, whereas the third-order quadratic upwind (QUICK) and monotonicity preserving total variation diminishing scheme (TVD) with different limiters (UMIST, MINMOD) have been used for flows in complex configurations and for very high Rayleigh numbers, Lien and Leschziner (1994). The time integration is performed by fully implicit three-consecutive-time-step method that allows larger time steps to be used compared with the explicit time integration. All flows, apart from the generic penetrative convection, were run in parallel mode, involving the domain-decomposition based message-passing interface (MPI) directives.

Because T-RANS is aimed at flows with strong semi-deterministic large-scale structures, the results are not very sensitive to the grid resolution (far less than LES). The mesh resolution requirements for T-RANS are qualitatively the same as for near-wall RANS, which means that the mesh in the wall-normal direction should be clustered towards the wall to resolve viscous layer. Typically 6–10 control volumes are sufficient with the non-dimensional wall distance of $z_w^+ = 1 - 2$. In the streamwise and spanwise direction, the grid spacing is much less restrictive and large aspect-ratio cells are tolerated, depending, of course, on the computational algorithm and the flow considered (whether strong variations are expected, such as around separation and reattachment).

4. A generic test case: Rayleigh–Bénard convection

In order to demonstrate the performance of the T-RANS approach and the importance of the subscale turbulence contributions, we consider first the classic Rayleigh–Bénard thermal convection in a 4 : 4 : 1 (LES) and 8 : 8 : 1 (T-RANS) aspect ratios with open lateral boundaries.

Figure 1. Vortical structures in a natural-convection thermal boundary layers on a horizontal heated wall of a low- Pr ($Pr = 0.025$) fluid. Left: $Ra = 10^6$, Right: $Ra = 10^8$. The results are obtained by a well-resolved LES ($256 \times 256 \times 128$ CVs). The colour label denotes the vertical velocity (W) component.

This geometrically simple buoyancy-driven flow between two infinite flat horizontal walls of different temperatures is often studied in the literature serving as a paradigm for complex thermal convection. The phenomenon is, however, directly relevant to flows in the atmosphere, in oceans, and in many industrial applications such as crystal growth, electronic cooling, nuclear reactors, indoor climate and many more, figure 1. From the engineering point of view, the most important issue is the accuracy of the wall-heat transfer predictions. Here, the challenge lies in the proper resolving of the boundary layers (both thermal and hydrodynamical) along the horizontal walls. From the physical point of view, the central focus is on investigating numerous challenges associated with possible different states of turbulence (soft, hard and ultimate) and nature of the coherent structures and their role in heat transfer over a wide range of working parameters. The inherent three-dimensional unsteady nature and questions about the role of large-scale coherent structures in this particular test case provided in fact the motivation for adopting the T-RANS approach in our research. Initially, this was just one of many typical test cases for the validation of advanced turbulence closure models when dealing with complex buoyancy-driven flows, Kenjereš (1998). In order to make it possible to compare such results with the long-term averaged DNS data and to be able to clearly separate the modelled subscale turbulence and the resolved deterministic contributions, we used a triple decomposition of Hussain and Reynolds (1970), which assumes that any instantaneous fluid flow variable at a point $\hat{\Phi}(x_i, t)$ can be expressed as a sum of a time-mean $\overline{\Phi}(x_i)$, deterministic (quasi-periodic) $\tilde{\Phi}(x_i, t)$ and the remaining turbulent $\phi(x_i, t)$ (stochastic) contributions: $\hat{\Phi}(x_i, t) = \overline{\Phi}(x_i) + \tilde{\Phi}(x_i, t) + \phi(x_i, t) = \langle \Phi(x_i, t) \rangle + \phi(x_i, t)$. After long-time averaging at a point in space and under assumption that there is no direct interaction between the small-scale turbulence and the deterministic motion, the second-order moment involving $\Phi(x_i, t)$ and another turbulent quantity $\Psi(x_i, t)$ can be generally written as $\overline{\hat{\Phi}\hat{\Psi}} = \overline{\Phi}\overline{\Psi} + \overline{\tilde{\Phi}\tilde{\Psi}} + \overline{\phi\psi} = \langle \Phi \rangle \langle \Psi \rangle + \overline{\phi\psi}$.

Snapshots of the instantaneous thermal boundary layer morphology for two values of Ra are shown in figure 1, extracted from results of a well-resolved LES. Note that in contrast to the conventional temperature isosurface, which an arbitrary threshold needs to be specified (usually slightly above the referent temperature), these figures are extracted using a novel postprocessing method in which the thermal boundary

layer is identified by connecting all points in space resulting from intersection of the instantaneous vertical temperature and the referent temperature. This eliminates arbitrariness in selecting a threshold and uniquely defines the thermal boundary layer morphology. Figure 1 shows a significant thinning of the thermal boundary layer with an increase of Ra illustrating why the DNS and LES studies reported in the literature can reach only relatively modest values of Ra (up to 10^9 , Peng *et al* 2006). While T-RANS requires also increasing mesh clustering in the wall-normal direction with Ra number, LES and DNS require very high resolution also in the horizontal directions in order to properly capture the near-wall small streak structures.

The LES results for $Ra = 10^9$ served as the reference for demonstrating the capabilities of T-RANS to accurately predict the wall-heat transfer under much smaller computational costs (significantly coarser numerical mesh, Kenjereš and Hanjalić 2002a, Kenjereš *et al* 2005). The predicted values of Nu show very good agreement with the available experimental studies for both values of Pr ($Pr = 0.71$: Chavanne *et al* 2001, Niemela *et al* 2000; $Pr = 0.025$: Glazier *et al* 1999), figure 2 (above). Note that the T-RANS makes it possible to compute also highly turbulent regimes ($Ra > 10^{12}$) showing a trend towards the Kraichnan's ultimate turbulence state characterized by the asymptotic solution $Nu \sim Ra^{1/2}$ for $Ra \rightarrow \infty$ (for $Pr = 0.71$, Chavanne *et al* 2001). The thickness of both, the hydrodynamical and the thermal boundary layers as a function of Ra also shows very good agreement with the available DNS of Kerr (1996), our well-resolved LES and experimental studies of Belmonte *et al* 1994, Xin and Xia (1997) and Zhou and Xia (2001), figure 2 (below). The results clearly disapprove the hypothesis that the ultimate turbulent regime is a consequence of a cross-over between hydrodynamical and thermal boundary layers as suggested in Belmonte *et al* (1994). While this cross-over does not take place for $Pr = 0.71$, a clear cross-over appears for $Pr = 0.025$ at $Ra = 10^8$, but this does not lead to an increase of the Nu (figure 2 (below right)).

The key to the success of the accurate predictions of heat transfer lies in the proper capturing of the near-wall second moments, figure 3, as proved by good agreement between the T-RANS and the well-resolved LES results. Note that the numerical mesh used for T-RANS simulations represents just 5% of the LES mesh for the same Ra number. Instead of using a very fine mesh in the near-wall regions, the T-RANS relies on the more advanced subscale turbulence models that together with the resolved (deterministic) contributions give total values in close accordance with DNS/LES. The modelled subscale contributions represent the main mechanism in the near-wall region for both turbulent heat flux and the temperature variance. In contrast, the deterministic part of the turbulent kinetic energy is the dominant mechanism in the wall proximity. The temperature fluctuations are the most intensive at the edge of the thermal boundary layer (very close to the wall) while the velocity fluctuations are present both in the horizontal boundary layers (through horizontal velocity fluctuations) and in the central part of the domain (because of the vertical velocity fluctuations). The velocity fluctuations are also associated with the large convective structures (cells/rolls) that are already well resolved by used numerical mesh. This explains the more dominant deterministic contribution for the turbulent kinetic energy in the near-wall region.

The successful validation of the T-RANS approach in the Rayleigh–Bénard convection over a range of Ra numbers that covers ten orders of magnitude including the Ra values far beyond the reach of LES, let alone DNS, provided sufficient credibility to apply the method to the simulation of real-life flows dominated by body forces. The potential of the T-RANS approach in dealing with realistic events with working parameters which are out of reach for other simulations techniques is demonstrated next.

Figure 2. Above: the integral heat transfer ($Nu - Ra$) dependency extending towards 'ultimate turbulence state' regime obtained by a T-RANS and compared with numerous experimental studies for different values of Pr ; below: thermal and hydrodynamical boundary layer thickness dependency on Ra for $Pr = 0.71$ (air) left, and $Pr = 0.025$ (mercury)—right, as working fluids: T-RANS, DNS and experimental studies.

5. Dynamics of fuel-oil cooling inside a tanker wreck

The tanker 'Prestige' carrying approximately 80 000 tonnes of the fuel-oil (more than twice the capacity of the notorious Exxon Valdez oil spill in Alaska in 1989) ran into trouble in heavy seas and strong winds in the proximity of Galician coast (the northwestern province of Spain) in November 2002, figure 4 (Bohannon *et al* 2002, Bohannon and Bosch 2003). A few days later (on 20 November 2002) the damaged tanker broke in half and finally sank to the depth of 3600 m with its fuel-oil tanks mostly intact. The oil spill from the tanker

Figure 3. The near-wall behaviour of the second-moments obtained by T-RANS ($82 \times 82 \times 72$ CVs): M, modelled; D, deterministic (resolved), T, total contributions, compared with the LES ($256 \times 256 \times 128$ CVs) (total), $Ra = 10^9$, $Pr = 0.71$ (Kenjereš and Hanjalić 2006).

wreck promptly alerted officials in Spain and Portugal to take measures to protect fisheries and beaches along the coastline. The most urgent task was to determine the time needed for the solidification of the fuel-oil in the tanker tanks. Based on this information, a decision was to be made on whether it is absolutely necessary to embark on the colossal undertaking to pump out the oil, or to leave it to solidify, with some less expensive actions to prevent further leaking in the meantime. The initial temperature of the oil inside the tanker tanks was 50°C , whereas the ocean temperature at that depth is about 2.5°C . Since the oil-spill cleanup operation and its potential consequences on tourism, fisheries and sea-life along the entire northwestern coast of Spain can have enormous environmental, social and economical impacts easily measured in billions of Euros, the Spanish government issued an urgent call for an appropriate estimation of total time needed for oil cooling and its possible solidification.

Because of the urgency, the problem was reduced to a two-dimensional analysis of cooling of the fuel-oil in the characteristic cross section of the tanker wreck (figure 5). The symmetry is assumed across the middle plane (line) of the central tank. A conjugate heat transfer problem is considered taking into account also a relatively thin vertical partition between the lateral and the central tank. In order to validate grid independence of the numerical results, simulations with $164 \times 4 \times 82$ and $322 \times 4 \times 162$ control volumes are performed. The numerical mesh is sufficiently fine in the proximity of the walls in order to fully resolve both the thermal and the hydrodynamical boundary layers making it possible to use the integration up to the wall of all variables (with appropriate low- Re extensions). The physical properties of the fuel-oil show a strong dependency on temperature (both the dynamic viscosity and Prandtl number), which have been taken into account during the simulations in the considered range of the temperatures ($2.5 \leq T \leq 50^\circ\text{C}$)³. The estimated Rayleigh number for this specific situation is $Ra \approx 5 \times 10^{13}$.

³ For example the fuel-oil properties at $T = 2.6^\circ\text{C}$, $Pr = 8.5 \times 10^6$, $\mu = 650$ Pa s, at $T = 50^\circ\text{C}$, $Pr = 10^4$, $\mu = 0.85$ Pa s.

Figure 4. The picture of the tanker ‘Prestige’ leaking oil (above); the location of the incident and the final sinking location (below left); The European Space Agency (ESA) satellite oil spill tracking on the day of sinking (below right). Source: European Space Agency (ESA), <http://www.esa.int>

Figure 5. The sketch of the computed cross section of the tanker ‘Prestige’ wreck with initial and boundary conditions (Kenjereš and Hanjalić 2003).

The time evolutions of the temperature at the characteristic monitoring points in the proximity of the lateral vertical wall are shown in figure 6 (above). The typical values of time step varied between 1 and 120 s in the initial and later stages of cooling, respectively. It can be seen that during the first 30 days, a significant drop of temperature takes place in the lower part of the lateral tank. This is the consequence of the active mechanism of convection, which despite relatively low intensity of velocity is still far more efficient mechanism of the heat transfer in comparison with the molecular diffusion. The central vertical and central horizontal temperature profiles are shown in figures 6. It is striking that despite a very low thermal resistance across the partition wall, the dynamics of cooling of the lateral and central tank shows significant differences. This is the consequence of the suppression of the horizontal movement as can be seen in figure 7, where the velocity vectors are shown for two time instants. The flow patterns portray complex interactions between the thin thermal boundary layers along the vertical walls and the large-scale convective rolls inside of the tanks. Interesting flow patterns similar to the typical Rayleigh–Bénard cells can be observed in the upper parts of both tanks generated by the unstable stratification (figure 8). The lower parts of the tanks are highly stratified and during the later period a strong damping of the velocity can be clearly observed.

Based on the calculations presented, it can be concluded that the process of cooling and potential solidification of the fuel-oil inside of the tanker wreck is extremely slow and that even after 6 months, the oil temperatures are still higher than the solidification threshold (Bosch 2006).

Note that in this particular case the importance of the subscale turbulent heat flux model was of the secondary importance, except in the very initial phase, since the extreme oil viscosity together with the stable thermal stratification in the bulk of the tanks (apart from the top narrow region) suppressed rapidly the initially created turbulence. But the fact that the entire problem can be treated as a two-dimensional conjugate-heat transfer phenomena (interpreted as ensemble averaged in the spanwise direction—similarly as in Kenjereš and Hanjalić 2000b) and that a fully implicit time integration is used—efficient and accurate predictions of heat transfer over very long period (6 months) have been obtained in a very short time.

6. Smog formation over a city valley capped by an inversion layer

Prior to the simulations of a realistic mesoscale thermal inversion layer and its effects on the distribution of passive pollutants over complex urban domains, a detailed validation of the turbulence closure used as the subscale model for T-RANS, was performed for an idealized one-dimensional model of penetrative convection for which an extensive database is available (Lenschow *et al* 1980, Schmidt and Schumman 1989, Willis and Deardorff 1974). The laboratory setup consists of a simple vertical container filled with water initially at rest with a stable thermal stratification imposed by a linear increase in temperature in the vertical direction. The setup is then subjected to heating with a variable heat flux at the bottom, while keeping the constant temperature at the top. A sketch illustrating the initial vertical temperature and heat flux distributions is shown in figure 9. Three distinctive layers can be identified: an unstable stratified wall layer, a well-mixed neutrally stratified central layer and a stable stratified upper layer. During heating, the interface location between the mixed ($S = 0$) and the stable-stratified top layer ($S > 0$) moves vertically as a result of erosion of the upper stable-stratified layer. This interface between the two layers is characterized by a strong temperature gradient and with a change in sign of the vertical heat flux

Figure 6. The time dependency of the fuel-oil temperature at three characteristic locations along the lateral vertical wall in the left tank inside of the tanker 'Prestige' wreck (above); the profiles of temperature along the central vertical plane of the left tank (middle) and the central horizontal plane along the entire intersection (below).

Figure 7. The velocity vectors in the tanker ‘Prestige’ wreck after 1 and 180 days of cooling, respectively (Kenjereš and Hanjalić 2003).

(figure 9 (right)). The existence of this interface zone makes this particular setup quite challenging for numerical simulations.

The time evolution of the vertical temperature and the normalized heat flux profiles are shown in figure 10. The omission of the temperature variance term in the subscale model for the turbulent heat flux (general gradient diffusion hypothesis (GGDH)) leads to a significant deterioration of the vertical temperature profiles, figure 10 (left): the computed temperature shows unrealistic large negative gradient in the well-mixed layer in order to adjust to the obviously inadequate eddy diffusivity model and thus to ‘swallow’ the vertical heat flux. This example illustrates well the importance of using an AFM representation of the turbulent heat flux with the inclusion of the temperature variance which should be provided from a separate transport equation. The vertical distribution of heat flux scaled with the buoyancy flux (calculated as a product of the buoyancy velocity ($w^* = (\beta g Q_0 Z_{\text{inv}})^{1/3}$) and temperature ($T^* = Q_0/w^*$)) is shown in figure 10 (right). Additional re-scaling of the vertical distance with the inversion height makes it possible to compare not only the laboratory-scale distributions (Willis and Deardorff 1974), but also the values obtained from the field observations (aircraft measurements) (Lenschow *et al* 1980) and LES (Schmidt and Schumman 1989). It can be seen that good correlation between different data is obtained, proving that the selected experimental setup mimics realistically the salient features of this genuine atmospheric phenomena. If we zoom in the interface region, the change of the sign of the vertical heat flux is predicted but its intensity is slightly higher in comparison with both the laboratory and field observations. It is interesting to note that this higher negative value is in close correspondence with the LES of Schmidt and Schumman (1989). Since the interface region significantly enhances the turbulence anisotropy, a much finer mesh in this region should be applied when the LES approach is used. Additional remedy can be in solving the full-second moment closure (differential stress/flux models (DSM/DFM)) as is shown in Kenjereš and Hanjalić (2002b) and Kenjereš *et al* (2002), where significant improvements in capturing the negative peaks of the vertical heat flux are observed. But due to the fact that full

Figure 8. The superimposed temperature and streamlines distributions in the region close to the top wall of the tanker wreck (the partition dividing the lateral and central tank is visible on the right side of the zoom-in): 1, 30, 180 days, respectively (Kenjereš and Hanjalić 2003). The temperature intervals red/blue (max/min) correspond to: $50^\circ/5^\circ$, $40^\circ/5^\circ$ and $10^\circ/5^\circ$ °C, for 1 (above), 30 (middle) and 180 (below) days, respectively.

Figure 9. Sketch of the temperature and heat flux distributions in an initially thermally stratified layer of fluid heated from below. Three distinctive regions can be observed: the unstable stratified ($S < 0$) near-wall region, the neutrally stratified highly mixed region ($S = 0$) and finally, the stable stratified upper layer ($S > 0$), where $S = \partial T / \partial z$.

Figure 10. The time evolution of the vertical temperature (left) and normalized heat flux in a mixed layer heated from below: comparisons between laboratory experiments, field measurements, LES and present simulations, Kenjereš and Hanjalić (2002b). The Z_{inv} indicates the inversion zone location defined as the height at which the vertical heat flux reaches its maximum negative value.

second-moment closure for Reynolds stresses and heat flux components DSM/DFM involves significantly larger number of equations compared with ASM/AFM (algebraic stress/flux model) approach—17 versus 8 partial differential equations—it can be concluded that the ASM/AFM subscale turbulence model represents a good compromise between the accuracy and numerical efficiency.

We move to the simulations of a realistic mesoscale thermal inversion layer and its influence on smog formation over an urban valley. The area surrounding the city of Sarajevo, the capital of Bosnia and Herzegovina and the site of the XIV Winter Olympic Games in 1984 is selected because of its notorious heavy smog during winter months caused by a temperature inversion (figure 11). This is a natural phenomena occurring when higher temperatures at higher elevation exceed those in the valley, forming a capping inversion layer that suppresses turbulent transport processes above the city. In addition to causing serious threat to human health, the main negative impact of heavy smog formation is on the air traffic⁴. By performing numerical simulations of different scenarios that consider existing and planned urban developments of the surrounding city area, useful information can be obtained that can serve as a basis for sustainable management of the city infrastructure (Hanjalić and Kenjereš 2005, Kenjereš and Hanjalić 2002b).

The specification of the initial and dynamically adjustable boundary conditions (temperature and concentration emission diurnal changes) are shown in figure 12. The residential and industrial areas are specified as distinct islands with differently elevated ground temperature ($+\Delta 2^{\circ}\text{C}$, $+\Delta 1^{\circ}\text{C}$ in respect to the surrounding ground temperature) and concentration (50 or 100% emission intensity) due to daily activities in the town. We assumed sinusoidal variations with different amplitudes (for residential and industrial zones, respectively) with respect to the surrounding areas. Two different levels of the initial thermal stratification (assumed to be of the same intensity) are simulated. For a weak stratification case, linearly increasing potential temperature ($\Delta T/\Delta z = 4 \text{ K m}^{-1}$) profile is assumed with

⁴ For example, the statistical data collected by Sarajevo airport show that for the period from 20 November to 20 December 2006 more than 30% of all flights were cancelled due to low visibility. Source: <http://z/sarajevo-airport.ba>.

Figure 11. Above: the Google-Earth view of an urban valley—city of Sarajevo, Bosnia and Herzegovina, the site of the XIV Winter Olympic Games in 1984; geographic location: $43^{\circ}52'0''\text{N}$, $18^{\circ}25'0''\text{E}$; population ≈ 0.5 Million (Source: Google Earth, <http://earth.google.com>.); below: photos of the city panorama where the smog formation is clearly visible—with a weak (left) and a strong (right) temperature inversion effects.

the base of the inversion layer at $2/3$ height distance (averaged) from the ground. In the strong stratification case, the temperature inversion layer base is moved to $1/3$ height towards the ground.

The simulated domain represents an area of $12\,500 \times 10\,000 \times 25\,00\text{ m}^3$, which is numerically resolved by $125 \times 100 \times 50$ control volumes. A stretched numerical mesh is applied in the vertical direction in order to properly capture the temperature gradients in the proximity of the ground (with an averaged value of the non-dimensional wall distance $z^+ \approx 150$). The buoyancy-accounting wall functions are applied for all variables (based on the local-equilibrium conditions, $P_k + P_k^B = -\tau_{ij}^u \partial U_i / \partial x_j - \beta g_i \tau_{\theta i} = \varepsilon$). The top boundary is kept at a constant temperature and with symmetry conditions for all remaining variables. The side boundaries are treated for convenience as symmetry planes, but moved away sufficiently

Figure 12. Specification of the initial and the dynamical boundary conditions (diurnal cycles) for the residential/industrial islands for temperature and pollutant emissions (Kenjereš and Hanjalić 2002b).

so that they do not influence the central domain of interest. This is possible since the most critical pollution scenario is considered, i.e. a windless winter period. The diurnal cycles cover a 48 h period with a typical time steps ranging from 1 min in the initial period to 5 min at the advanced stage of ground heating. The potential temperature and the turbulent kinetic energy distributions for particular time instants for two stratification cases are shown in figures 13–16. From the distributions of the potential temperatures one can observe the erosion of the capping inversion layer. The thermal plumes originating both from the local hill peaks and from the industrial and residential ‘heat islands’ are shown in figures 13 and 15. The contours of the turbulent kinetic energy indicate the spatial distribution of the turbulent mixed layer (figures 14 and 16). Significant differences between the two stratification levels can be observed. The strong stratification dampens all turbulent transport making the evolution of the buoyancy-created velocity fields very slow. Consequently, significantly higher pollution levels are observed when compared with the weak-stratification case (figure 17) (where the characteristic time realizations correspond to the identical times as in the previous figures). The smog formation is visualized by showing layers of the consecutive transparent iso-surfaces of the passive scalar, characterized by selected fractions, i.e. 0.9–0.01 (five levels) of the maximum concentration levels. It can be concluded that the T-RANS approach can serve as a powerful and efficient numerical tool for predictions of mesoscale pollution distributions over complex urban terrains.

7. Mimicking the generation and self-sustenance of planetary magnetic fields in laboratory conditions

The final example addresses an application of the T-RANS approach in providing a confirmation of the magnetic dynamo theory, regarded to be the basic mechanism of the

Figure 13. Diurnal changes of the potential temperature distributions over an urban valley for the weak-stratification case.

self-generation and self-sustenance of planetary magnetic fields. It is believed that partial conversion of the mechanical energy of a moving electrically conductive fluid into the magnetic energy is the key mechanism behind the origin of magnetic fields in spiral galaxies, stars and planets. The essence of the magnetic dynamo is in electromagnetic induction: electric currents created by movement of a conductive fluid (liquid metal) will in turn generate a magnetic field—like a wire carrying the electric current that creates local magnetic field. The working fluid will then feel the presence of such an induced magnetic field through the Lorentz force that can be calculated as $\mathbf{F}^L = \mathbf{J} \times \mathbf{B}$, where $\mathbf{J}$ is the total electric current and $\mathbf{B}$ is the induced magnetic field. In order to achieve possible self-excitation of a background magnetic

Figure 14. Diurnal changes of the turbulent kinetic energy over an urban valley for the weak-stratification case.

field, it is necessary to reach the flow regime where the stretching of the magnetic field will overpower its resistive damping, i.e. $Re_M = UL/\nu_B > 1$ (where L and U are characteristic length and velocity scale and ν_B is magnetic diffusivity). These flow regimes imply the two-way interactions between the fluid-flow- and magnetic-induction equations, i.e. a fully coupled Navier–Stokes/Maxwell equations system should be simultaneously solved.

The complex turbulent convection of the hot liquid iron inside the Earth's liquid outer core makes a good candidate for testing a magnetic dynamo theory (Glatzmaier and Roberts 1995, Olson and Aurnou 1999). This turbulent motion originates from the interactions between the thermal and concentration (composition) buoyancy, rotation and Lorentz force.

Figure 15. Diurnal changes of the potential temperature distributions over an urban valley for the strong-stratification case.

Addressing the recent advances in computational simulations of the geo-dynamo phenomena, Glatzmaier (2002) questioned the relevance and accuracy of the up-to-now performed simulations since none of them was able to operate in realistic Earth's regimes because of the limitations in numerical resolutions. The critical issue in the present generation of numerical models is in their oversimplified representation of the turbulent transport. The majority of the geodynamo models are based on simple linear stress-strain models and constant turbulent diffusivity (both time- and spatial variations are neglected). This calls for advanced model of turbulent transport, which are expected to mimic better the geodynamo phenomena in working regimes that correspond more closely to the realistic conditions.

Figure 16. Diurnal changes of the turbulent kinetic energy over an urban valley for the strong-stratification case.

It is easy to imagine that validation of realistic simulations of the Earth's like conditions can be only indirect, for example by comparing the recorded magnetic field distributions at the Earth surface. In order to provide direct and valid proofs of the magnetic dynamo mechanism, it is necessary to have well-defined and controlled working conditions, while retaining the basic physics of the dynamo phenomenon. The essence of the buoyancy-driven vortical motion inside of the Earth outer liquid core can be mimicked for example by a vertical column of a swirling liquid metal placed inside of an outer loop, as shown in figure 18 (left). For reaching the working conditions required for self-excitation of a magnetic field ($Re_M > 1$) it is necessary to generate high velocity of an electrically conductive fluid inside of a sufficiently

Figure 17. Time evolution of the smog front originating from combined residential (traffic) and industrial pollution emissions for weak- (left) and strong-stratification (right) conditions.

large geometry. The problem is that even for sodium as one of the best electrically conductive fluids ($\nu_B \approx 0.1 \text{ m}^2 \text{ s}^{-1}$) the potential experimental setup needs to be large, which means that the flow inside of such a setup will be highly turbulent ($Re \approx 10^6$). This explains why the very first experimental detection of a flow induced magnetic field eigenmode was reported only in 1999 in Riga (Gailitis *et al* 2000, Karlsruhe, Stieglitz and Müller 2001), after almost 30 years of numerous attempts in different laboratories all over the world.

The details of the Riga-dynamo experimental setup are shown in figure 18 (right); (Gailitis *et al* 2000, 2001, 2004). The central part contains the inner cylinder where liquid

Figure 18. Left: sketch of the spiralling vortex motion by turbulent convection inside of a planet liquid core; right: the Riga dynamo experimental setup (Gailitis *et al* 2000, 2001, 2004): (1) driving engine, (2) propeller, (3) inner cylinder with helical flow, (4) outer cylinder with back flow, (5) surrounding ring of sodium at rest and (6) tanks with sodium; characteristic dimensions are: $D_1 = 0.25$, $D_2 = 0.41$, $D_3 = 0.8$ and $L = 3$ m, $15 \leq Re_M \leq 20$, $Re \approx 3.5 \times 10^6$.

sodium is driven by a propeller powered by two electric motors (with maximum power of 100 kW each) that generates highly turbulent swirling flow, $Re \approx 3.5 \times 10^6$, and where $15 \leq Re_M \leq 20$. The spiralling movement of liquid sodium continues after a 180° bend through the outer annular passage making a fully closed loop. The entire central part of the setup is surrounded by a ring of liquid sodium at rest (this is done in order to prevent possible escaping of the self-generated magnetic field).

Considering the typical values of the non-dimensional working parameters (Re and Re_M) it is obvious that neither DNS nor LES can be applied for this flow regimes. In addition, it can be estimated that a typical magnetic diffusion length scale defined as $\eta_B = (\nu_B^3/\varepsilon)^{1/4}$ is much larger than the typical Kolmogorov scale ($\eta_K = (\nu^3/\varepsilon)^{1/4}$) since the magnetic Prandtl number is $Pr_M = \nu/\nu_B = 6.5 \times 10^{-6}$. Based on these arguments, we combined the T-RANS approach for the velocity and turbulence fields, while the magnetic induction equation is directly resolved in time and space. We note that these direct numerical *solutions*, denoted hereafter as *DNS*, are not to be confused with the conventional DNS because the mesh used is far too coarse to resolve full turbulence spectrum. It does, however, resolve large-scale, self-generated flow unsteadiness and accompanied vortical structure that faithfully mimic the oscillatory amplification and sustenance of the generated magnetic field, what was the target of the present simulations. This hybrid T-RANS/*DNS* approach is similar to a mixed numerical scheme of Ponty *et al* (2004, 2005) where a LES was applied for the velocity fields and the magnetic induction equation was fully numerically resolved. But Ponty *et al* (2005)

considered only a relatively simple Taylor–Green vortex configuration and for a significantly lower Reynolds numbers ($Re \leq 1.5 \times 10^4$).

The entire experimental configuration is discretized—not only the parts occupied by the working fluid—since the magnetic induction equation should be solved everywhere (analogous to the conjugate heat transfer problem). The final mesh consisted of approximately 4×10^6 control volumes distributed over 90 structured multi-blocks. The mesh is locally refined in the proximity of walls as well as in regions where the flow streamlines exhibit strong curvature i.e. along the 180° bends (lower and upper) between inner and outer cylinders. This is needed in order to ensure proper capturing of the velocity gradients that in turn return accurate production of the turbulent kinetic energy. The non-dimensional wall distance of the nearest to wall control volumes lies in the range recommended for the application of wall functions ($40 \leq (x^+, z^+) \leq 100$) (Kenjereš *et al* 2006). One of the challenges was to prevent artificial confinement of the self-generated magnetic field inside the discretized domain and how to keep its escape under control. For that reason, we imposed vertical magnetic field boundary conditions at the outer wall of the surrounding ring of sodium at rest. This type of boundary condition for the magnetic induction equation allows the self-generated magnetic field to escape while still keeping the critical value of the saturation threshold (Avalos-Zuniga *et al* 2003, Kenjereš and Hanjalić 2007a, b).

Numerically predicted contours of the radial and tangential magnetic field components in the central horizontal plane of the Riga-dynamo setup ($y = 0$ m) are shown in figure 19. The maximum of the radial component is located in the inner cylinder in contrast to the tangential component, which reaches its maximum at the wall separating the inner and outer cylinders. The dynamics of the fluid-flow, turbulence and magnetic field interactions at characteristic monitoring points along the inner cylinder is shown in figure 20. Starting from the fully developed and convergent steady RANS solutions, the fully coupled time-integration procedure is activated (two-way interactions between Navier–Stokes and Maxwell solver) by imposing a very weak ($|B| = 10^{-6}$ T) divergence-free initial magnetic field. It can be seen from figure 20 that approximately after 2 s, the self-induced magnetic field is strong enough to provide the Lorentz force capable of influencing the fluid motion and turbulence fields. Then, as the magnetic field further increases, it generates the Lorentz force that begins to brake the flow, thus suppressing the initial self-excitation of the magnetic field. If the genuine saturation regime is captured, then this interplay between fluid flow, turbulence and self-induced magnetic field will result in a constant amplitude oscillations characterized with a ‘plateau’ of the self-induced magnetic field. This can be clearly seen in figure 20 (below) where both the kinematic (for $0 \leq T^* \leq 3$ s) and the saturation (for $T^* > 3$ s) regimes can be observed.

Finally, the amplitude and frequency of the self-generated magnetic field are compared with the experimental records at two characteristic probes located in the outer cylinder, (figure 21). It can be concluded that very good agreement between the numerical simulations and experiments is obtained confirming the validity of the magnetic-dynamo mechanism behind generation and self-sustenance of the planetary magnetic fields.

8. Conclusions and outlook

A review of diverse applications of the T-RANS approach is presented illustrating its niche as a robust method for rationale computation of real-life complex turbulent flows. All cases considered have in common that they are dominated by strong internal (natural) or external forcing, which generates large-scale coherent structures of a semi-deterministic character. These structures can be interpreted more as internal unsteadiness of the flow as a whole

Figure 19. Numerically predicted contours of the radial (above) and tangential (below) self-induced magnetic field components in the central horizontal plane of the Riga-dynamo setup ($y = 0$ m) in the kinematic (left column) and saturation (right column) regime.

rather than coherent turbulent eddies, but they act as the major carriers of momentum and heat and mass, whereas turbulence in most cases plays minor role and (at least away from a wall) behaves almost as a passive scalar. That is why numerical resolution of these large-scale structures in time and space is essential for reproducing the overall features of flow and turbulence, as well as for heat and mass transfer on the bounding solid surfaces. Another common feature of all cases considered is that they all operate at very high Reynolds and Rayleigh numbers, which make them out of reach of the conventional LES or DNS. This claim was illustrated in test computations of the Rayleigh–Bénard convection in an open-ended high-aspect ratio domain, where we succeeded in extending the simulated range of Rayleigh numbers by seven orders of magnitude ($Ra = 2 \times 10^{16}$) beyond up-to-now the highest value reachable by LES (10^9), obtaining good agreement with the available DNS (for $Ra \leq 10^7$), LES (for $Ra \leq 10^9$) and experimental data for higher Ras . The key to the success of the accurate predictions of the wall-heat transfer lies in the proper capturing of the near-wall behaviour of the second moments by an advanced RANS closure serving as the subscale model for the unresolved motions, which in the near-wall region provides the major contribution. The model used is based on the truncation of the full transport equations of the second moments to algebraic forms, regarded as the minimum modelling level that

Figure 20. The time dependency of the axial velocity (above), turbulent kinetic energy (middle) and axial magnetic field (below) at characteristic monitoring locations along the inner cylinder of the Riga-dynamo setup (Kenjereš and Hanjalić 2007b).

Figure 21. Comparison of the recorded signals of the axial magnetic field at two characteristic probes in the outer cylinder for the fully developed saturation regime; Left: experimental recordings; right: results of numerical simulation (Kenjereš and Hanjalić 2007b).

can account for the near-wall turbulence anisotropy originating either from the presence of solid walls or from action of externally imposed body forces (thermal buoyancy and electromagnetic fields).

The applications considered include environmental and multi-physics phenomena. The first case addressed the prediction of cooling of oil in the wreck of tanker ‘Prestige’ over a very long period of time, extending for more than 6 months. Despite reducing the problem to two dimensions in space (because of urgency), the T-RANS returned the dynamics of the complex flow pattern—especially in the upper unstable region—that was believed to reflect closely the real process. The results served as the basis for estimating the potential environmental impact of the leaking oil and for subsequent rescue and cleanup activities.

The second case involved a combination of complex geometry (natural orography of a urban mountain valley) with challenging physics (stable and unstable thermal stratification, capping inversion, locally concentrated urban heat islands, dynamical boundary conditions). Because no data for validation of the simulations are available for such real-life large-scale problems, prior testing of the subscale heat flux model was performed against experimental and field data for a simple (one-dimensional) unsteady penetrative thermal convection into a stably stratified fluid, showing excellent agreement. The simulations of the air movement and pollutant spreading over the city during two daily cycles for two scenarios of atmospheric conditions (low and high elevation of the inversion layer) revealed interesting dynamics and intensity of the smog formation under critical windless conditions, illustrating the potential of T-RANS as a suitable computational tool for managing and controlling pollution in urban areas.

The final example addressed interactions between highly turbulent helical flow of an electrically conductive fluid (sodium) and Lorentz force originating from the self-generation of a magnetic field. This case represents a nice example of multi-physics phenomena—interactions between fluid dynamics and electromagnetism. This process is the key for understanding of the magnetic-dynamo phenomena that is of great importance in numerous geo- and astro-physical applications, including origin of the Earth’s magnetic field. The novel hybrid combination of T-RANS for fluid flow and turbulence parameters and *DNS* for magnetic induction, resulted in the first successful simulation of the magnetic-dynamo effects under realistic experimental conditions. The hybrid T-RANS/*DNS* reproduced well the two-way interactions between fluid flow and electromagnetic field, as demonstrated by realistic predictions of both, the initial self-generation (kinematic regime) and the subsequent self-sustenance (saturation regime) of the magnetic field. The amplitude and frequency of the generated magnetic field were both found to be in very good agreement with experimental data confirming thus the accuracy of numerical predictions.

The examples presented showed that the T-RANS approach has a potential and clear advantages as compared with the conventional (steady) RANS. It is also shown that for flows characterized by strong internal or external forcing, T-RANS can serve as a surrogate for the more exact, but computationally much more demanding LES and DNS when solving realistic complex turbulent flows, heat and mass transfer at very high Re and Ra numbers. For such situations, T-RANS proved to be a useful simulation tool making it possible to reach flow regimes out of reach of other simulation techniques.

It should be stressed, however, that in flows with (near-) steady boundary conditions and without dominant forcing or with weak coherent structures, T-RANS will produce standard RANS results, the quality of which depends on the model chosen. This feature of T-RANS should not be regarded as a shortcoming: in a steady near-equilibrium flows one does not need to run three-dimensional time-dependent computations because a well-chosen RANS will produce results of sufficient quality for engineering use. As an example, consider a vertical infinite side-heated channel with the same geometry and boundary conditions as the above discussed Rayleigh–Bénard convection (one can think of simple turning the Rayleigh–Bénard configuration by 90° with respect to gravitation vector). A near-equilibrium flow with no

large-scale deterministic structures appears now, being very different from its horizontal (R-B) counterpart. Such and similar flows are well reproduced with steady computations using the same algebraic stress/flux RANS model as in the here-reported T-RANS.

If, however, capturing of some spectral dynamics is required (e.g. for accurate prediction of heat transfer in some separated flow areas dominated by local coherent structures or for design of flow and heat transfer control), it is necessary to sensitize the RANS model to weaker instabilities. An example of such an approach is a seamless hybrid T-RANS/LES approach proposed in Kenjereš and Hanjalić (2006), where the equation for dissipation rate of the subscale turbulent kinetic energy is sensitized in a manner similar to that of Schiestel and Dejoan (2005) using the ratio of the RANS and LES turbulence length scales as a control parameter. This method was tested in parallel with the T-RANS and a well-resolved LES of the Rayleigh–Bénard convection at $Ra = 10^9$. Naturally, the hybrid approach resulted in capturing a significantly larger portion of smaller eddy structures as compared with the T-RANS, but less than with LES. In all cases, however, the wall-heat transfer was well predicted. The hybrid T-RANS/LES and similar models are seen as potentially suitable for complex flows where internal forcing may not be sufficient to excite the T-RANS to return the time-dependent solutions.

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