Identification and Visualization of Coherent Structures in Rayleigh-Bénard Convection with a Time-dependent RANS

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Abstract: A time-dependent Reynolds-average-Navier-Stokes (TRANS) method is applied to capture and analyze the large-scale coherent structure in Rayleigh-Bénard (RB) convection over a flat and wavy bottom wall at a range of Rayleigh numbers. The method can be regarded as a Very Large Eddy Simulation (VLES) in which the unresolved random motion is modelled using a low-Re-number $k-\varepsilon-\theta$ algebraic stress/flux single-point closure model. The large scale motion, which is the major mode of heat and momentum transfer in the bulk central region, is fully resolved by the time solution. In contrast to LES, the contribution of both modes to the turbulent fluctuations are of the same order of magnitude. The approach was assessed by comparison with the Direct Numerical Simulations (DNS) and experimental data using several criteria: visual observation of the large structure morphology, different structure identification criteria, and long-term averaged mean flow and turbulence properties. A visible similarity with large structures in DNS was observed, confirming the suitability of TRANS approach to reproduce the flows dominated by large coherent motions.

Keywords: Rayleigh-Bénard convection, structure identification, time-dependent RANS.

1. Introduction: Some Features of Rayleigh-Bénard Convection

A distinct feature of a laminar Rayleigh-Bénard convection are the stable convective cells which fill the vertical spacing between the two horizontal walls. Their origin is in plumes which rise from the outer edge of the boundary layer at the heated surface (updrafts) and sink downward from the upper cold boundary (downdrafts). The rise of plumes and their impingement on the opposite horizontal surface produce a horizontal motion in the wall boundary layer which governs the wall heat transfer. This in turn generates buoyancy which causes the rise of plumes. With an increase in Rayleigh (Ra) number the regularity of the cell pattern disappears, the plumes detach from the horizontal boundary layers and evolve into thermals, the large structure becomes unsteady and more disorderly. Despite extensive research, it is still difficult to determine whether this structure in turbulent regimes can be regarded as a form of mean motion (with inherent unsteadiness), or it evolves at a certain Ra number fully into turbulence (smooth spectrum and PDF) while retaining some coherence related to the flow geometry, (vertical dimension) and boundary conditions.

Both, the experiments (e.g. Chu and Goldstein, 1973) and DNS (Grözbach, 1982; Cortese and Balachandar, 1993) indicate that despite disorder, large coherent structure can be identified even at very high Ra numbers. Recent DNS by Kerr (1996) in the range of Ra numbers close to hard turbulence regime (Ra ≤ 2 × 10^6) show that the large structure governs the apparent chaotic behaviour of turbulent RB convection. This evidence indicates the existence of two distinct scales of motion: large amplitudes associated with thermals, plumes and convective cells, and the turbulence generated mainly in the wall boundary layer and carried away by the large scale structure.
1.1 The Time-dependent RANS and Large Structure

The dominant role of the large-scale structure in transporting momentum and heat is the major reason of failure of the conventional single-point closures to reproduce the mean flow features and turbulence statistics in Rayleigh-Bénard convection, even though in long-term average the flow seems very simple with only one (vertical) inhomogeneous direction. The main deficiency of eddy-viscosity/diffusivity models is the gradient transport hypothesis for the momentum and heat flux. The second-moment closure, in which the turbulent flux is provided by differential equation, offers no better prospects because the gradient transport model of triple moments and, especially, of pressure diffusion seems to be totally inadequate for this type of flows (e.g. Wörner, 1994). The only way to capture the large-scale-transport is to resolve this motion in space and time, as practiced in DNS or LES. However, the latter techniques are still restricted to low Rayleigh numbers and simple geometries and are at present inapplicable to complex flows.

The separation of the scales of the coherent convective cellular motion and the rest of turbulence in RB convection (and other turbulent flows with dominant large structure) offers a possibility to apply the RANS approach in transient mode. By fully resolving the large-scale convective structure and associated momentum and heat transport (regarded as particularly difficult to model with single-point closures), a simple eddy-diffusivity or algebraic closure can be used to model the unresolved motion. Applying the triple decomposition of the instantaneous motion into long-term mean, the large-scale periodic and random fluctuations, the turbulence statistics can be evaluated as a sum of the large-scale contribution (resolved motion) and the unresolved contribution obtained from a single-point model (Kenjereš and Hanjalić, 1998). As compared with LES, the model accounts almost fully for the turbulence statistics in the near-wall region. The TRANS brings also a substantial computational advantage. The 'subgrid-scale model' here RANS, is less dependent on the spatial grid, the time step can be larger, allowing implicit time marching, the numerical mesh away from a solid boundary does not need to be very fine, and a good statistics can be obtained with a relatively small number of realizations. The problem of defining inflow conditions at open boundaries is less restrictive. The method can be applied at much higher $Ra$ numbers than it is possible with LES and can, therefore, be used for computation of complex flows of practical relevance.

The application of the TRANS to the computation of Rayleigh-Bénard convection over a flat and wavy wall for a range of Rayleigh numbers produced mean temperature and second-moments (turbulent heat flux and temperature variance) in excellent agreement with several sets of experimental and DNS data (Kenjereš’s and Hanjalić, 1998).

In this paper we present some results of a further qualitative analysis of the large structure morphology, using different flow visualization techniques and structure-identification criteria. Additional TRANS computations have been performed at the same Rayleigh number as for DNS of Wörner (1994) to enable a direct comparison. The transient realizations are analyzed using the criteria from the critical point theory for filtering of the coherent structure, studying its spatial organization and its role in RB convection at high Rayleigh numbers.

Numerical simulation were performed by a fully vectorised version of the finite volume Navier-Stokes solver for three-dimensional flows in structured non-orthogonal geometries, with Cartesian vector and tensor components and collocated variable arrangement. The second order accurate central difference scheme (CDS) was applied to discrete diffusion terms and second order linear-upwind scheme (LUDS) and CDS for convective terms. The time marching is performed by fully implicit second order three-time-level method which allows larger time steps to be used, in view of the fact that only large scales are being resolved. Typical computations covered 150–400 nondimensional time units $\tau^* = \frac{\tau \sqrt{\rho g \Delta T H}}{H}$ which correspond roughly to 10 –30 convective time scales based on convective velocity and characteristic cell circumference (Kerr, 1996). Considered were two different configurations and three values of $Ra$ number: (a) the case with a horizontal flat wall at $Ra = 6.5 \times 10^5$ and $10^7$ for which two different aspect ratios were considered (4:4:1 and 8:8:1) with the grid of 62 and 122 $\times$ 62 CV respectively, and $Ra = 10^7$ (with 4:4:1 aspect ratio and grid size of 82 $\times$ 82 CV), and (b) the case with a wavy horizontal wall, with the wavelength $\lambda = H$ and the wave amplitude $\delta = 0.1H$ with aspect ratio (4:4:1), (grid size 102 $\times$ 82 CV).

The larger value of $Ra$ number ($10^7$) was chosen in order to demonstrate applicability of TRANS to high $Ra$ numbers where the DNS is still inapplicable (Grötzbach, 1983; Kerr, 1996). The configuration with a wavy horizontal wall was performed to investigate effects of waviness on the spatial organization of the large flow structure and heat transfer, as well as to demonstrate applicability of the method for flows in nonorthogonal geometries.