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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 $k–\varepsilon–\overline{\theta^2}$ 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 ($Ra \leq 2 \times 10^7$) 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 time 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 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 discretise 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 nondimensionall time units $\tau^* = \tau\sqrt{\beta g \Delta T H}/H$ 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 62^3 and $122^2 \times 62$ CV respectively, and $Ra = 10^9$ (with 4:4:1 aspect ratio and grid size of 82^3 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 102×82^2 CV).

The larger value of Ra number (10^9) 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.

2. Structure-morphology Identification Criteria

The process of visualization and interpretation of the physical characteristics of three-dimensional unsteady velocity and vorticity fields and their dynamical evolution are still a challenge mainly because of their vector character. The most common approach in the representation of the salient features of three-dimensional unsteady fields is to "freeze" the instantaneous fields and to apply the classical methods for steady-state regimes and plotting velocity vectors, streamlines and contours of scalar quantities such as temperature, turbulent kinetic energy, temperature variance etc. The RB convection at higher values of Rayleigh numbers is particularly challenging problem because the general pattern of the flow is not known in advance. Besides there are still many controversial explanations about the structure of the flow.

The most common definition of coherent structures is associated with vortical motion. However, different possibilities for identification of vortex cores as representatives of a vortical motion have been proposed as well as the definitions of a vortex. Following Robinson (1991), a vortex is defined by a circular or spiral pattern of the instantaneous streamlines mapped onto a plane normal to the vortex core, when viewed in the reference frame moving with the vortex core center. But streamlines representation requires a significant CPU time and very often it does not bring a clear picture of the flow, especially in complex situations. In order to avoid extensive calculations, the introduction of some representative scalar quantities is needed. Robinson (1991) proposed low-pressure regions as regions which are expected to correspond well to the vortex cores. Kasagi (1995), adopted the same approach in analyzing their DNS database of the channel flow by plotting the instantaneous vectors in various sections and found that many of the low-pressure regions correspond to the rotational fluid motions. But low-pressure regions can misrepresent the vortex core due to non-local character of the pressure which may have a larger scale than the vortex core, as shown by Joeng and Hussain (1995). The next scalar parameter used for the identification of the flow topology is the modulus of vorticity: $|\omega_i| = |\varepsilon_{ijk}\,\partial U_j/\partial x_k|$. This approach was successful in free-shear flows, Joeng and Hussain (1995), but problems appears in near-wall regions where the high vorticity originates from shear and not from a swirling or rotational motion. This leads to a conclusion that $|\omega_i|$ is not a suitable parameter for vortex identification in RB convection.

A method of critical points (defined as positions where the streamlines slope is indeterminate and the velocity is zero) was introduced in Perry and Chong (1987) in order to assess the flow pattern at each point of the flow. According to this theory, the eigenvectors and eigenvalues of the mean velocity gradient tensor ($A_{ij} = \partial U_i/\partial x_j$) evaluated at a critical point define the flow pattern. The eigenvalues and eigenvectors of the velocity gradient tensor (A_{ij}) are obtained by solving the characteristic equation, $\lambda^3 - I_1\lambda^2 + I_2\lambda - I_3 = 0$, where $I_1 = \partial U_i/\partial x_i$ $I_2 = -1/2$ $(\partial U_i/\partial x_j)$ $(\partial U_j/\partial x_i)$ and $I_3 = Det\ (A_{ij})$ are three invariants of A_{ij} and for incompressible flows $I_1 = 0$.

A definition of vortex core as a region with complex eigenvalues of A_{ij} was proposed in Chong *et al.* (1990), implying that the local streamline pattern is closed or spiral in a reference frame moving with the point of interest. The discriminant of the characteristic equation can be written as:

$$\Delta = \left(\frac{1}{3} I_2\right)^3 + \left(\frac{1}{2} I_3\right)^2 \qquad (1)$$

This determines the nature of the eigenvalues of A_{ij} as follows: $\Delta > 0$ gives one real and two conjugate-complex eigenvalues, $\Delta < 0$ gives three real distinct values and finally, $\Delta = 0$ gives three real values of which two are equal. A map of all possible solutions of characteristic equations can be created by plotting trajectories of constant discriminant Δ in I_2-I_3 plane. From definition of the discriminant of the characteristic equation it follows that complex eigenvalues occur when $\Delta > 0$. Recently, Chong *et al.* (1998) applied their "Δ" approach to analyze structures of wall-bounded shear flows including the zero-pressure-gradient flow and the boundary layer with separation and reattachment. They found that a positive small value of the discriminant identifies very well vortical regions.

The definition of the eddy structure as the region with positive second invariant I_2 of the velocity gradient tensor A_{ij} was introduced in Hunt *et al.* (1988). The second invariant I_2, denoted in figures as Q in accord with notation of Hunt *et al.* (1988) can be interpreted as a measure of the relative importance of the strain $S_{ij} = 0.5(\partial U_i/\partial x_j + \partial U_j/\partial x_i)$ and the rotation rate $\Omega_{ij} = 0.5\ (\partial U_i/\partial x_j - \partial U_j/\partial x_i)$. Where I_2 is positive, the rotational rate prevails over the strain rate and where I_2 is negative, the reverse is true.

A kinematic vorticity number N_k was used in Melander and Hussain (1993) as a measure of the quality of rotation, defined as:

$$N_k = \left(\frac{|\omega_i|^2}{2S_{ij}S_{ij}} \right)^{1/2} \quad (2)$$

When $N_k = 0$, the irotational motion is present and in the case $N_k = \infty$, the motion has a character of a solid-body rotation. In the present identification of the large coherent structures in RB convection, we analyse in parallel one realisation of DNS and several realisations of TRANS, using three different criteria: Δ, I_2, and N_k.

2.1 Flow Visualization: Streamline Patterns, Planform Structures and Fingerlike Plumes

Before applying the critical-point criteria, we compare first some results of visualization of the instantaneous structure patterns (randomly selected realizations) in DNS and TRANS computations for the same or similar Rayleigh numbers. Of particular interest is the identification of the finger-like regions with intense spiraling updrafts extending in vertical direction. Cortese and Balachandar (1993) detected such a structure in their DNS arguing that the origin of vorticity is in horizontal flow induced by large scale motion towards irregularly spaced updrafts (or away from irregularly spaced stagnation points), which is tilted and stretched by buoyancy in vertical direction, producing spiral structures. Fig. 1(left), obtained by releasing a number of massless particles in one frozen realization of DNS of Wörner (1994) and one TRANS realization, indeed supports the above finding: the trajectories show a spiraling tendency. A release of particles from line sources placed at the vertical midplane (Fig. 1 (right)) showed also the spiraling motion around randomly oriented horizontal axes. A better proof to the existence of three-dimensional vortical structure is obtained by plotting the projection of instantaneous trajectories on the central horizontal plane, $z^* = 0.5$ and on three vertical planes, $y^* = 0.15, 0.5, 0.85$. In Fig. 2, the trajectories are plotted by releasing 1500 massless particles from uniformly distributed origins over the sampling planes of the instantaneous fields, and their distributions were calculated by applying second order Runge-Kutta time advection method. Although the streamline pictures portray very complex flow, three main distinctive regimes can be easily observed: the regions with strong and well defined plane circulation (roll structure), the regions with one-dimensional movements (dark lines) and divergent stagnation regions (unstable focus points). As seen, the DNS and TRANS results show qualitatively very similar patterns. The only difference is in the size of the rolls - DNS shows smaller roll patterns, but this is to expect because the TRANS can per se capture only the very large structure while the smaller ones are filtered out. The comparison of vector velocity fields obtained by DNS (Balachandar, 1992) and TRANS, is given in Fig. 3 showing very similar patterns as well as the temperature fields. In order to demonstrate further the similarity between the hydrodynamic fields and to illustrate that this pattern similarity extends also to the thermal field, the isosurfaces of the temperature, colored with the vertical velocity component, are shown in Fig. 4. The visualized fields show a network of polygonal cell type structures with fingerlike plumes in between. These plumes are actually the main carriers of heat, and the plume locations

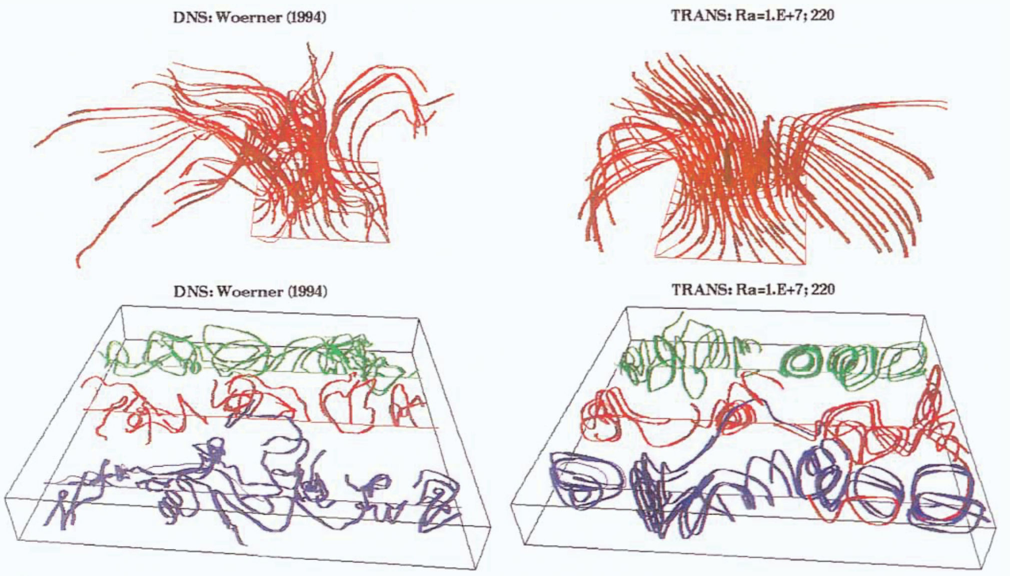

Fig. 1. Instantaneous trajectories of massless particles in DNS at $Ra = 6.5 \times 10^5$(left) and TRANS at $Ra = 10^7$ (right) indicating spiraling updrafts (above) and evolution from three line sources (below).

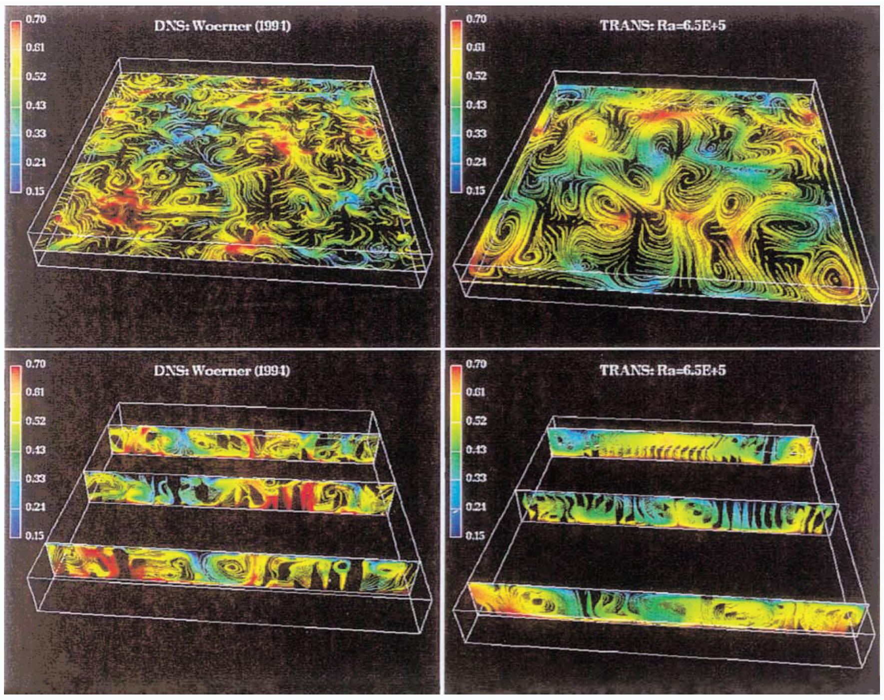

Fig. 2. Temperature colored instantaneous trajectories in the central horizontal plane and on three vertical planes in DNS (left) and TRANS (right), (both at *Ra* = 6.5×10^5).

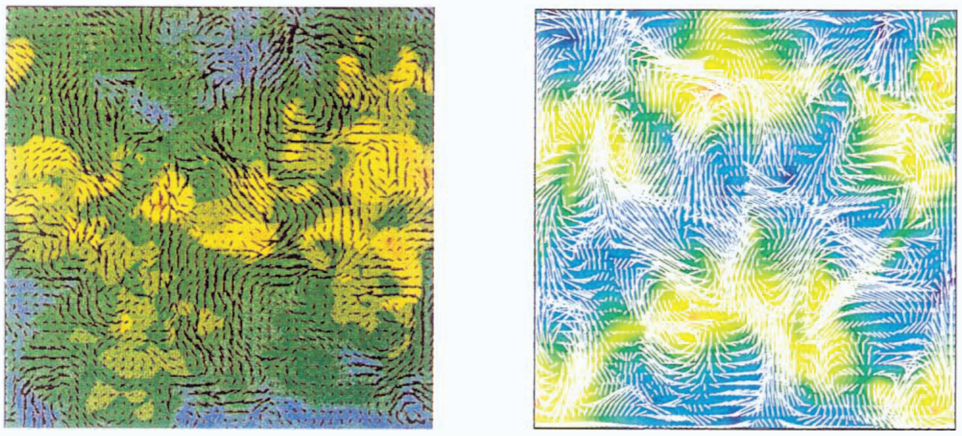

Fig. 3. Velocity vectors and colored temperature field at the horizontal midplane in DNS (left), Balachandar (1992) and TRANS (right), (*Ra* = 6.5×10^6).

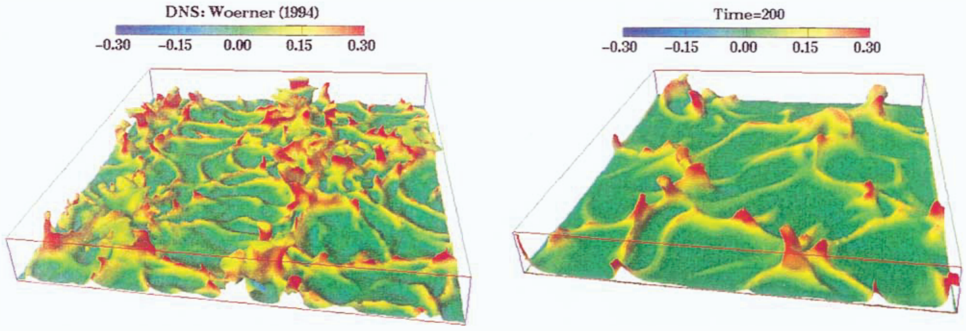

Fig. 4. Planform structure with fingerlike plumes in between in DNS (left) and TRANS (right) (*Ra* = 6.5×10^5); temperature isosurfaces colored with the intensity of the vertical velocity.

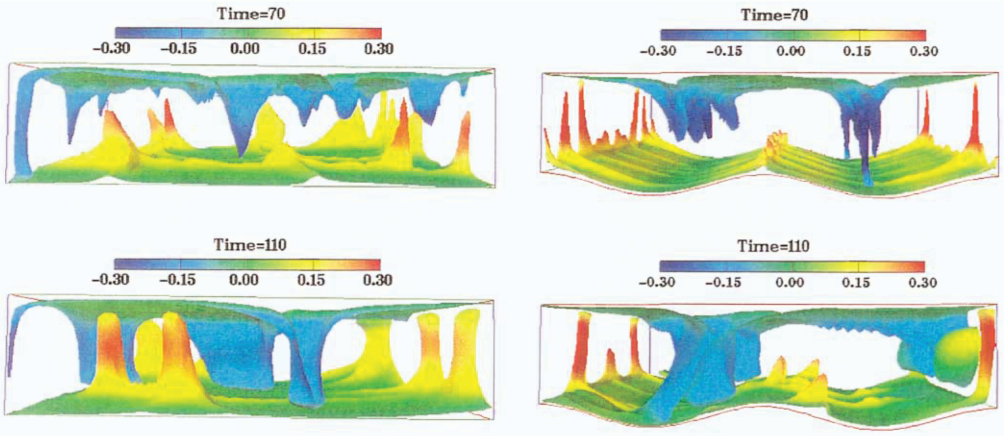

Fig. 5. Side view of fingerlike plumes for flat and wavy wall at *Ra* = 10^9(TRANS).

correspond to those where the local Nusselt numbers reach their maximum values, Fig. 5. The plumes move randomly and interact with each other causing a strong vertical motion. Again, very similar pictures were obtained for DNS and TRANS results, except for a difference in scales. The identical scenario of planform structures have been observed in experimental studies of Theertan and Arakeri (1997).

2.2 Structure Identification: Effects of the Bottom Wall Topology

In order to provide a further analysis of the spatial organization of the flow, various vortex identification techniques were applied in parallel to DNS and TRANS realizations. The second invariants of the velocity gradient tensor ($I_2 = Q$) are presented in Fig. 6. By taking different positive values of I_2, regions with different vortical intensities can be easily filtered out. With decreasing values of I_2, the vortical eddy population becomes more dense. In parallel to I_2, the Δ approach was applied to the same dataset. Very similar structures were captured with both methods. The same identification techniques were applied for instantaneous TRANS results. As seen, many of the characteristic vortical-eddy shapes observed in DNS field are recognized in TRANS results, too.

We turn now to the application of the structure identification in more complex flows. An example we consider in parallel the Rayleigh-Bénard convection over a flat and wavy wall at a high Rayleigh number ($Ra = 10^9$), which is inaccessible to DNS. The wavy wall is expected to impose a dominant orientation of the eddy structure, in this case in U and W velocity components. In order to select a representative realization in a fully developed regime, the characteristic time evolution of the maximum velocity components and of the overall Nusselt number at hot and cold wall are monitored in both cases. For the flat wall, the initial period ($0 < \tau^* < 40$) is characterized by slow activities, which is succeeded by a fast development of a convection dominated regime, characterized by a dramatic increase of all velocity components and, consequently, by very intensive heat transfer. A fully developed regime characterized by irregular but periodic oscillation of monitoring properties of similar amplitudes and frequency and constant overall Nusselt numbers on both walls, is established roughly at $\tau^* \approx 70$. At the end of this period, the streamline distribution shows a very intensive motion over the entire flow domain, Fig. 7. The spatial distributions of the second invariant of the velocity gradient tensor (I_2) are evaluated and presented in the same figure in order to portray the organized structures in the flow. By means of the visual inspection of the

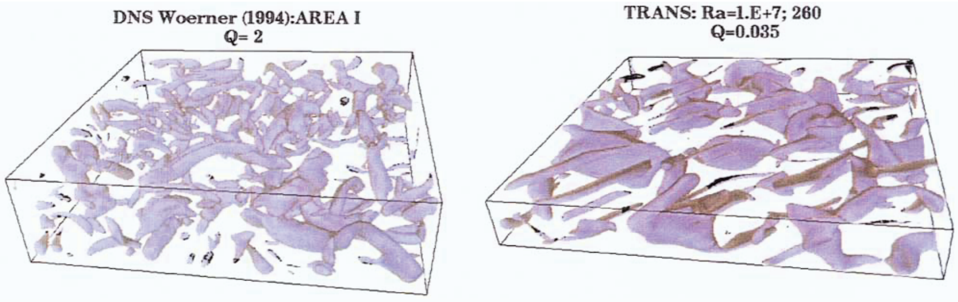

Fig. 6. Morphology of vortical structure in DNS and TRANS; Q is the second invariant of the velocity gradient tensor.

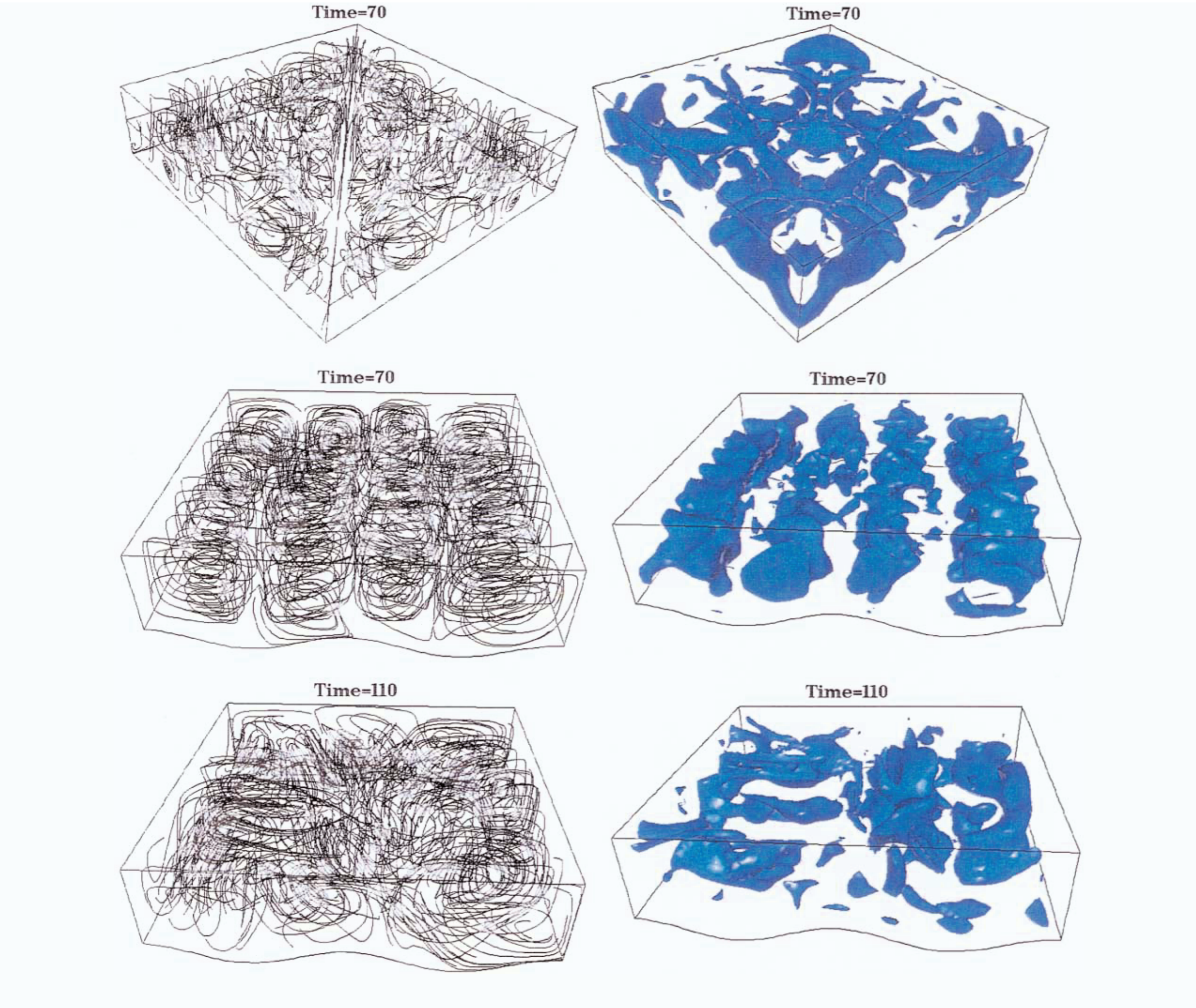

Fig. 7. Instantaneous trajectories of massless particles released at midplane (left) and contours of the second invariants of velocity gradient tensor (right) for flat and wavy wall.

streamlines and the corresponding distribution of I_2, it seems that I_2 approach captures well the regions where rotation is present. Very similar pictures are obtained by applying Δ and N_k criteria.

A similar analysis is applied for the configuration with the horizontal wavy wall. Because of the wave pattern orientation, the V velocity component develops significantly slower in comparison with the other two. The pronounced increase in heat transfer occurs much earlier than in the case with horizontal flat wall ($\tau^* = 10-20$ instead of $\tau^* = 40$–60). After this initial period of time, the distribution of the overall Nusselt number shows almost a constant value ($30 < \tau^* < 110$). A slight increase is noticed at the time instant $\tau^* \approx 110$ when V velocity component reaches the same value as other two velocity components. This increase in V destroys the dominant two-dimensional orientation of the large structures and, consequently, produces a batter mixing and intensification of the heat transfer. This conclusion is confirmed by distributions of streamlines as well as the kinematic vorticity number at two different time steps, $\tau^* = 70$ and $\tau^* = 110$, Fig. 7.

The two-dimensional orientation of both streamlines and N_k is clearly visible at the $\tau^* = 70$. At the later stage ($\tau^* = 110$), the complete reorganization of the flow takes place and, as a consequence, a higher heat transfer occurs than in the case with the flat wall. Again, very similar distributions of the large coherent structures were obtained by applying other criteria, I_2 and Δ.

3. Conclusions

Numerical simulations of Rayleigh-Bénard convection with a conventional single-point turbulence closure demonstrate that the time-dependent Reynolds-Averaged-Navier-Stokes method (TRANS) reproduces mean flow properties, wall heat transfer and second-moment turbulence statistics. Moreover, the computations capture the large scale-structure in accord with DNS and experimental findings. The approach can be regarded as Very Large Eddy Simulations, with a single-point closure playing the role of a 'subgrid scale model.' In comparison with the conventional LES, the model of the unresolved motion (here an algebraic $k-\varepsilon-\overline{\theta^2}$ model) covers a much larger part of turbulence spectrum (in fact almost the complete turbulence, apart from the large coherent structure). The weaknesses of the conventional single-point model, particularly in regard to the convective transport by large structures (modelled usually as turbulent gradient diffusion) are removed by time and space resolution of the large structures. The computed mean temperature, its variance, turbulent heat flux and wall heat transfer for Rayleigh-Bénard convection over a flat and wavy wall in a range of Rayleigh numbers ($6.5 \times 10^5 \div 10^9$) agree well with available DNS and experimental results. Application of several structure identification methods (second invariant of the velocity gradient tensor, discriminant of the characteristic equation, and kinematic vorticity number) to a parallel analysis of selected TRANS and DNS realizations show a close similarity of the spatial organization and features of the large coherent structure. This is also confirmed by instantaneous trajectory visualization.

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