SIMULATION AND IDENTIFICATION OF SEMI-DETERMINISTIC STRUCTURES IN TURBULENT CONVECTION

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Large-scale vortical structures are found in many fluid flows whether in the laboratory, in nature or in industrial equipment. They play major role in transporting momentum, heat and species and often provide the major communication link between the bounding walls controlling thus friction and drag, heat and mass transfer. Often, as in the case of vortex shedding, in flows driven by thermal buoyancy, or subjected to magnetic field or system rotation, the large structures have a deterministic character. Vortical structures also appear in laminar flows, but in turbulent regimes it is not always clear whether these structures should be regarded as "true" turbulence, or whether they should be interpreted as a form of secondary motion with inherent, but deterministic (organized) unsteadiness.

INTRODUCTION

Whatever their origin the identification of vortical structures and their morphology is the key prerequisite for understanding their role in controlling the flow and transport processes. Properly identified, coherent structures can be subjected to various methods of flow control and tested for optimum performance for the preset optimization criteria. Several techniques for structure identification have been proposed and used successfully, but they all require detailed information about the instantaneous velocity and scalar fields. Such information can be provided by direct or large-eddy numerical simulations (DNS, LES), or by extensive and tedious experiments. However, all these techniques have serious limitations: because of excessive demand on computational resources, DNS and LES are still restricted to simple geometries and low-to-moderate Reynolds and Rayleigh numbers, while experiments are still limited in the extent of information they can provide, and are very time-consuming. Handling complex geometries and, especially, resolving the flow very close to solid walls bounding the flow, are the challenges that still pertain. On the other hand, the RANS (Reynolds-average Navier-Stokes) approach, used widely for computational prediction of complex turbulent flows, cannot recognize any specific eddy structure because of inherent one-point and single-scale assumptions.

VERY LARGE EDDY SIMULATIONS BY T-RANS

In order to overcome the cost and capacity problems and still resolve large-scale structures - at least in flows where they play a dominant role, several combined or hybrid methods have been proposed recently, aimed at utilizing advantages of the simplicity and computational efficiency of RANS, and the potential of LES to fully resolve the large-scale part of the turbulence spectrum. These methods can generally be classified as Very-Large Eddy Simulation (VLES), the name implying essentially a form of LES with a cut-off filter at much lower wave number. This means: resolve less and model more! Modeling a larger part of the spectrum requires a more sophisticated model than the standard sub-grid-scale model, i.e. a form of RANS model that is not related to the size of the numerical mesh. The solution of the resolved part of the spectrum can follow the traditional LES practice using grid size as a basis for defining the filter (hence the name hybrid RANS/LES), or solve ensemble- or conditionally averaged equations, which implicitly involve time filtering. The latter method, called T-RANS (Transient RANS) is discussed in this paper with specific application to confined turbulent flows subjected separately or jointly to thermal buoyancy and magnetic field.

METHOD VERIFICATION BY STRUCTURE IDENTIFICATION

The primary criteria for verifying a solution method in fluid mechanics and transport phenomena involve integral parameters (friction, heat and mass transfer coefficient) and averaged velocity, temperature and concentration fields. However, such properties give no indication about vortical structures and reasonable agreement with reference data (e.g. provided from experiments) can sometimes be obtained even if the structures are fully ignored or not properly captured. Either the coherent structures play no important role in spatial or temporal nonuniformity (e.g. in wall attached - non-separating flows, dominated by pressure gradient), or the errors in models of various terms in equations compensate each other. Needless to say that in the latter case strong spatial and temporal variations in flow properties with possible excessive values, e.g. extrema in friction or heat transfer (hot spots) may either remain hidden or be predicted wrongly.

Since VLES is an approximate method aimed at capturing only large coherent or deterministic vortical structures, where they exist, the best verification of this approach is to compare identifiable structures obtained by VLES with those computed by DNS or LES. Here one has a choice between several identification techniques and criteria: relative or maximum vorticity moduli, kinematic vorticity number, pressure minimum, the Q criterion (second invariant of velocity gradient tensor), the λ_2 criterion (second eigenvalue of the characteristic equation of the velocity gradient tensor), and others. While in some flows, different criteria may give very similar outcome, in other flows (e.g. close to a solid wall) this may not be the case and a careful selection is needed to reach clear identification of coherent structures.

EXAMPLES: CONVENTIONAL AND MAGNETIC RAYLEIGH-BENARD CONVECTION

We present some results of application of various methods for the identification of distinct structure morphology and their use to validate the VLES approach in examples of classic Rayleigh-Benard (R-B) convection over walls with flat and corrugated topography, and in the case that the system is also subjected to a magnetic field (1,2). These structures are known to exist in such flows as a consequence of self-organization of convective roll cells. First, large-scale deterministic structures captured with VLES will be compared with those obtained by DNS and LES for the same Rayleigh number, using several identification criteria. Next, some results of structure reorganization in R-B convection at very high Rayleigh numbers will be presented, illustrating the potential of VLES to handle such flows and to get an insight into eddy structure morphology in conditions which are inaccessible to either DNS, LES or even experiments. The last example involves combined effects of thermal buoyancy and magnetic field in magnetic R-B convection, which is featured by a strong reorganization of large-scale vortical structures, with a profound effect on wall heat transfer. Enclosed figures illustrate some of the findings that will be discussed in the full paper.

REFERENCES

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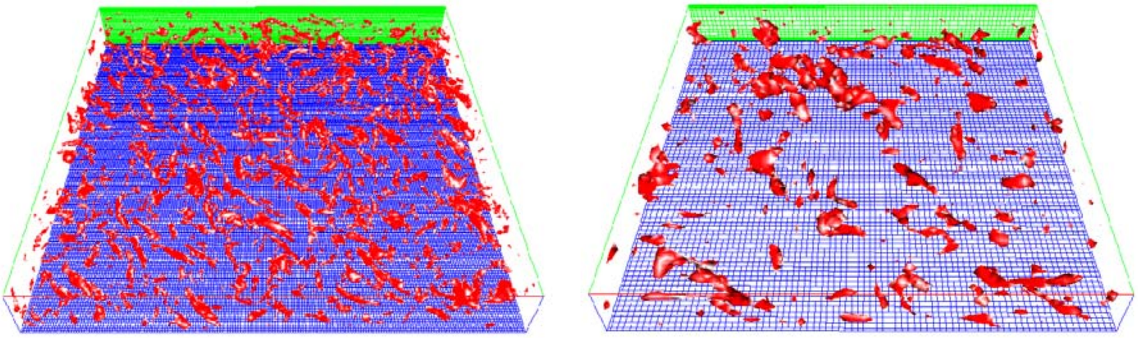

Figure 1*: Qualitative comparison of captured vortical structures (N_k=2) for DNS and T-RANS realizations:* Ra=6.5×10^5, Pr=0.71*; perspective view with underlying mesh*

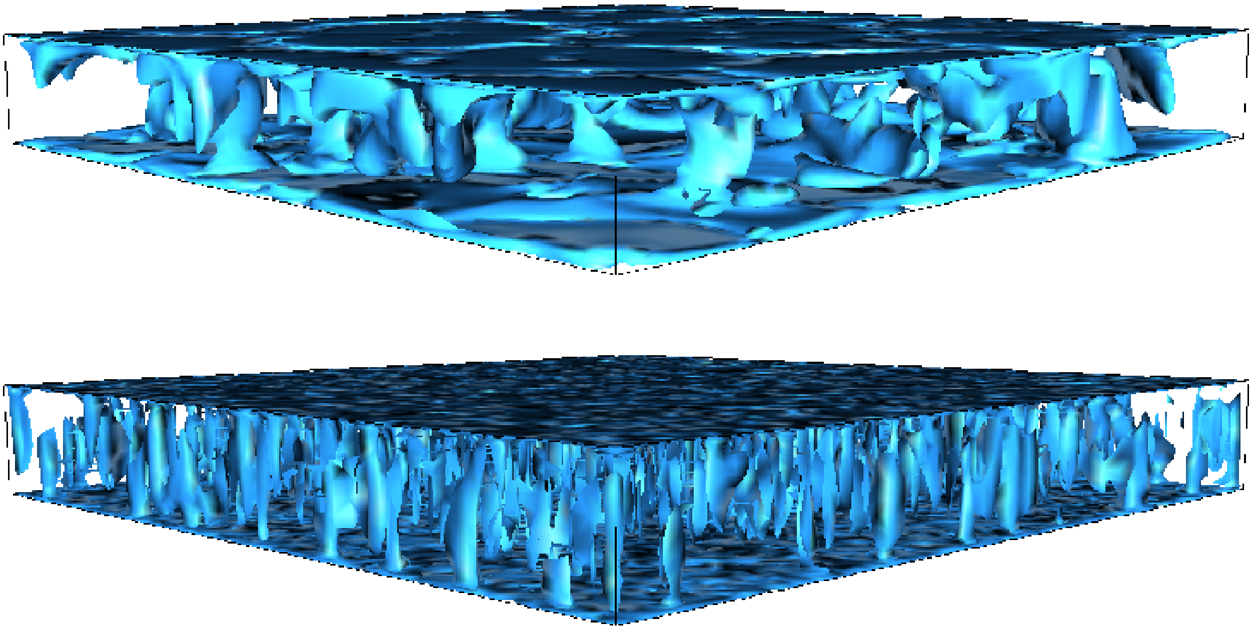

Figure 2: *Effect of magnetic field on spatial reorganization of vortical structures,* Ra=10^7, Ha=0,100; *modulus of vorticity* $\left|\omega_i\right| = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} = 5\%\left|\omega_{\max}\right|$

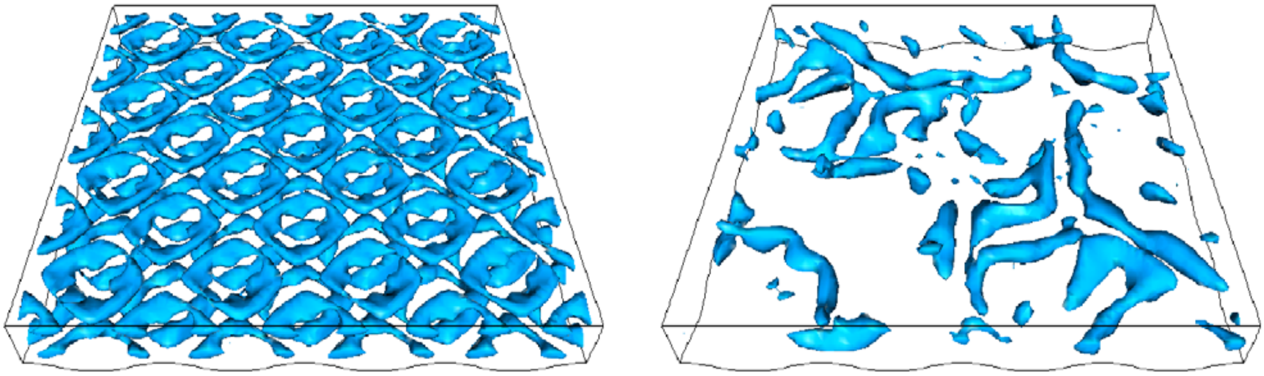

Figure 3*: Time evolution and spatial organization of large coherent structures defined and identified by* N_k=2 *at* τ^*=50 *(left) and* τ^*=200 *(right), 3D waviness*, S_B=0.1cos(xπ) cos(yπ)