Mechanical Engineering Doctoral Defense

Identification, Decomposition and Analysis of Dynamic Large-Scale Structures in Turbulent Rayleigh-Bénard Convection

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abstract

The central purpose of this work is to investigate the large-scale, coherent structures that exist in turbulent Rayleigh-Bénard convection when the domain is large enough for the classical "wind of turbulence" to break down. A series of visualization studies, Fourier analysis and proper orthogonal decomposition (POD) are employed to qualitatively and quantitatively inspect the large-scale structures' length and time scales, spatial organization, and dynamic properties. The data in this study is generated by direct numerical simulation to resolve all the scales of turbulence in a 6.3 aspect-ratio cylinder at a Rayleigh number of 9.6x107 and a Prandtl number of 6.7. Single and double point statistics are compared against experiments and several resolution criteria are examined to verify that the simulation has enough spatial and temporal resolution to adequately represent the physical system. The large-scale structures are found to organize as roll-cells aligned along the cell's side walls, with rays of vorticity pointing toward the core of the cell. Two different large-scale organizations are observed and these patterns are well described spatially and energetically by azimuthal Fourier modes with frequencies of 2 and 3.These Fourier modes are shown to be dominant throughout the entire domain, and are found to be the primary source for radial inhomogeneity by inspection of the energy spectra. The precision with which the azimuthal Fourier modes describe these large-scale structures shows that these structures influence a large range of length scales, and are modal in nature. Conversely, the smaller scale structures are found to be more sensitive to radial position within the Fourier modes showing a strong dependence on physical length scales. Dynamics in the large-scale structures are observed including a transition in the global pattern followed by a net rotation about the central axis. The transition takes place over 10 eddy-turnover times and the subsequent rotation occurs at a rate of approximately 1.1 degrees per eddy-turnover. These time-scales are of the same order of magnitude as those seen in lower aspect-ratio Rayleigh-Bénard convection for similar events and suggests a similarity in dynamic events across different aspect-ratios.

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