Helicity of turbulent flow with coherent structures in Rayleigh-Bénard convective cell

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Abstract We present results of experimental study of turbulent flow with large scale structures in Rayleigh-Bénard convective cell. Experiments were conducted in air flow in a rectangular chamber with a heated bottom wall and a cooled top wall. Velocity field was measured using a digital particle image velocimetry (PIV) in 15 cross-sections parallel to the vertical walls of the chamber. Experiments revealed three distinct flow components in a large scale circulation (LSC): (i) a main roll with a length scale of a size of the chamber that been observed in previous studies and (ii) two elongated vortex rings adjacent to the bottom and top of the main roll. A characteristic length scale of a vortex in two eddy rings is by a factor of 5 smaller than a length scale of a main roll. A mean horizontal velocity of the main roll and a mean vorticity of two eddy rings are aligned in the center of a cell so that the helicity of the mean flow is quite high. We estimated helicity of turbulence using the measured cross-correlation functions of the velocity field. Spectra of turbulence reveal two distinct ranges in the inertial interval with slopes close to $-5/3$ and $-7/3$. Remarkably, similar inertial subranges in turbulent velocity spectra were observed in various geophysical and astrophysical turbulent flows. We found that the magnitude of the length scale where a slope of the velocity spectra changes and the magnitude of the length scale defined as a ratio of turbulent energy to the helicity are close. Since the mean and turbulent components of the flow velocity field in a Rayleigh-Bénard convective cell are helical, the Rayleigh-Bénard convection allows investigating properties of helical turbulence which is quite difficult in other flow configurations.

EXPERIMENTAL SET-UP

Experiments were conducted in a rectangular chamber having a height Z, a length Y, a width X (26×58×26 cm^3 with aspect ratio 2.23) with a heated bottom wall and a cooled top wall (Fig. 1). The side walls of the chambers are made of transparent Perspex with the thickness of 10 mm. The top wall of the chamber is a bottom wall of the aluminum tank with circulating cooling water having a constant temperature. The aluminum bottom plate is attached to the electrical heater that provides a constant heat flux and uniform heating. Temperatures of the top and bottom plates were measured with four thermocouples attached at the surface of each plate. The experiments were conducted in air flow with a mean temperature of $308K$ and temperature difference of $\Delta T = 50K$ between the bottom and the top walls that corresponds to the Rayleigh number of the order of $Ra = 10^8$. Velocity fields were measured using a digital particle image velocimetry (PIV) in perpendicular planes in the center of the chamber: 5 cross-sections in YZ plane (frontal cross-sections having a size 42×24 cm^2) and 10 side cross sections in XZ plane (side cross-section having a size 23×23 cm^2) with the distance of 5 cm between the adjacent sections. Sets of 130 pairs of images acquired with a frequency of 1 Hz were stored for calculating the velocity maps and for ensemble and spatial averaging of turbulence characteristics. Mean and r.m.s. velocities, Reynolds stresses, mean vorticity, spectra of turbulence, two-point cross-correlation and correlation functions were determined in the measured velocity fields using averaging over the instantaneous maps. Helicity of the mean flow H_m was determined as a product of the mean velocity U_y and the mean vorticity ω_y components measured in intersections of YZ and XZ velocity maps. The mean helicity H_m was averaged over all 10 intersections of each front view cross-section with every side view cross sections. Helicity of turbulence H_e was obtained in the approximation of locally homogeneous and isotropic turbulence using a cross-correlation function of the velocity [1].

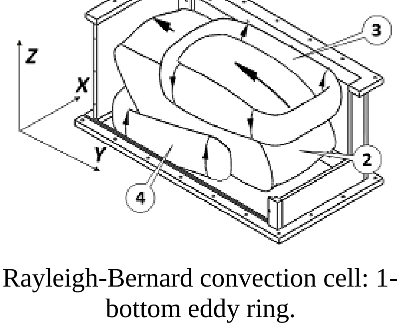

Figure 1. Large scale circulation flow in Rayleigh-Bernard convection cell: 1- chamber, 2 – a roll, 3 –top eddy ring, 4 – bottom eddy ring.

RESULTS AND DISCUSSION

Large-scale circulation (LSC) in Rayleigh-Bénard convection was investigated previously in our laboratory experiments [2]. Three different flow components in the LSC are shown in Fig. 1. Inspection of Fig. 1 reveals a main roll having a vorticity which is aligned in X direction and a length scale of the order of the size of the chamber. This feature of the flow in Rayleigh-Bénard convective cell has been reported previously [2] while the existence of two eddy rings adjacent to the bottom and top of the main roll and elongated in Y direction is reported here for the first time. A length scale of a vortex in these two eddy rings is by a factor of 5 smaller than the length scale of the main vortex. A mean horizontal velocity of the main roll and the mean vorticity of two eddy rings are aligned in a central region of the flow so that the mean helicity of a flow H_m is relatively large. Inspection of the distribution of the mean helicity H_m in a side cross-section shows that the signs of the mean helicity in the left and in right regions in the flow are opposite. A ratio of turbulent kinetic energy to the turbulent helicity H_e determines a characteristic length scale L_m that is of the order of $7 - 10$ cm. Distribution of turbulent kinetic energy is close to the distribution of the turbulent kinetic energy in a homogeneous and isotropic turbulence in the significant part of the central flow region. Measured spectra of three components of the velocity reveal two sub-ranges in the inertial interval having different exponents: one is close to the Kolmogorov's $-5/3$ slope for larger scales and the other has a slope of $-7/3$ for smaller scales. Velocity spectrum of u_y is showed in Fig. 2, where the transition between these two sub-ranges in the velocity spectrum in log-log coordinates occurs at the characteristic length scale L_s of the order of $7 - 9$ cm. The latter length scale is of the order of the length scale determined by the ratio of the turbulent kinetic energy and helicity, L_m. Analysis of the obtained experimental data allows to make a conjecture that turbulent convective flow in a closed volume, e.g. in a Rayleigh-Bénard convective cell, has a nonzero helicity that is manifested by the velocity spectrum [3]. The spectral density of the helicity of the mean flow is distributed over an interval of length scales 3 – 6 cm. Spatial distribution of the turbulent kinetic energy density is almost homogeneous and isotropic in the central region of the flow. The flow in the Rayleigh-Bénard convective cell is an example of a relatively simple flow where the mean and turbulent components of the velocity field have nonzero helicity which determines the properties of the flow. Remarkably, similar inertial subranges in turbulent velocity spectra were observed in various geophysical and astrophysical turbulent flows [3].

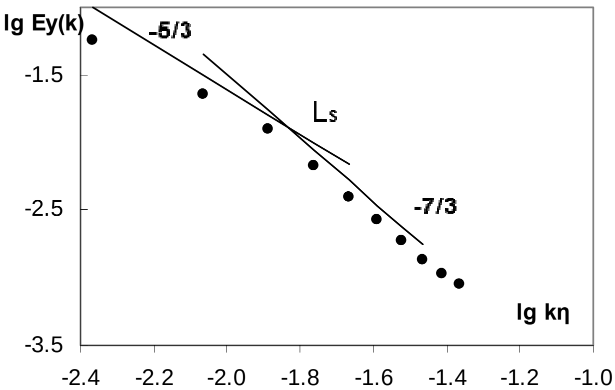

Figure 2. Specter of velocity

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