TURBULENT CONVECTION IN BOUNDED VERTICAL LAYERS

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Abstract Turbulent Rayleigh-Benard convection in a bounded vertical layer of size $1 \times \Gamma \times 1$ (Γ is the aspect ratio that characterizes the layer thickness) is studied by two-dimensional (2D) and quasi-two-dimensional (Q2D) direct numerical simulations (DNS) mainly performed for Rayleigh number $\mathrm{Ra} = 2.2 \cdot 10^9$ and Prandtl number $\mathrm{Pr} = 7$. The simulation results are verified by comparison with the results of an experimental investigation into the convective flow of water in a rectangular box heated from below with dimensions $250 \times d \times 250\ \mathrm{mm}^3$ (d varied from 15 to 50 mm). It is shown that, even in the framework of a crude model of linear friction used in the Q2D model, consideration of friction on lateral boundaries allows us to get a realistic structure of the turbulent flow with the aspect ratio $\Gamma \leq 0.1$. In addition, the Q2D model correctly describes the dynamics of the large-scale flow and reproduces the experimental power spectral density of velocity fluctuations.

INTRODUCTION AND STATEMENT OF THE PROBLEM

Turbulent Rayleigh-Benard convection in a bounded vertical layer of size $L \times d \times L$ with $d \leq L$ demonstrates a variety of dynamical regimes governing by the aspect ratio $\Gamma = d/L$ as well as by the Rayleigh and the Prandtl numbers [1, 2]. The behavior of large-scale circulation appearing against the background of Rayleigh-Benard turbulent convection in rectangular cavities of various rectangular geometries (from a thin layer to a cubic cell) has been experimentally investigated in [2]. One observed three different regimes of circulation. The first is characterized by stable circulation whose intensity undergoes stochastic oscillations, but the circular direction remains unchanged. The second regime involves reversals, i.e., the alternation of time intervals with large scale circulation in different directions. The durations of these intervals are random and the behavior of large scale circulation within one interval is the same as in the first regime. The third regime is characterized by numerous changes in the direction of large scale circulation, which are not separated by intervals with quasi-stable circulation in one direction. It is important to note, that regime with reversals observed only in a limited range of the aspect ratio ($\Gamma \approx 0.2$); This particular regime was modeled in [1] by 2D calculations.

In this work we continue the experimental study of the turbulent convection in rectangular boxes of different aspect ratio, focusing on the characteristics of small-scale turbulence, and we perform DNS, aiming to study the ability of two-dimensional (2D) and quasi-two-dimensional (Q2D) mathematical models for describing the most important characteristic of turbulent Rayleigh-Benard convection in a bounded vertical layer of size $L \times d \times L$. Both mathematical models are based on the Boussinesq equations for free convection of incompressible fluid. In the first case we considered plane 2D flow in the square domain (2D model). In the second case we considered flow in the thin vertical layer ($d << L$) using the linear friction model (Q2D model). This model uses modified 2D equations, which derived from Navier-Stokes equations in assumption of laminar transverse velocity profile. Equations were solved numerically by a high performance multiprocessor system using the finite volume method. The calculation grid was 512×512 nodes.

Furthermore, experimental investigation into the convective flow of water in a rectangular box heated from below with dimensions $250 \times d \times 250\ \mathrm{mm}^3$ (d varied from 15 to 50 mm) was carried out. The experimental setup is a cubic cell with the side $L = 250$ mm whose horizontal walls are massive copper heat exchangers and vertical walls are made of 25 mm thick plexiglas. Two opposite walls of the cell are equipped with a system of vertical slots in which plexiglas partitions are mounted, which separate a rectangular region with the thickness d in the central part of the cube. The experiments were performed with $d = 15$, 24, and 50 mm. The cube was completely filled by distilled water and the motion of water in the central cross section of the inner cell was investigated using particle image velocimetry (PIV).

RESULTS

Direct numerical simulations (DNS) mainly performed for Rayleigh number $\mathrm{Ra} = 2.2 \cdot 10^9$ and Prandtl number $\mathrm{Pr} = 7$ (it corresponds to average water temperature $25°C$ and temperature difference between heat exchangers $\theta = 10°C$).

Fig. 1 shows qualitative distinction in the flow structure between 2D model (Fig. 1a) and Q2D model with linear friction for $d = 15$ mm (Fig. 1b). In this figure samples of instant velocity fields are shown. In Fig. 1c we show experimental velocity field, which was measured using a PIV system in the central section with the same parameter values. One can see that scales of dominating structures in Q2D calculations are similar to structures which were observed in experiment, whereas 2D calculations lead to one large scale vortex in the center with the pair of counter-rotating vortexes in the corners of the domain.

Fig. 2 shows power spectral density of vertical velocity component v_z fluctuations at the layer center($x = y = z = 0$) and

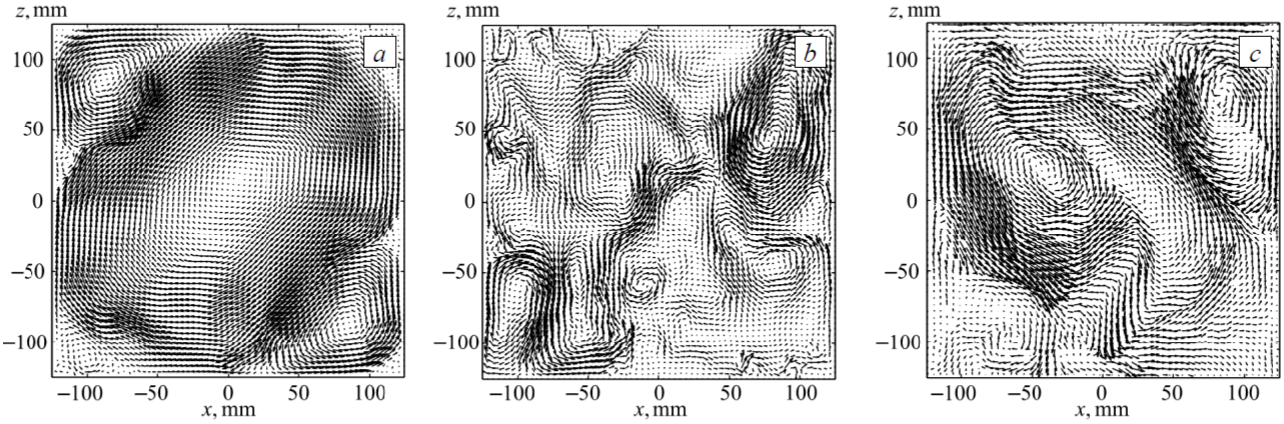

Figure 1. Instant velocity fields for $\mathrm{Ra} = 2.2 \cdot 10^9$: (*a*) – 2D calculations; (*b*) – model with linear friction, $d = 15$ mm (Q2D calculations); (*c*) – experimental results at $d = 15$ mm.

at the point ($x = y = 0$, $z = -94$ mm) near the bottom of the domain. Q2D calculations (thin solid line) gives a power law "$-5/3$" in the frequency range $0.01 - 0.1$ Hz. For 2D turbulence a power law "$-5/3$" corresponds to inverse energy cascade at the scales larger than injection length. At the scales smaller than injection length, power law "-3" is clearly seen. It corresponds to the enstrophy cascade. Spectra measured in experimental study is shown in Fig. 2 by dashed line. Experimental spectra is similar to Q2D spectra, the main difference is that there is no transition to power law "-3" in experiment at small scales. It should be noted that spectra obtained by 2D calculations (thick solid line in Fig. 2) reveal principally different structure. In this case pulsation energy is lower by an order and no any power law exists.

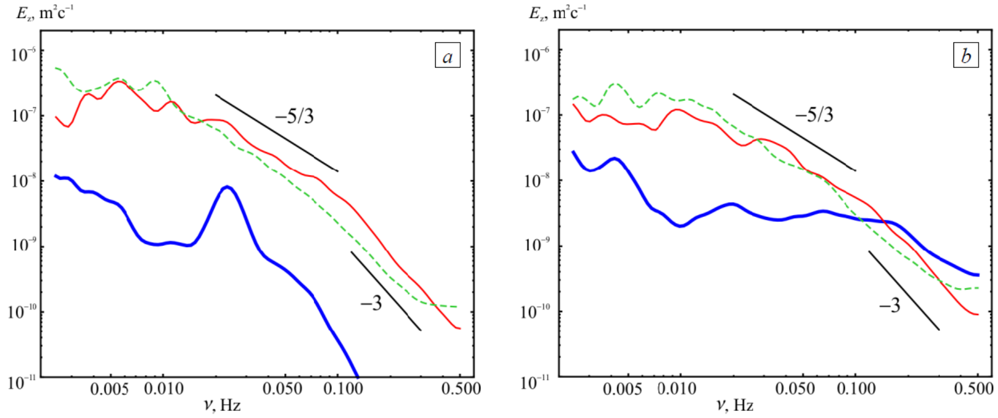

Figure 2. Power spectral density of vertical velocity component v_z fluctuations at the layer center point ($x = 0, z = 0$ mm) (*a*) and at the point ($x = 0, z = -94$ mm) (*b*). Q2D numerical results (thin solid line) and experimental data (dashed line) for $d = 24$ mm; 2D numerical results (thick solid line).

Detailed comparison between numerical and experimental results show that, even in the framework of a crude model of linear friction used in the Q2D model, consideration of friction on lateral boundaries allows us to get a realistic structure of the turbulent flow with the aspect ratio $\Gamma \leq 0.1$ (where aspect ratio $\Gamma = d/L$ characterizes layer thickness). In addition, the Q2D model correctly describes the dynamics of the large-scale flow and reproduces the experimental power spectral density of velocity fluctuations. Meanwhile 2D results reveal poor correlation with the real structure of fluid flow in the domain for any aspect ratio.

References

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