SIDEWALL EFFECTS IN CONFINED TURBULENT ROTATING RAYLEIGH–BÉNARD CONVECTION

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Abstract We experimentally investigate turbulent rotating Rayleigh–Bénard convection in an upright cylinder. Particle image velocimetry measurements are carried out in a planar cross-section of a water-filled cylinder with diameter-to-height aspect ratio $\Gamma = 1/2$. In comparison with previous measurements in $\Gamma = 1$ convection cells there are remarkable differences in flow structuring which may be attributed to the closer proximity of the sidewall. We quantify the dynamics of the large-scale circulation at low rotation rates and the spatial distribution of the vortical plumes at higher rotation rates.

INTRODUCTION

Rotating Rayleigh–Bénard convection (RRBC) is a simple model system for the investigation of flows in which buoyancy and rotation play an important role. It is experimentally most conveniently studied in a rotating upright cylinder, where the fluid inside is heated from below and cooled from above. The Rayleigh number $Ra = g\alpha\Delta T H^3/(\nu\kappa)$ quantifies the destabilizing temperature gradient; here g is the gravitational acceleration, α is the thermal expansion coefficient of the fluid, ΔT is the applied temperature difference, H is the height of the fluid layer, and ν and κ are the kinematic viscosity and thermal diffusivity of the fluid, respectively. The Prandtl number $\sigma = \nu/\kappa$ describes the diffusive properties of the fluid, the inverse Rossby number $1/Ro = 2\Omega\sqrt{H/(g\alpha\Delta T)}$ is a dimensionless rotation rate, with Ω the angular velocity. Finally, the aspect ratio $\Gamma = D/H$, with cylinder diameter D, describes the geometry.
In geometries for which $\Gamma \approx 1$ the rotational dependence of heat transfer and flow structuring are quite well-known [1, 2, 5, 7]. However, in a recent study [6] of a $\Gamma = 1/2$ cell many results were found which were very much unlike the findings for $\Gamma = 1$. This has led us to investigate RRBC in a $\Gamma = 1/2$ cylinder with *in situ* planar velocity measurements close to the top plate to directly evaluate the flow inside the cell. At a constant Prandtl number $\sigma = 6.4$ and Rayleigh number $Ra = 5.9 \times 10^9$ we apply various rotation rates, so that $1/Ro$ takes values between 0 and 15. We find nonuniform distributions of vortical plumes that may account for the different observations between the two aspect ratios.

VORTEX CLUSTERING

An hypothesis of two recent papers [4, 6] is that the vortical plumes with like-signed vorticity might cluster on laterally opposite sides of the cylinder. A sidewall temperature profile would show a 'hot' side where the rising plumes cluster and a 'cold' side due to the cluster of sinking plumes. We quantify clustering close to the top plate by calculating the mean positions (the centroids) of positive, cold vortices and negative, hot vortices. PDFs of the radial distance $r_c^\pm$ to the cell

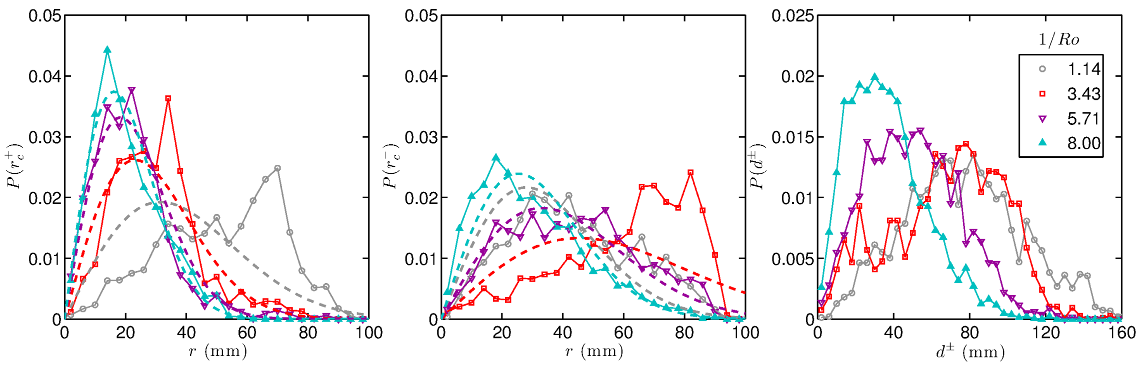
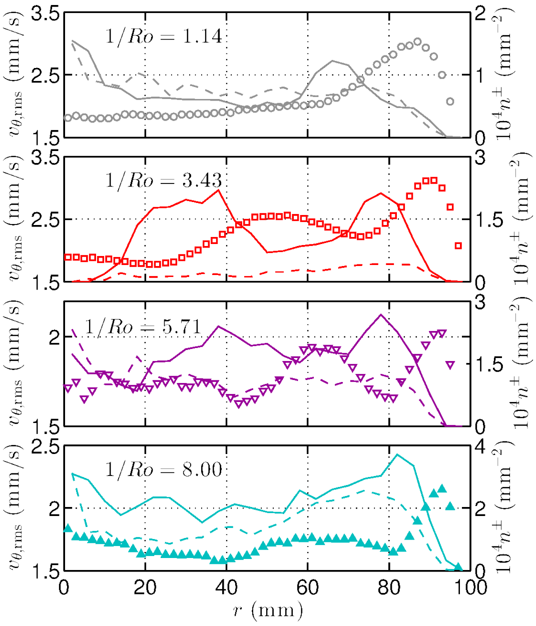


Figure 1. Azimuthally averaged PDFs of the centroid r_c^+ of positive, cold vortices (left), the centroid r_c^- of negative, hot vortices (middle), and their mutual distance $d^\pm$ (right). Several inverse Rossby numbers $1/Ro$ are included. The dashed lines are reference distribution with mean centroid position at the cell center.



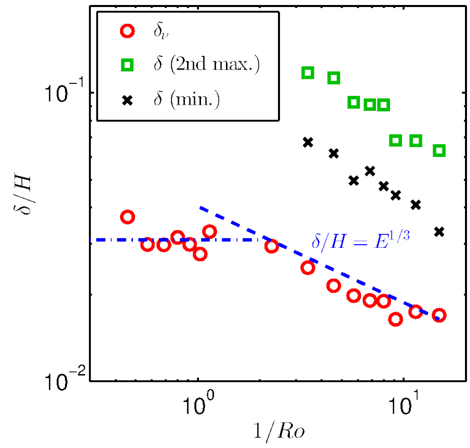


Figure 2. Left: radial profiles of vortex number density of positive (n^+, solid lines) and negative (n_-, dashed lines) with radial profiles of root-mean-squared azimuthal velocity $v_{\theta,\mathrm{rms}}$. Right: BL thickness δ_ν based on the radial position of the peak value of $v_{\theta,\mathrm{rms}}$ as a function of $1/Ro$. Positions of the minimum and second maximum of $v_{\theta,\mathrm{rms}}$ are included when present. The diagonal dashed line indicates the theoretical scaling $\delta_\nu/H = E^{1/3}$; the horizontal dashed line is a guide to the eye.

center of these centroids are depicted in figure 1, along with the PDF of the distance $d^\pm$ between the positive and negative centroids. For a uniform vortex distribution the mean position would be in the center and a certain standard deviation in both horizontal directions would be observed. For added statistical averaging, we take the azimuthal mean of the PDFs. The solid lines are the actual PDFs, while the dashed lines are azimuthally averaged distributions of zero mean and the same horizontal standard deviations of the solid curves. It is clear that the vortex distributions for the grey and red curves must have off-center centroids, and thus nonuniform, clustered vortex ensembles. This is further shown in the PDFs of $d^\pm$, which reveal that at these rotation rates the distance between the centroids may reach values that are comparable to the cell diameter, indicating a spatial separation of the clusters of rising and sinking plumes.

Another ordering of vortices is induced by the sidewall boundary layers (BLs). In the left plate of figure 2 the areal vortex number density $n^\pm$ is plotted as a function of the radial coordinate r (solid lines: n^+ for the postive vortices; dashed lines: n^- for the negative vortices), along with radial profiles of the root-mean-squared azimuthal velocity $v_{\theta,\mathrm{rms}}$ (symbols). At intermediate rotation rates $1/Ro = 3.43$ and 5.71 it is found that peaks of n_+ and lows of $v_{\theta,\mathrm{rms}}$ coincide, and vice versa. This negative correlation is only found after a transition to a Stewartson-type sidewall BL: as is shown in the right panel of figure 2 the BL thickness δ_ν undergoes a transition at $1/Ro \approx 2$ to the typical Stewartson scaling $\delta_\nu/H = E^{1/3}$, where $E = \nu/(\Omega H^2)$ is the Ekman number. These sidewall BLs have an intricate spatial structure with internal recirculations [3]. Vortices can get trapped in the sidewall BL. However, at high enough rotation rates the sidewall layers are too thin to trap vortices and uniform radial vortex distributions are found for $1/Ro \gtrsim 8$.

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