BOUNDARY LAYER VISUALIZATION IN TURBULENT RAYLEIGH-BÉNARD CONVECTION IN AIR

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Summary We present results of boundary layer flow visualization in turbulent Rayleigh-Bénard (RB) convection in air at Rayleigh number of Ra=1.4 x 10^{10}. The experiments have been performed in a slender rectangular test cell with the dimensions of 2.5 m x 2.5 m x 0.6 m. The cell was installed in our large-scale RB experiment 'Barrel of Ilmenau' using its uniformly tempered heating and cooling plates as bottom and top bound of the small cell. Highly resolved movies as well as single frames of the boundary layer flow have been captured at various positions above the heating plate. They show that the idea of a basically laminar boundary layer does not hold at low Prandtl and moderate Rayleigh numbers.

INTRODUCTION

The heat transfer throughout the boundary layers at the hot bottom and the cold top plates is the key to understand the global heat transport in turbulent Rayleigh-Bénard convection. Over the last decade the assumption of a basically laminar structure according to the Prandtl/Blasius model has been established as long as the Rayleigh number does not exceed the critical value towards the so-called ultimate regime [1]. Until now this assumption is verified comprehensively neither by experiments nor by numerical simulations. Highly resolved local velocity and temperature measurements at the "Barrel of Ilmenau" [2,3] as well as very recent numerical simulations [4] focussing particularly on the boundary layers give reason to believe that this might be not true, especially at low Prandtl numbers Pr $\leq$ 1and high Rayleigh numbers Ra $\geq 10^{10}$.

EXPERIMENTAL SET-UP

We performed a set of flow visualizations in turbulent Rayleigh-Bénard (RB) convection in air. In order to fix the mean plane of the mean wind driven by the temperature difference between the hot bottom (ϑ_h=35°C) and the cold top plates (ϑ_c=25°C) a slender rectangular test cell (2.5 m x 2.5 m x 0.6 m) was installed in our large-scale RB experiment 'Barrel of Ilmenau' (see photo in Fig. 1). The flow in this cell is described by a Rayleigh number Ra=1.4x10^{10}, a Prandtl number Pr=0.7 and aspect ratios Γ_x=1 and Γ_z=4. We were mainly interested in the boundary layer flow at the bottom plate and we illuminated a plane light of about 7 cm in height and 0.1 cm in depth over the full length of the plate. The light was generated by a 2,000 mW Laser in combination with a beam expander according to the sketch in Fig. 1.

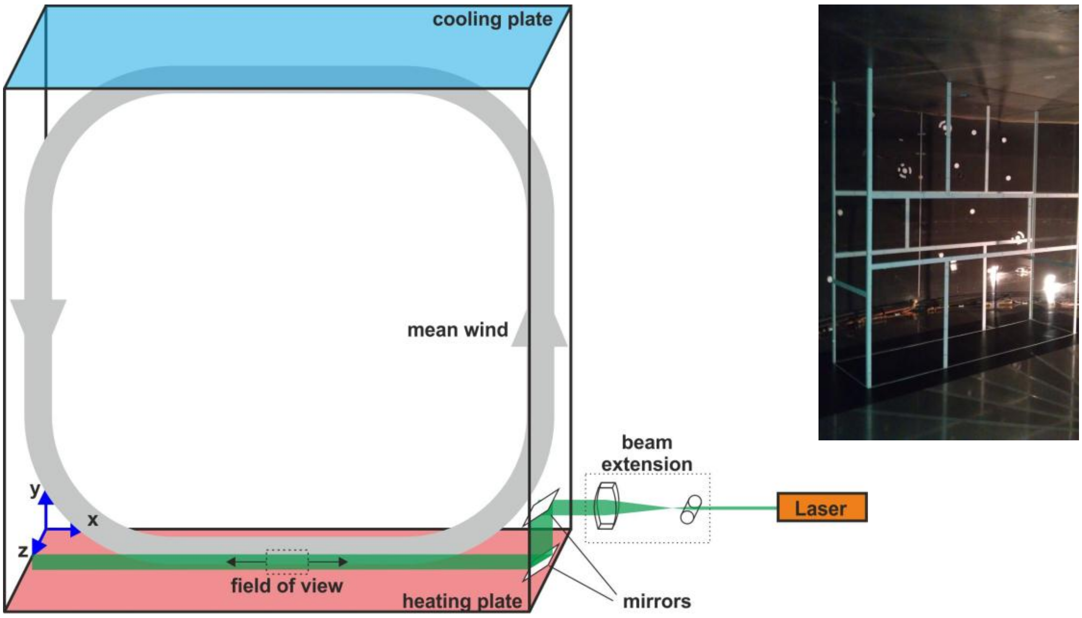

Figure 1: Set-up of the boundary layer visualization in turbulent Rayleigh-Bénard convection. The rectangular test cell with the dimensions of 2.50 m x 2.50 m x 0.60 m is embedded in the large scale experiment "Barrel of Ilmenau" using its heating and cooling plates with uniform temperature as bottom and top bound. The photo on the right shows the rectangular test cell.

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In order to make the air flow visible we added cold-atomized droplets of Di-Ethyl-Hexyl-Sebacat (DEHS) with a size of about 1 µm. Before starting the visualization the injection of droplets was stopped and we wait a few eddy turn overs. Using a Canon EOS 600 D camera movies with a resolution of 1920 x 1080 pixels and a frame rate of 30 frames/s as well as highly resolved single pictures with 5184 x 3456 pixels but shorter exposure time have been captured.

RESULTS

In Fig. 2 one snapshot of a movie of the boundary layer captured above the centre of the heating plate is shown. The large-scale circulation above the plate surface is from left to right as indicated in Fig.1. The scale on the left hand side of the figure represents the wall- normal distance z in units of millimetres, z = 0 mm corresponds to the surface of the plate.

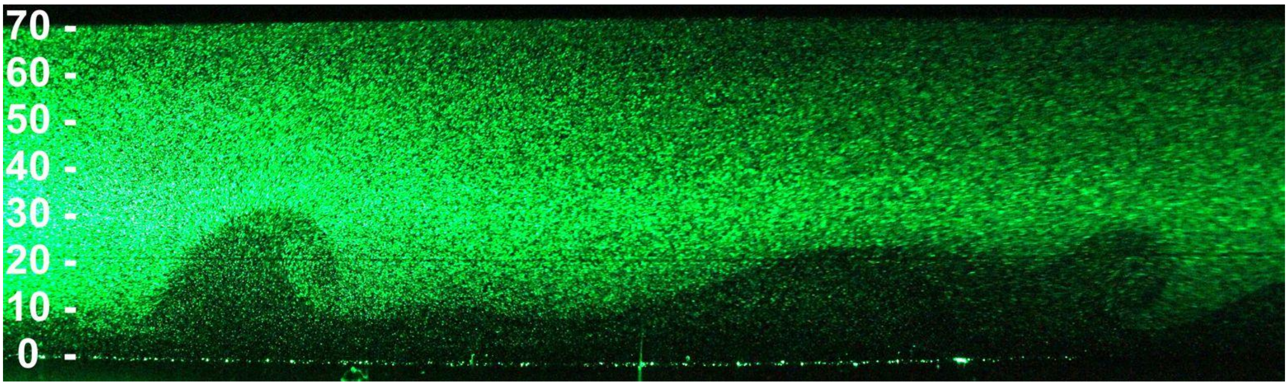

Figure 2: Boundary layer in turbulent Rayleigh-Bènard convection in air at Ra=1.4x10^{10}. The mean flow is from left to right. The scale on the left hand side is the distance z from the heating plate in units of millimeter, z=0 mm corresponds to the surface of the plate.

The picture shows the wavy structure of the viscous boundary layer with a mean (time-averaged) thickness of δ_v = 7.5 mm. It illustrates how thermal plumes evolve as buoyancy driven boundary layer instabilities and how they interact with the mean wind. In the movies that we wish to present in our talk it becomes clearer that the laminar region of the boundary layer is very thin and limited only to a small region very close to the surface of the plate. In Fig. 3 one of the typical structures - a mushroom-like thermal plume - is shown. The photo has been taken as a high resolution single picture with an exposure time of 10 ms. It shows how the plume dissolves from the boundary layer and generates a strong wall normal flow component along its stem indicated by the long particle tracks. The maximum length of these tracks amounts up to 5 mm corresponding to a velocity of 0.5 m/s in this region. This is about as much as twice the maximum of the mean horizontal velocity of the driving circulation and significantly contributes to the heat flux throughout the boundary layer.

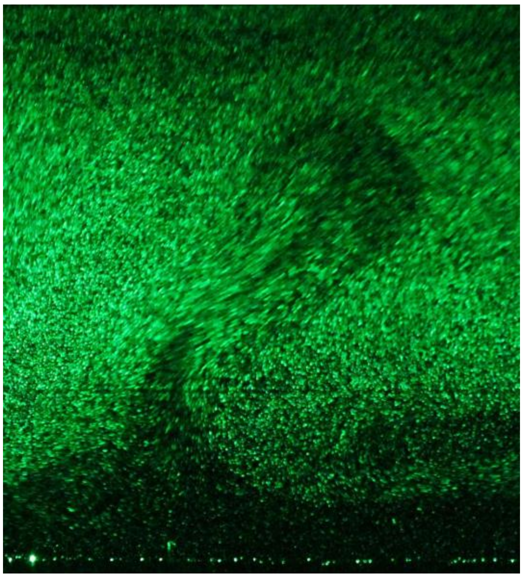

Figure 3: Mushroom like thermal plume evolving as boundary layer instability, the velocity of the fluid corresponds to the path length of the particle traces (exposure time: 10 ms)

CONCLUSIONS

Flow visualization in the bottom boundary layer of turbulent RB convection in air has been performed. The experiments have been done in a slender rectangular test cell at Ra = 1.4 x 10^{10} and Pr=0.7. The movies as well as a series of highly resolved single pictures clearly demonstrate that particularly at low Prandtl numbers the idea of a basically laminar boundary layer does not hold even in case of only moderate Rayleigh numbers significantly below the transition towards the so-called ultimate regime [1].

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