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Viscous boundary layers in turbulent Rayleigh-Bénard convection

L Li, C Resagk and R du Puits

Institute of Thermodynamics and Fluid Mechanics, Ilmenau University of Technology, POB 100 565, D-98684 Ilmenau, Germany

E-mail: `l.li@tu-ilmenau.de`

Abstract. Highly resolved local velocity profiles inside the boundary layers in turbulent Rayleigh-Bénard convection in air are presented and discussed. The present work makes progress to our work in the past (see du Puits & Resagk, 2007) that our actual set-up permits the measurement of the wall-normal velocity component w up to a distance of 200 mm away from the wall. All component profiles were performed in a cylindrical box with an aspect ratio $\Gamma = 1$, a Prandtl number $Pr = 0.7$ and Rayleigh numbers $Ra = 3 \times 10^9$, $Ra = 3 \times 10^{10}$. We compare the experimental results with numerics at $Ra = 3 \times 10^{10}$ directly. We found that the profiles of mean velocity from both experiments and numerics collapse very well with each other and both of the mean horizontal velocity profiles differ from the laminar Blasius prediction at the boundary layer. The wall-normal mean velocity at the central window tends to zero in both experiment and numerics.

1. Introduction

Many natural or technical flows are associated with a heat transfer from a hot or cold solid surface to a surrounding fluid. The temperature difference produces a coherent flow structure, circling with a steady mean along the cooling surface and returning along the heating surface. In the middle of the circulation, is the bulk region, which is not affected by the boundary layers any more. One of the crucial questions of this type of flows is the heat transport throughout the fluid which is mainly determined by two very thin boundary layers close to the wall. However, particularly in case of highly turbulent flows the knowledge about the temperature and the velocity field inside the convective boundary layer is still limited (see Ahlers & Grossmann, 2009; Chavanne & Chillá, 2001; Niemela & Sreenivasan, 2006; Funfschilling & Bodenschatz, 2009). We study the velocity field in a large-scale Rayleigh-Bénard experiment which is called the "Barrel of Ilmenau" meeting two important criteria, a very high Rayleigh number of $\mathrm{Ra}_{\mathrm{max}} = 10^{12}$ and a large size of 7.15 m in diameter and 6.30 m in height. A sketch of the experimental facility is shown in Figure 1.

The dynamics of the flow in a cylindrical RB cell is determined by two dimensionless parameters and the geometry of the cell, which are the three "input parameters": the Rayleigh number $Ra = (\gamma g \Delta\vartheta H^3)/(\nu\kappa)$, the Prandtl number $Pr = \nu/\kappa$, and the aspect ratio $\Gamma = D/H$ whereas its response to the applied temperature difference is reflected by the global "output parameters": Reynolds number $Re = (\bar{v}H)/(\nu)$ and Nusselt number $Nu = (4H\dot{Q})/(\lambda\pi D^2\Delta\vartheta)$. In these definitions variables stand for the following physical quantities: γ-isobaric expansion coefficient, g-gravitational acceleration, $\Delta\vartheta$-temperature difference between both horizontal plates, ν-kinematic viscosity, κ-thermal diffusivity, D-diameter of the cell, H-plate distance, $\bar{v}$-mean velocity, $\dot{Q}$-convective heat flux, and λ-thermal conductivity.

The aim of this paper is to enhance the understanding of the structure of viscous boundary layers. For this purpose we compare our experimentally obtained velocity profiles with data from Direct Numerical Simulations (DNS). This will be the first time that a direct comparison between experimental and numerical data as well as with the theoretical predictions becomes possible at $Ra = 3 \times 10^{10}$.

2. Experimental setup

In order to fit the experimental parameter to those from the DNS ($Ra_{sim} = 3 \times 10^9$, $Ra_{sim} = 3 \times 10^{10}$) we have installed a smaller cell with a diameter of 2.5 m and a height of 2.5 m in our big RB system. Four windows are located at several positions of the cooling plate (see Fig 1) permitting the optical access for the LDA measurement.

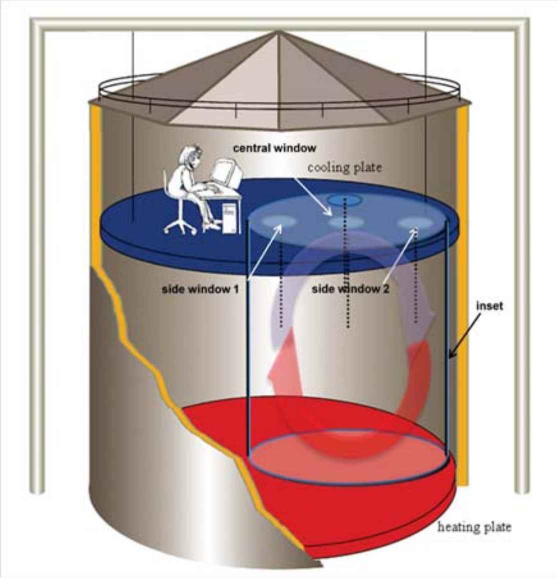

Figure 1. Sketch of the large-scale experiment “Barrel of Ilmenau.”

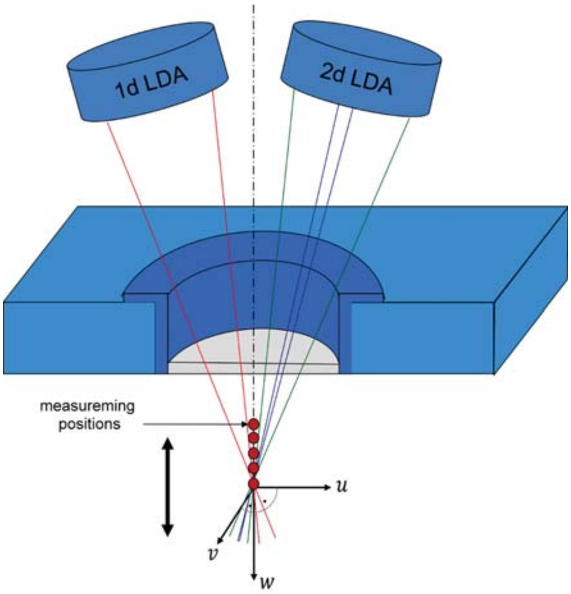

Figure 2. Set-up of the 3d-Laser Doppler anemometry measurement.

Using a combination of a 2d- and a 1d-Laser Doppler Anemometer (LDA), we measured highly resolved profiles of the velocity (see Figure 2). The probes were arranged above the various windows in the cooling plate to provide field information at different locations in the flow. They are mounted on a high precision traverse system, which could be moved in vertical z-direction in steps of $\Delta z = 0.01$ mm. Moving the probes up and down the velocity can be measured at different locations beneath the lower plate surface. At each position different time series of 1800 s, 3600 s, 7200 s are captured and analyzed. Typical data rates are of the order of 100 Hz on average sufficiently high to resolve the fastest velocity fluctuations in the flow. We use cold-atomized droplets of Di-Ethyl-Hexyl-Sebacat (DEHS) with a size of about 1 μm as tracer particles and inject them through an opening close to the sidewall.

3. Results and discussion

First, we address the question whether the profiles of the mean velocity of RB convection match with the laminar Blasius/Prandtl prediction. Up to now, the simulated solutions of the boundary layer equations are still limited. For RB convection, people used to comparing the boundary layer results with the Blasius solution. Two measured horizontal mean velocity profiles at $Ra = 2.88 \times 10^9$ and $Ra = 2.88 \times 10^{10}$ are plotted, see Fig 3. Because of the oscillation of this large-scale circulation (see Resagk & du Puits , 2006), we calculate the magnitude $U = \sqrt{u^2 + v^2}$ as the mean horizontal velocity. On the top of them, Blasius solutions of the two-dimensional boundary layer equations (see Schlichting & Gersten , 2004) are plotted. Although, it has been found, in previous mean profile study at $Ra = 10^{11}$ see (see du Puits & Resagk, 2009), that Blasius profile does not provide a good approximation to the profiles of mean velocity in turbulent RB convection, let's see our results at slightly lower Ra numbers. At both Ra numbers, the near-wall part of the profiles grow almost linearly and almost coincide with the Blasius solution. Following the shape of the profiles toward larger distances, the profiles noticeably deviate from the prediction of the laminar shear layer, especially the velocity at lower Ra number. In the outer boundary layer region, where is effected by the plumes, the measured profiles have slight fluctuation around Blasius solution. In one word, the Blasius profile does not match the profiles of mean velocity in turbulent RB convection at $Ra = 2.88 \times 10^9$ and $Ra = 2.88 \times 10^{10}$.

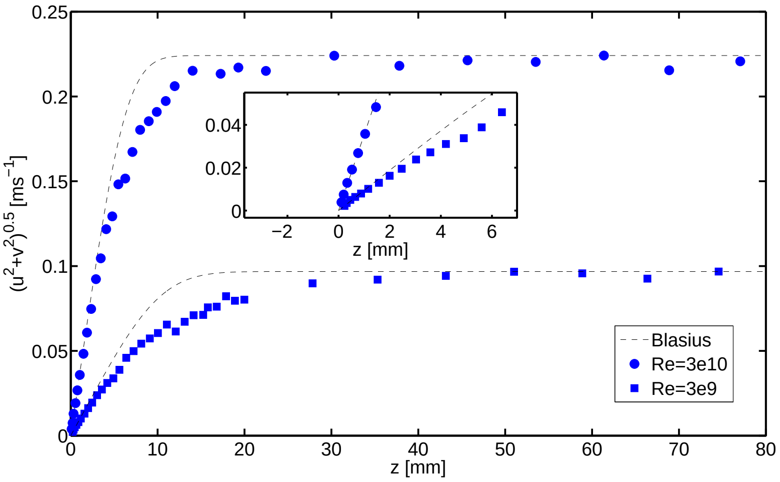

Figure 3. Profiles of the mean horizontal velocities measured at $Ra = 2.88 \times 10^{10}$ (fullcircle) and measured at $Ra = 2.88 \times 10^9$ (fullsquare) over the plate distance z compared with Blasius solution (dashed) at aspect ratio $\Gamma = 1$. The velocities were measured at the central window. The inset shows the details of the near-wall region.

Second, the relatively smooth mean horizontal velocity, see Fig 3, shows that we have a single large scale circulation and we suppose it also has a flywheel structure, which was first proposed by Kadanoff et al. (see Kadanoff, 2001), later verified by Xia (see Shang & Qiu, 2003). Then we want to see if our experimental results from the side windows will show the consistent structure. Here I need to make clear where these two side windows are located, which is shown in Fig 1. The big circulation is the mean flow and these two windows, number 1 and number 2 are located right over the mean flow. In Fig 4, the mean horizontal velocity profiles are presented, they do not collapse with each other and the velocities increase with different gradient, which means this single circular flow is with an asymmetric pattern. The mean wall-normal velocity profiles are shown in Fig 5. which have a clear pair of upwards and downwards velocity, confirming the idea of a large-scale convection roll in RB cells of aspect ratio of one. Finally, we want to compare our experimental results with those from DNS and the theoretical prediction by Blasius. The mean

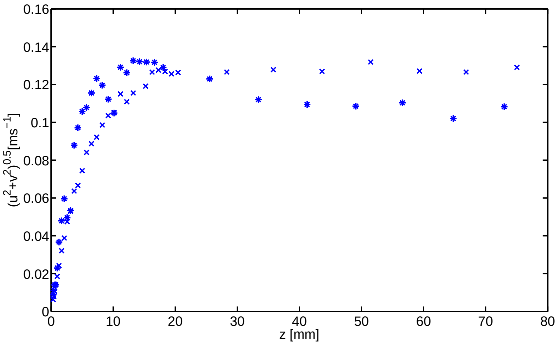

Figure 4. Profiles of the mean horizontal velocities measured at the side window 1 (cross) and the side window 2 (star) over the plate distance z at aspect ratio $\Gamma = 1$, $Ra = 2.88 \times 10^{10}$.

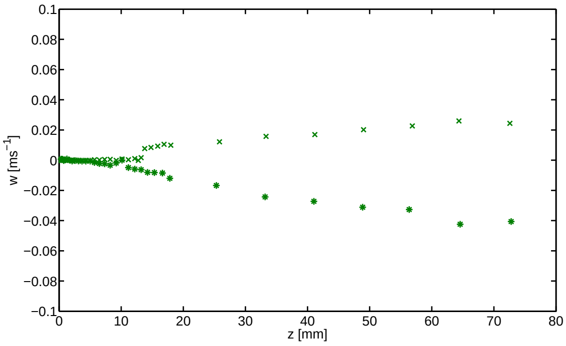

Figure 5. Profiles of the mean wall-normal velocities measured at the side window 1 (cross) and the side window 2 (star) over the plate distance z at aspect ratio $\Gamma = 1$, $Ra = 2.88 \times 10^{10}$.

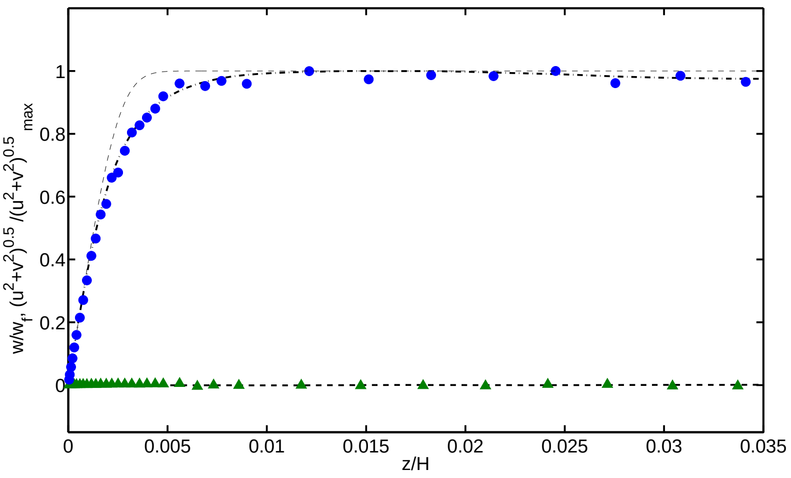

Figure 6. Profiles of the measured (fullcircle) and numerical (chain) mean horizontal velocities over the plate distance z, compared with Blasius solution (dashed) as well as the corresponding wall-normal velocity components w (fulltriangle, longbroken) at aspect ratio $\Gamma = 1$, $Ra = 2.88 \times 10^{10}$. The mean horizontal velocities are normalized by the maximum velocity of each other's. The wall-normal velocities w are normalized by the free four velocity, $w_f = \sqrt{\gamma g \Delta\vartheta H}$. The distance is normalized by the height of the small cell, 2.5 m. The velocities were measured at the central window.

horizontal velocity and the mean wall-normal velocity profiles plotted in Fig 6 are measured or calculated at the central position of the cooling plate at $Ra = 2.88 \times 10^{10}$. We can see that the two mean horizontal velocity profiles agree with each other very well, and both of them differ from the Blasius solution at the boundary region. For the wall-normal velocity, which plays a important role to know how the heat transport behaves in this system or if there is a wall-normal velocity created by the thermal plumes, in Fig 6, the fulltriangle data shows the wall-normal component velocity tends to zero, which means there is no mean flow from the wall-normal component. On the other hand, the numerics collapses with the measured data very well and also shows that the wall-normal velocity does not exist.

4. Conclusions

The measurements of all three velocity components in and outside the boundary layer have been carried out and discussed. The mean profiles from various positions show that we have a single asymmetric circulation in our RB system. At $Ra = 2.88 \times 10^0$ the measured mean velocities parallel and vertical to the wall collapse quite well with the numerics and both of mean horizontal velocity profiles differ from the Blasius solution of a laminar non-isothermal shear layer. Both of the measured and the numerical wall-normal velocities show that there is no mean wall-normal velocity.

5. Acknowledgments

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