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Experimental Investigation on Velocity of Large-Scale Rayleigh-Bénard Convection

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Abstract

High-resolution profiles of all three velocity component in large-scale Rayleigh-Bénard convection in air are presented and discussed. We investigate the mean velocity profile along the central axis close to the cooling plate of the RB system. In order to reduce Ra, but keeping the aspect ratio Γ constant we install a smaller sample of 2.5 m diameter and 2.5 m height into the large cell. The resulting parameter domain of $3\times10^9 < Ra < 6\times10^{10}$, $\Gamma=1$ and Prandtl number Pr=0.7 collapses with simultaneously conducted numerical simulations and it permits a direct comparison of the results for the first time. We present time series and profiles of the velocity measurement inside the boundary layer using 3d-Laser-Doppler-Anemometer (LDA).

1, Introduction

From an applied viewpoint, thermal convection at high Ra number is a basic and important ingredient for the motion of air in the Earth's atmosphere or the flow of water in the oceans. One of the best known experiments to study the basics of convection is the Rayleigh-Bénard (RB) experiment—a buoyancy driven flow of a fluid heated form below and cooled from above.

First velocity measurements inside the boundary layer of an air-filled RB experiment were undertaken by Deardorff and Willis [1] and Fitzjarrald [2] using a hotwire anemometer. However, their measurements were limited to Ra numbers $Ra<10^7$ and too small for similarity theories to be applicable. Subsequent velocity measurements inside the boundary layer in highly turbulent RB convection were carried out exclusively in water (Pr≈5, . . . ,7). Belmonte *et al.* (1993) extended these measurements to the Ra range $5\times10^5 < Ra < 10^{11}$ in compressed gas (air) at room temperature (Pr=0.7), but still at fixed lateral position [3]. However, the spatial resolution was limited to about six measurement points between the wall and the location of the velocity maximum. The development of laser-based measurement techniques about 15 years ago allowed nonintrusive velocity measurements avoiding any disturbance of the flow. Xia and co-workers [4,5] obtained profiles of the horizontal velocity up to $Ra=10^{10}$ by measuring the transfer time of particles between two parallel laser beams. Further velocity measurements in water using Particle Image Velocimetry were reported in [6, 7] or very recently in [8]. All those experiments confirm the linear rising of the mean velocity with the plate distance very close to the wall. However, one has to keep in mind that because of the large Pr of water the thermal boundary layer is small compared with the viscous one and it nests within the latter. It clearly differs from Pr≈1 fluids where both boundary layers exhibit the same thickness. The aim of this paper is to provide high resolution data and to enhance the understanding of the boundary layers.

2, Experimental Setup

For better understanding of the boundary layers, we use a large-scale RB experiment which has been operated by our group since the year 2001. The experiment was conducted in an experiment facility, which is sketched in Fig. 1. It is a so called the "Barrel of Ilmenau" — a cylindrical container with a heating plate at the bottom and a cooling plate at the top. The side walls are nearly free of heat loss. The outer cover is made of fiberglass-epoxy compound with an embedded thermal isolation layer. The heating plate at the bottom consists of a heating wire in a concrete layer similar to an electrical underfloor heating. To keep the heat loss through the bottom to a minimum a 30 cm thermal isolation layer is placed below the heating layer. The surface of the heating plate is covered by a water-flown aluminum plate to homogenize the temperature at its surface. The maximum temperature at the surface is 80 °C. The cooling plate consists of 16 separate water cooled segments. The thickness of the segments is 4 cm and they consist of two aluminum plates with an interconnecting cooling coil. Together with a cooling system and a big tank for the balance of temperature an accurate regularity of the temperature at the surface of the cooling plate was reached. In all cases the temperature deviation over the whole surface is lower than 1 K. One can study the velocity field at a maximum $Ra=10^{12}$. In order to compare experimental and numerical study of the boundary layer, we reduce the Ra number in $3\times10^9<Ra<6\times10^{10}$, installing a smaller sample of 2.5m diameter and 2.5m height into the big cell.

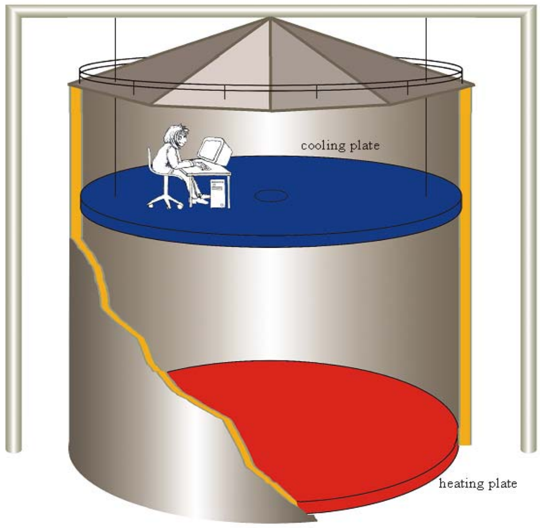

Fig. 1. Sketch of the "Barrel of Ilmenau" in which the experiment will be performed. The lower plate is heated. The upper (cooling) plate can be moved up and down, thus varying the height of the cell and the aspect ratio.

The present work is to measure all three components of the velocity near the cooling plate for Ra numbers up to $Ra=6\times10^{10}$ and aspect ratio $\Gamma=1$ using a three-dimensional (3d) Laser Doppler anemometer (LDA). The near-wall region LDA measurement is strongly affected by the length of the measuring volume, which are ellipsoids with a diameter of about 75 μm and a length of about 1000 μm were located precisely at the lower surface of the glass window. In order to lay the measurement volume as close as possible to the cooling plate to reduce the adverse effect with the measurement accuracy from the measurement volume size, two different focal length (f=160 mm and f= 500 mm) lenses were applied into two depth rang. We decided to measure the near-wall region, from z=0 mm to z=10 mm, by the short focal length lens f=160 mm, which can increase the intersection angle, at the same time it decreases the distance of original measuring position to the wall, shown in Fig. 2. Then the focal length lens f=500 mm is used to measure from z=5 mm to z=100 mm.

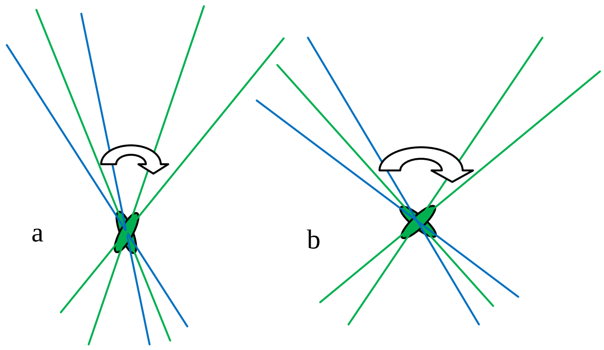

Fig. 2. Sketch of measuring volume produced by focal length f=500 lens (a) and f=160mm lens (b).

We have measured three components of the velocity combining a 1d probe and a 2d probe, shown in Fig. 3. The green (514.5 nm) and blue (488.0nm) colors from 2d probe are used to measure the horizontal components in x-direction and y-direction, parallel to the plate surface. The other pair of green beam from 1d probe is used to measure the vertical component in z-direction, normal to the plate surface. The probes were mounted on a high precision traverse system, which could be moved in vertical z-direction in steps of Δz=0.01 mm. With the lens of f=160 mm focal length, the symmetry rotated angle of the probes is φ=25º. They were adjusted to ensure that the measurement volumes coincide in the same crossing point. The position z=0 mm was defined as the point at which the centers of the measurement volumes. In order to decrease the error caused by the reflection when beams penetrate the glass window, we adjust the focal points and the crossing point all behind the window.

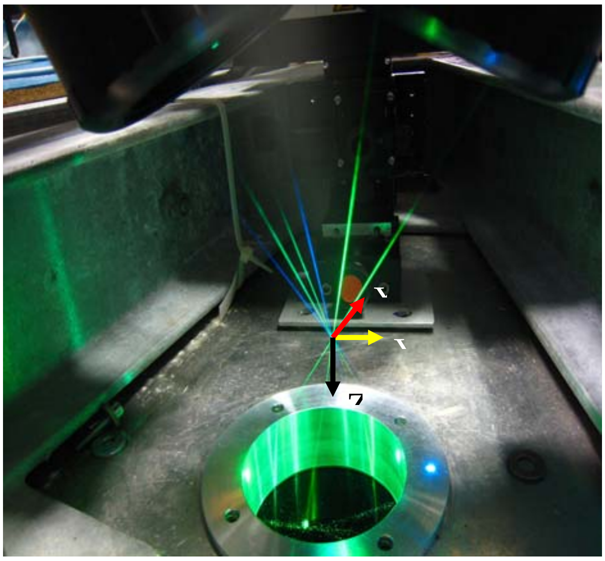
Fig. 3. The 2d LDA probe measures the horizontal components in x-component, which we define it as mean flow and in y-component, which we call it cross flow. The wall-normal direction, z-component is measured by the combined 1d probe.

For all our LDA measurements, cold-atomized droplets of Di-Ethyl-Hexyl-Sebacat (DEHS) with a size of about 1µm were used as tracer particles. They were injected through the cooling plate, along the side wall of the small cell, far from the mean flow during a short time spraying.

We are mainly interested in the mean velocity and its fluctuations. In order to obtain reliable data free from statistical errors it is required that the length of the time series significantly exceeds the longest time scales of the velocity signal. Measurement locations close to the wall have an inherently low data rate due to the low fluid volume flux, so the largest acquisition time should be according the time spent in this region. Due to this fact time series of at least 50h at each position z would be required to have sufficient data for an accurate statistical description of the flow, but it was impossible to realize it in our present setup, so we decided to limit the measurement time to 1 h at each position keeping in mind that the results are slightly more uncertain than, e.g., those obtained in isothermal shear flows [9].

3, Results & Discussion

Before the real experiment, I scaled down the experimental set-up, shown in Fig. 4, to simulate the internal flow of the barrel to test the 3-component velocity measurement using LDA. There is a cooling plate lifted to the height h=440 mm up to the table. The temperature difference ΔT=5.7˚C, which is the temperature difference between the room air and the cooling plate surface. The velocity of the wind is v=1.5 m/s produced by a wind blower. The original measuring position is z=0.08 mm underneath the cooling plate. The measurement configuration is from 0 mm (original position) ~ 47.1 mm, 10 points.

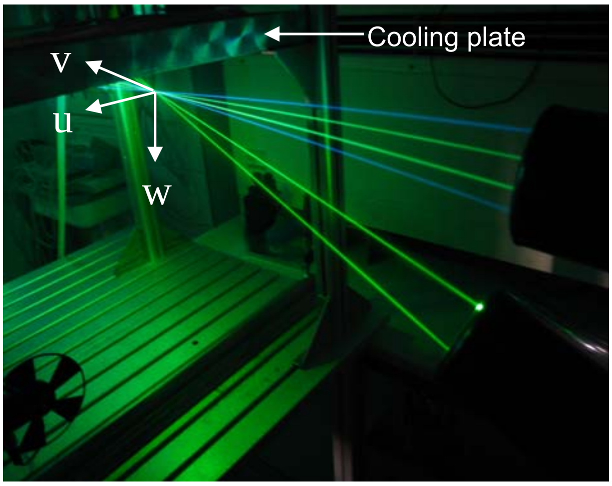

Fig. 4. The test experiment set-up

In Fig. 5, we have the 3-component velocity

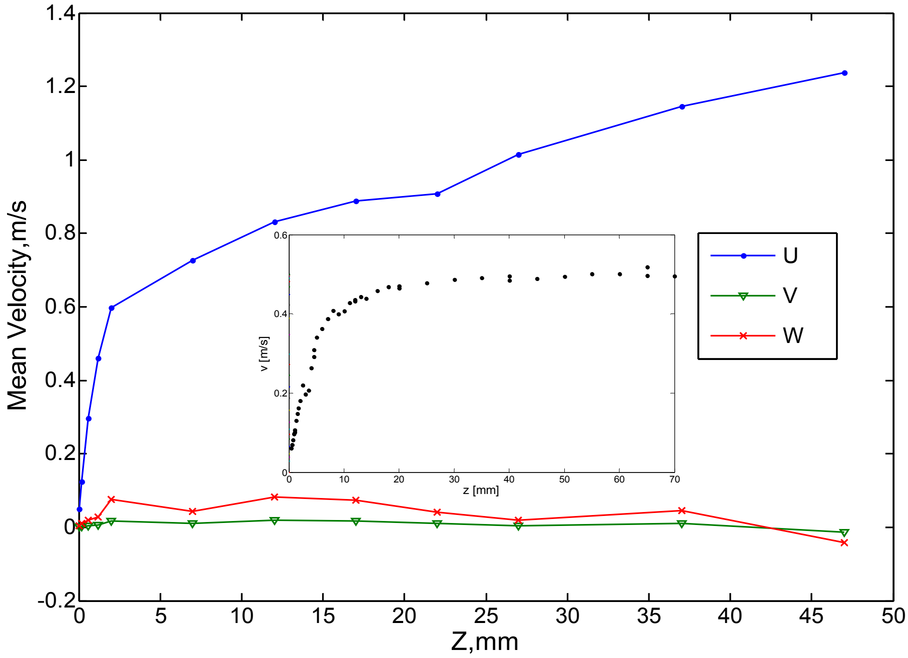

Fig. 5. The profile of the transformed 3-component velocity, u, v and w, in which the mean velocity u shows nearly linear behavior of the velocity field close to the cooling plate. The insert shows the mean velocity profile from our previous 2d LDA measurement [10].

profile. The mean velocity u is nearly linear，which roughly agrees with the mean velocity profile from 2d measurement (see the insert graph of Fig. 5) [10]. The other horizontal velocity v and the wall-normal velocity are around 0 m/s. From this simplified test experiment, we can have the expected 3-component velocity that means we can expect the 3-component high resolution velocity profile from the barrel.

4, Conclusions

With the similar, but simplified RB experiment conditions, we can measure 3-component velocity close to the cooling plate. The mean velocity shows nearly linear behavior. With the optimized experimental method and the real RB experiment condition we expect to have the high resolution 3-component velocity profile from the barrel. The latest result will be presented on the GALA conference.

5, Acknowledgment

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