Velocity and temperature measurements in a large-scale Rayleigh-Bénard experiment using LDA and micro thermistors

by

C Resagk[1], R du Puits[1], A Thess[1], F H Busse[2], A Tilgner[3]

[1] Dept. of Mech. Engineering, Ilmenau University of Technology, POB 100565, 98684 Ilmenau, Germany
[2] Institute of Physics, University of Bayreuth, 95440 Bayreuth, Germany
[3] Institute of Geophysics, University of Göttingen, Herzberger Landstraße 180, 37075 Göttingen, Germany
Email: Christian.resagk@tu-ilmenau.de

ABSTRACT

The objective of our paper is to investigate the temperature and the velocity field in a large-scale Rayleigh-Bénard(RB)-Experiment ("Barrel of Ilmenau BOI", Fig. 1). Measurements with high spatial and temporal resolution especially in the boundary layers can help to verify predictions of various theoretical models concerning the mechanism of the heat transport by highly turbulent thermal convection. Previous RB-experiments at high Rayleigh(Ra) numbers usually have used liquid helium or water with the consequences, that the spatial dimensions and the thickness of the boundary layers respectively, are relatively small. In the "BOI", a large-scale RB-cell with a height of h=6,40m and a diameter of d=7,15m we are able to study the velocity and the temperature field in great detail (du Puits et al 2002). We investigate profiles as well as the statistical properties of both fields in the air-filled RB-cell. At $Ra=10^{12}$, the thickness of the thermal boundary layer is about d_{th}=10 mm and the thickness of the viscous boundary layer is about d_v=3 mm. The velocity measurements are performed with a Laser-Doppler-Anemometer (LDA) on a traverse system with an accuracy of 10 µm. Because of the small size of the measurement volume (l_{mv}=500µm, D_{mv}=50 µm) in comparison to the thickness of the viscous boundary layer, the spatial resolution of the velocity profile is higher than in all previous RB-experiments. For the temperature measurement a micro thermistor with a diameter of d=125µm is used. Together with a computer controlled measurement system based on a HP3458-multimeter (8.5 digit, 100.000 readings/s) temperature fluctuations down to the smallest scales will be detectable. In agreement with theoretical predictions the LDA velocity measurements show a logarithmic profile in the viscous boundary layer at $Ra=10^{12}$ and Γ=1.1 (aspect ratio). In this case one can see one stable single-roll structure of the mean flow through the cell. This coherent structure will break down if the aspect ratio will be increased to 1.8 and at higher Γ we expect a stable-multi roll flow. The autocorrelation function of mean, cross flow velocity and temperature at $Ra=10^{12}$ indicates characteristic time scales of 20s and 40s. Furthermore an additional "low precession" of the single-roll flow structure with 500s has been observed.

Fig.1: View of the large-scale Rayleigh-Bénard-Experiment "Barrel of Ilmenau"

1. INTRODUCTION

The objective of our paper is to investigate the temperature and the velocity field in a large-scale Rayleigh-Bénard (RB) experiment at high Rayleigh number (Ra). The RB experiment, a closed box with a heated bottom plate and cooled top plate, offers good conditions for a systematic study of thermal convection. Measurements with high spatial and temporal resolution especially in the boundary layers can help to verify predictions of various theoretical models concerning the mechanism of the heat transport by highly turbulent thermal convection.

In previous RB experiments at high Ra usually liquid helium or water was used with the consequences, that the spatial dimensions and the thickness of the boundary layers are relatively small. The new investigations at the large-scale RB experiment allow precise measurements both at high Ra and at high aspect ratio Γ.

In detail two different experimental tasks are to be solved: first the measurement of velocity and temperature profiles in the boundary layer near the cooling plate and the determination of mean value data, and second the recording of long- term time series of velocity and temperature with the computation of power density spectra and autocorrelation function.

2. EXPERIMENT

The here discussed results were obtained in the presence of passive side walls with a thickness of 160mm, that do not allow a precise control of the thermal boundary conditions. Therefore all results have preliminary character. In the case of velocity and temperature profile measurements near the center line of the cylindrical convection cell these influence can largely be neglected.

In the present RB experiment with a variable height between h=0.1m and 6.30m and a diameter of d=7.15m we are able to study the velocity and the temperature field in great detail. We investigate profiles as well as the statistical properties of both fields in the boundary layer of the air-filled convection cell.

The velocity measurements are performed with a 1d Laser--Doppler--Anemometer (LDA) through a small glass window located in the center of the cooling plate (Fig. 2). Two laser beams emitted from the LDA probe (Polytec) pass the window and intersect in the measurement volume. Tracer particles, inserted into the convection cell by a fog generator, scatter the laser light from the measurement volume back to the receiver of the LDA probe. The frequency of intensity modulated back-scattered light is proportional to the velocity component perpendicular to the optical axis in the plane of incidence.

Because of the small size of the measurement volume (l_{mvz}=0.250mm, d_{mvx}=0.050mm) in comparison to the thickness of the viscous boundary layer, the spatial resolution of the velocity profile is higher than in previous RB experiments. The LDA burst signal rate depends on the concentration of white fog particles and varies between 1Hz and 20Hz.

In order to measure the velocity profile the LDA probe is moved by a PC controlled traverse system with a positioning accuracy of 0.01mm in vertical (z) direction through the boundary layer up to a depth of 425mm. The distance between the 70 measuring points amounts to 0.1mm close to the wall and to 25mm in the bulk. The measuring time for each position averages 35min, for the complete profile 2 days. The 1d LDA probe measures the velocity in the dominant direction first, which we define as mean flow. After each profile recording the LDA probe is turned at 90° to obtain the y-component, which we call cross flow.

For the temperature measurement a glass encapsulated NTC thermistor (Thermometrics) with a diameter of d_{th}=0.140mm and a response time of 120ms is used. The temperature probe is moved in vertical direction at the same position and with equal measuring coordinates as the LDA measurements. Together with a computer controlled measurement system based on a HP3458 multimeter (8.5 digit, 100000 readings/s) temperature fluctuations down to the smallest scales are detectable.

The measurement system allows a recording of temperature time series with a sampling rate up to 333 Hz for each point. A recording time of 35min leads to a total number of temperature data of 700000 per measurement point.

The complete set of experimental parameters for the velocity and temperature measurements is listed in Tab.1.

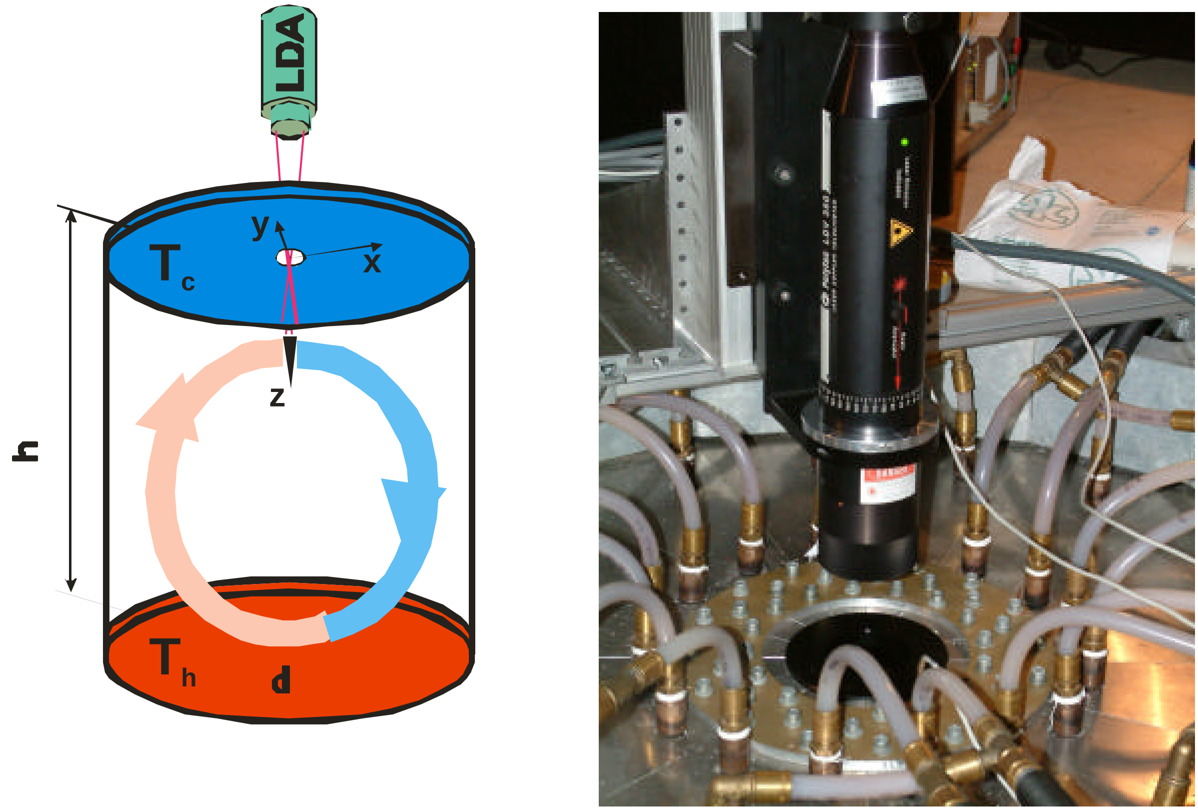

Fig.2: Schematic sketch (left) of the cylindrical convection cell with heating plate on the bottom (red) and cooling plate at the top (blue). LDA and temperature measurements (right) are accomplished through a glass window in the center of the cooling plate.

Tab.1: Experimental parameters of velocity and temperature measurements

Ra	**10^{10}**	**10^{11}**	**10^{12}**
Temperature of heating plate	26.0 °C	37.2 °C	71.2 °C
Temperature of cooling plate	19.9 °C	20.1 °C	22.0 °C
Height of cell	2.62 m	4.00 m	6.30 m
Aspect ratio Γ	2.73	1.79	1.13

3. RESULTS AND DISCUSSION

3.1 Velocity field structure

One of the most important but until now unsolved problems is the characterization of the large-scale circulation (wind) in the bulk region of the convection cell. In view of the mean flow hypothesis by Tilgner et al (1993) and Qui and Tong (2001) the investigations should answer the question whether the predicted coherent single-roll structure still exist at aspect ratio Γ=2 or goes over into a multi-roll flow at higher aspect ratio Γ>2.

The measured long-term velocity data with a duration of 48h per profile show a very different behaviour dependent on Ra and Γ (Fig. 3). At Ra=10^{12} and Γ =1.1 we can clearly recognize a stable velocity profile in the viscous boundary layer. The constant direction of the mean flow over a period of 48h indicates the existence of a stable single roll.

By increasing Γ to 1.8 and decreasing Ra to 10^{11} the uniformity of the mean flow direction is broken and no well defined velocity profile can be measured. This tendency culminates in a total breakdown of the coherent structure at Ra=10^{10} and Γ=2.7. In this case the steady mean flow velocity component is completely substituted by large fluctuations in all directions.

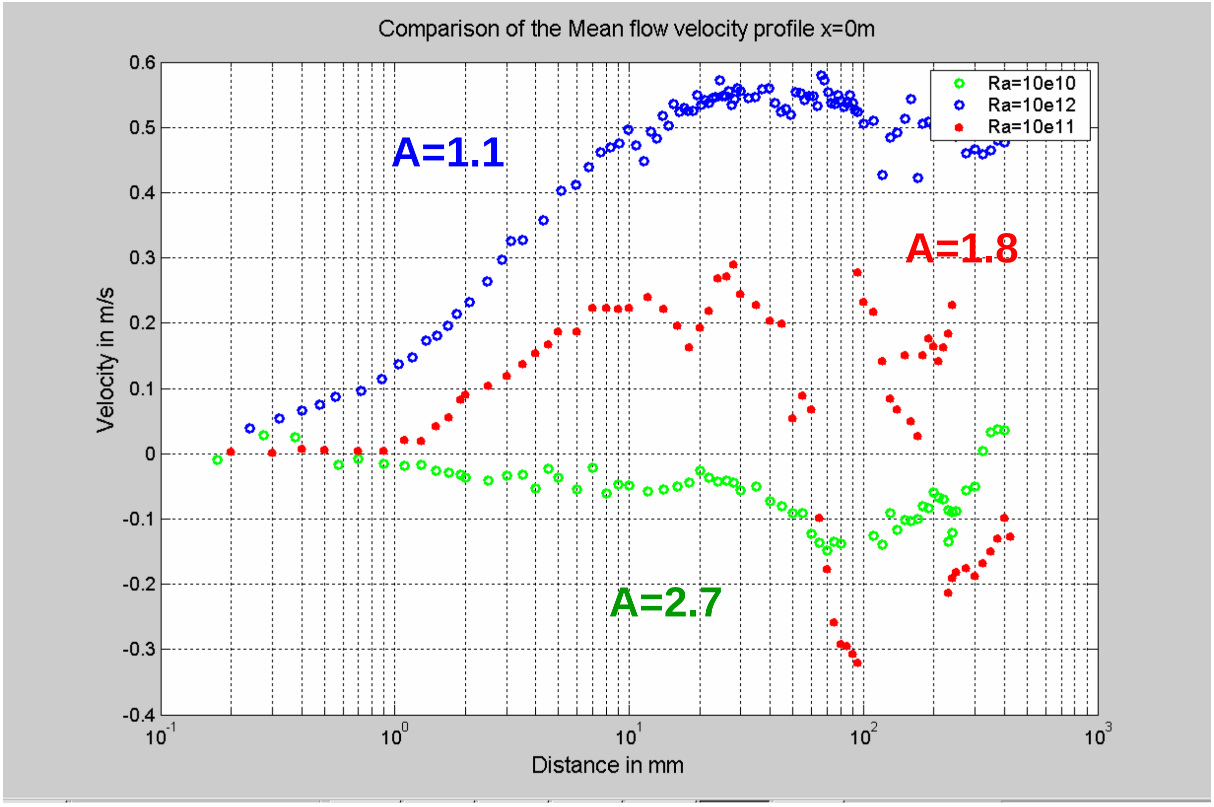

Fig. 3: Mean flow velocity profiles at different Ra numbers and aspect ratios, measured in the boundary layer under the cooling plate.

3.2 Temperature field structure

The measured temperature profiles are overall smoother than the velocity profiles. There is little dependence of the profiles on Ra and Γ . In all cases we get typical boundary layer profiles with a thermal boundary layer thickness of 1.6mm, 1.7mm and 1.8mm at Ra=10^{12}, Ra=10^{11} and Ra=10^{10} respectively. These values are determined by the distance at which the extrapolation of the linear portion of the mean profile equals the central mean temperature.

The comparison of temperature fluctuations and velocity profiles permits an estimation of viscous boundary layer thickness (Fig. 4). Belmonte et al (1994) described a method based on the determination of the cut-off frequency in the temperature spectra. The highest cut-off frequency was found in a spectra at a position where the standard deviation of velocity has a maximum.

The investigation at the convection cell at Ra=10^{12} shows a viscous boundary layer thickness of 20mm determined by cut-off frequency, of 22mm given by the maximum of the velocity standard deviation and 25mm measured in the mean velocity profile. These results confirm previous measurements of the Libchaber group (Tilgner 1993).

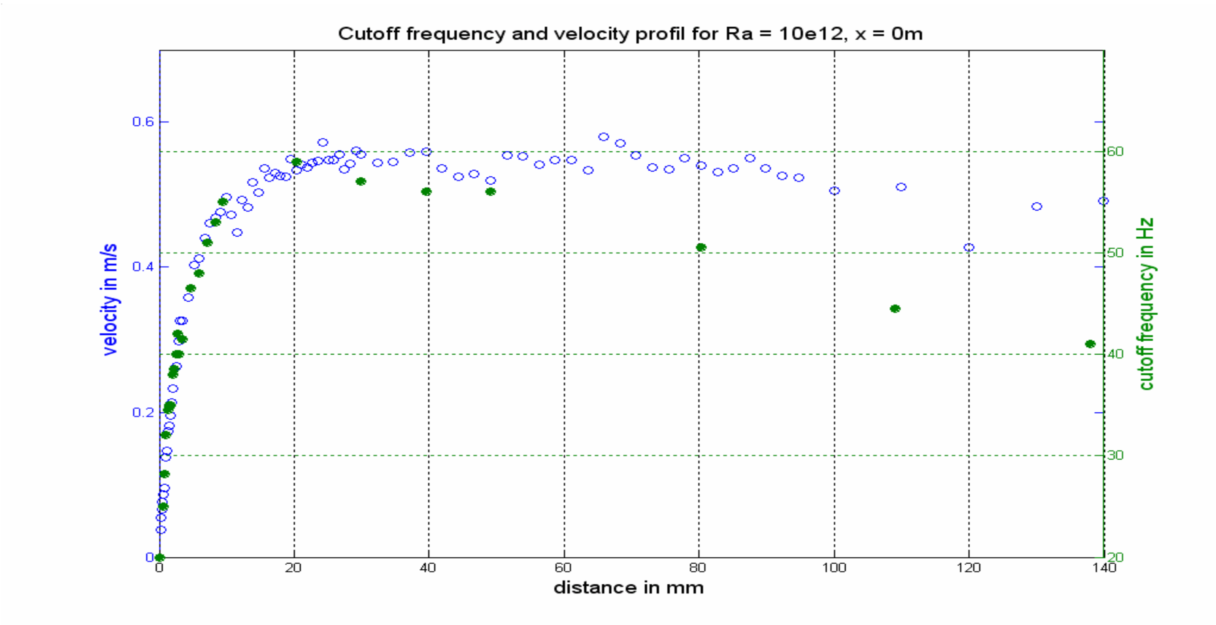

Fig. 4: Comparison of velocity profile and cut-off frequency of temperature spectra

3.3 Coherent oscillations

Coherent structures in Rayleigh-Bénard convection were objectives of several experiments. Castaing et al (1989) and Villermaux (1995) describe them as a delayed coupling of boundary layer instabilities caused by hot and cold plumes. Our analysis of $v_x(t)$ and $v_y(t)$ should test this model and investigate the dynamic behaviour of velocity and temperature oscillations.

The autocorrelation functions of mean and cross flow velocity at Ra=10^{12} show characteristic time scales of 20s and 40s (Fig. 5). The dominant time scale of the temperature signal corresponds also 40s and agrees with the turnover time of the convection cell. Additional to the short-term fluctuations one can find a long-term oscillation with a period of 500s.

The physical interpretation of the measured coherent oscillations requires further experimental investigations in the future.

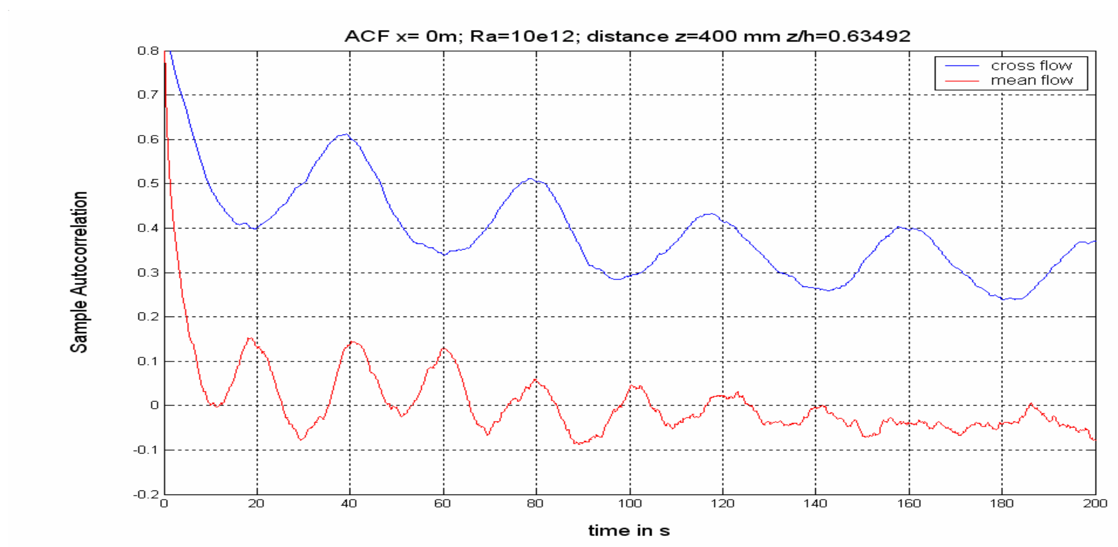

Fig. 5 : Autocorrelation functions of mean and cross flow velocity time series.

4 CONCLUSIONS

Our large-scale RB experiment permits high-resolution local measurements of velocity and temperature at Ra >> 1. The velocity data at Ra=10^{12} and Γ=1.1 indicate the existence of a turbulent boundary layer.

The detection of a single-roll mean flow structure at Γ =1.1 is in a good agreement with the theoretical predictions. For higher aspect ratio the single mean flow roll appears to completely breakdown. Coherent structures are detectable in both velocity and temperature time series at Ra=10^{12} and Γ =1.1.

At the present time our RB experiment is being upgraded by the installation of a counterheating system. Thus future results will be obtained with more precise boundary conditions.

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