Flow Visualization in a Large-Scale Rayleigh-Bénard Experiment

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Abstract

The objective of our paper is to investigate the flow pattern in turbulent Rayleigh-Bénard convection from large scales down to the smallest scales. We present a method to visualize the turbulent convection in a large-scale Rayleigh-Benard experiment with air as a working fluid. The so called "Barrel of Ilmenau" with a diameter of 7.15 m and a variable height between 0.1 m and 6.40 m allows to investigate turbulent convection flows at high Rayleigh numbers. By varying the distance and the temperature difference between the heating and the cooling plates a large range of Rayleigh numbers (10^5 to 10^{12}) and aspect ratios (1.1 to 150) can be investigated. The visualization is based on a 7mx7m light sheet produced by a 3 W Argon Laser source combined with an oscillating mirror. Tracer particles, for example helium filled soap bubbles or particles from a smoke generator were injected into the light sheet. A camera records either the pattern of the smoke or the tracks of the soap bubbles. On the monitor of the visualization system which is based on a fast personal computer one can see the camera images in real time. At the same time they are stored on hard disk in a standard AVI-File. We present preliminary results of the visualization of the mean flow in this large-scale Rayleigh-Bénard experiment at a Rayleigh number of $Ra=5x10^{11}$ and an aspect ratio of A=1.2. Characteristic flow pattern, for example one large convection roll in the cell, are shown.

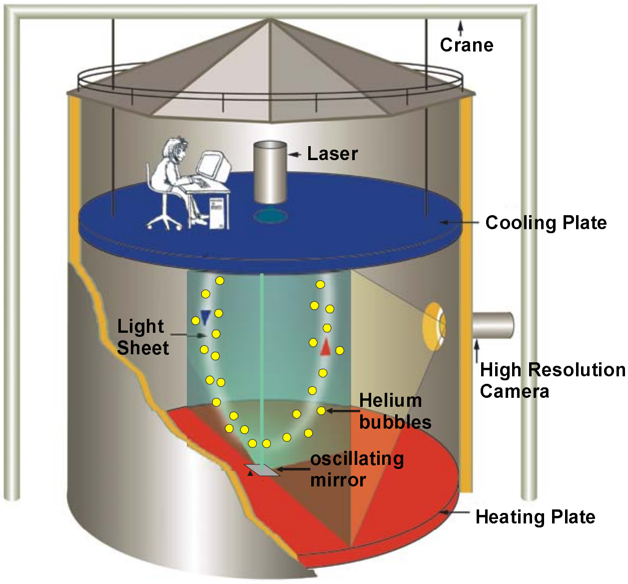

Figure 1: Sketch of the large-scale convection cell and the experimental set-up for flow visualization

1 Introduction

Thermal convection at high Rayleigh numbers Ra is a basic 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 investigate such flow is the Rayleigh-Bénard experiment.

Recently performed RB experiments by Castaing et al. (1997) and Niemela et al. (2000) determined the global heat flux between the heating and the cooling plate in a range of Ra numbers of $10^5<Ra<10^{14}$ (Castaing) and $10^6<Ra<10^{17}$ (Niemela). The investigations was performed in a RB-cell filled with Helium at a temperature near the critical point (5 K). Although the experiments in Helium allow investigations at the highest Ra number, it is very hard to measure local temperatures and nearly impossible to measure local velocities or both. Tilgner et al. (1994) performed a RB experiment in a small high-pressure cell with SF_6 and water. The group succeeded with the measurement of temperature profiles and time series in the boundary layer at $10^5<Ra<10^{11}$. Because of the decrease of the thickness of the boundary layer with increasing Ra numbers (d_{BL}=1 mm at $Ra=10^{11}$) the resolution of the measured temperature profile is low. Single velocities in the boundary layer were determined with a correlation of temperature fluctuations on two temperature sensors situated next to each other. By the application of LDA technique Tong et al. (2000) could measured velocity profiles and time series in the boundary layer of a RB experiment with water at $Ra=3.7x10^9$. However there are only few data concerning the structure of the flow, the velocity and the temperature field and the correlation between temperature and velocity in a RB experiment at high Ra numbers. In summary, visualization and high resolution measurement of thermal convection at very high Ra number remains a largely unresolved issue.

The Barrel of Ilmenau, shown in figure 2, is an experimental facility to perform RB experiments with air as the working medium and a maximum Rayleigh number of $Ra=10^{12}$. Because of the large size of the experiment (the inner diameter is 7.15 m and the height is adjustable in the range of 0<h<6.40 m) it allows to visually observe the convective flow, to measure global temperature and velocity fields and to measure local temperature and velocity profiles and time series in the boundary layer. It can be done with higher spatial resolution than in other experiments.

In this paper we present a method to visualize the global convective flow in the cell, called the mean flow or the wind. Preliminary results at $Ra=5x10^{11}$ are shown and give a first insight in the possibilities of this method used for large scale flow visualization.

Figure 2: Barrel of Ilmenau with crane (blue steel construction), cooling system (green refuge) and measuring container

2
Experimental set-up

The Barrel of Ilmenau is a cylindrical container 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 coated with aluminium foil to prevent the radiation exchange with the cooling plate and the side walls. The maximum temperature at the surface is about 75 °C.
The cooling plate consists of 16 separate water cooled segments. The thickness of the segments is 4 cm and they consist of two aluminium 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 most cases the temperature is fixed at 20°C and the temperature deviation over the whole surface is lower than 1 K.

2.1
Light sheet

The basis for making visible the convection flow between the heating plate at the bottom and the cooling plate at the top is a light sheet in the direction of the mean flow and appropriate tracer particles in the flow. The light sheet is produced by a 3 W Argon Laser. Via a 20 m long fiber link (100µm multi mode fibre) the light comes to the oscillating mirror and is spread into the light sheet. In the future a rapidly rotating mirror with a 45° plane will be used. The speed is variable and can be synchronized with the camera.
Other, commonly used methods of flow visualization, e.g. white light sheet generated by a high power halide or arc lamp or use of a cylindrical lens did not lead to success results in our experiment.

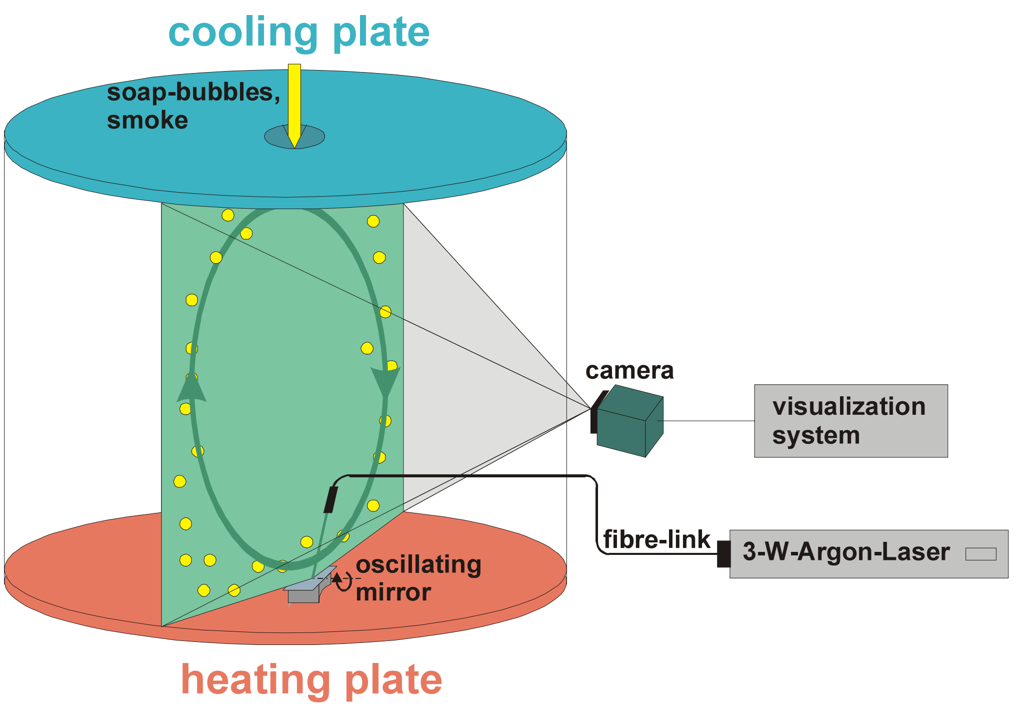

Figure 3: Sketch of visualization

2.2
Seeding particles

We use two several kinds of seeding particles to make the convective flow visible. One of that is white fog from Dantec's fog probe system. Especially developed and optimized for flow field visualization in wind tunnels it allows to inject small threads of smoke into the experimental volume or directly in the boundary layer. Flow pattern near the injection point are visible very well but after a way of about 3...5 m the fog structures disappears because of the high level of turbulence (T_u=1) in case of thermal convection.
The other kind of tracers are helium filled soap bubbles. By adjusting the size of the bubbles it is possible to adapt the density of the helium filled soap bubbles to the density of the air. First tests were performed with the commercial SAI™ Model 5 Bubble Generator (Sage Action Inc.). Currently the bubbles are injected into the light sheet trough a window in the center of the cooling plate. The low generation rate of the bubble generator (400 bubbles p.s.) and the short life time (1 min) does not allow to fill the experimental volume completely with soap bubbles. For that cause the light sheet is to adjust in the same direction as the mean flow in order to keep the bubbles inside. In the future four bubble sources one in each corner of the light sheet will produce a larger amount of bubbles.

2.3
Image processing

The motion of the particles is recorded either with a high resolution B/W Camera TM-1320-15CL or with a semiprofessional digital camcorder CANON XL1s. Both Cameras are able to cover the complete area of the light sheet. The position of the TM-1320-15CL inside of the experimental volume can changed, whereas the position of the CANON-camera is fixed outside.

<u>Specifications of TM-1320-15CL (PULNIX)</u>

Imager:	2/3" (8.7mm x 6.9mm) progressive scanning CCD with on-chip micro lenses
Pixel:	1300 (H) x 1030 (V)
Frame rate:	0.5...15fps
Frame shutter:	2s...1/16000s
Size:	44mm x 44mm x 64mm
Weight:	133g

<u>Specifications of CANON XL1s</u>

Imager:	3 CCD 1/3" with pixel shifting
Pixel:	720 (H) x 576 (V)
Frame rate:	25fps
Frame shutter:	1/6s...1/16000s
Size:	223mm x 214mm x 415mm
Weight:	2.86kg

In spite of the use of a high power laser the amount of reflected light from the soap bubbles or the fog particles is very small. It is caused by the low coefficient of reflection of the soap bubbles and the small size of the particles of the fog. But still the high sensitivity and the full dynamic control of the TM-1320-15CL allows to separate the small light reflections of the soap bubbles from the light of the background. In combination with a PC-system it is possible to record not only single frames, multiple frames and short sequences but also complete AVI-movies to the hard disk. Presently the large amount of the data limits the length of records to about 2 hours. In the future a powerful compression tool will reduce the amount of data and make possible long-term recordings.
Depending on the exposure time two kinds of pictures or sequences are generated. A short exposure images the bubbles as bright points on dark background. Two consecutive pictures can be correlated in order to compute the velocity field. A long exposure delivers tracks of the soap bubbles. This method is ideal for the qualitative analysis of the convective flow.
The CANON-camera in combination with a VCR is generally used for long-term visualization with moderate demands on the resolution. This camera can only applied together with smoke, because the sensitivity is insufficient to record the motion of the illuminated soap bubbles.

3
Visualization

Before to start the visualization it is necessary to wait for the steady state. In case of our experiment it usually takes about four days. In this time all systems around the experiment especially heating and cooling must work uninterrupted.
In case of an ideal RB experiment, the direction of the so called wind is purely by chance. It is not fixed and the direction can vary during the experiment. By first investigations to determine the global heat flow it was observed, that smallest disturbances of the temperature deviation on the heating plate influences the direction of the wind. The wind is vectored downwards on the coldest and upwards on the warmest position of the heating plate. We used this fact and cooled down a part of the heating plate in a controlled manner by about 2 K. The mean direction of the wind could be stabilized, but the fluctuation of cause of the high turbulence are still as large as ±30° with respect to the plane of the light sheet.
First visualizations were performed by the injection of fog through a window in the center of the cooling plate. The applied fog from Dantec's fog probe system was directly injected into the experimental volume. The velocity of the particles and their temperature are relatively high when they enter. Only a short track (less than 0.5 m) their velocity adapts to the velocity of the convective flow. To keep the influence of the fog of the convective flow to a minimum, in next experiments the fog will be lead through a large buffer container to brake it and to cool it down.

4
Results

In figure 4, it is shown a sequence of pictures which was extracted from a video recorded with the digital camcorder Canon XL1s. The exposure was 1/6s.

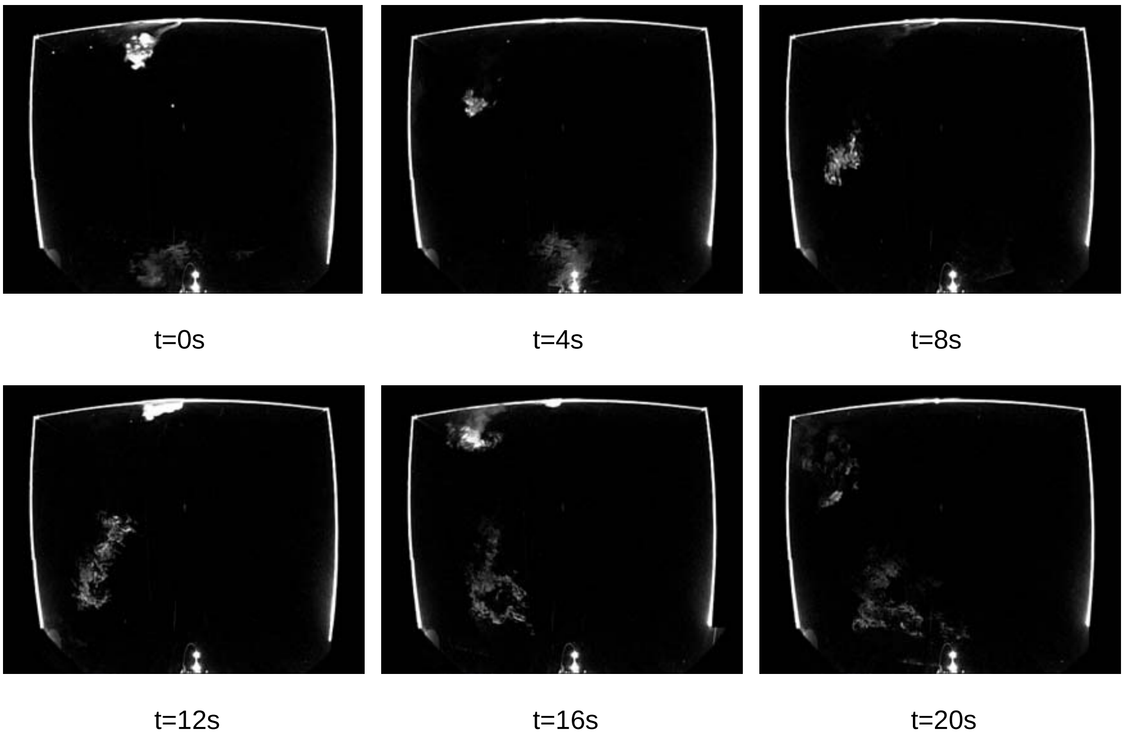

Figure 5: Visualization of a highly turbulent convective flow by fog

<u>Parameter of the experiment:</u>

Distance between the heating and the cooling plate:	*6.00m*
Aspect ratio:	*1.2*
Size of the light sheet:	*7 x 6m*
Rayleigh Number:	$5x10^{11}$

There is pictured the first visualization of the transport of a scalar field in a large-scale RB cell at a Prandtl number of Pr=0.7 by fog. Furthermore it was demonstrated the existence of a mean flow in the form of one large convection roll over the whole cross section of the RB cell. The estimated average velocity was $v_{mean} \approx 0.5$ m/s. The spreading of the fog during it's motion through the cell is a result of the high level of turbulence.
The experiments with helium filled soap bubbles are in work at this time. Preliminary experiments with the commercial generator and one nozzle were performed. The brightness of the small light reflexes of the soap bubbles in the light sheet is very low. For filling the light sheet with a sufficient number of soap bubbles, more than one generator has to be used. This work is currently in progress and will be reported elsewhere.

5
Conclusions

Two methods of large scale visualization of turbulent convection flow in a Rayleigh-Benard experiment were presented. Our preliminary results clearly demonstrate the feasibility of visualizing the turbulent large-scale motion using fog and a large high power laser light sheet. The disadvantage of visualization by fog, it's quick dispersion, can be avoided by using of helium filled soap bubbles. Moreover, first experiments with the SAI™ model 5 generator and one nozzle situated in the centre of the cooling plate shows the basic suitability of this method. However this method will require significant work.

6
Acknowledgement

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