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Temperaturfeldmessung in turbulenter Rayleigh-Bénard-Konvektion

Temperature field measurement in turbulent Rayleigh-Bénard convection

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Abstract

Turbulent Rayleigh-Bénard convection is a less-studied phenomenon in large aspect ratio convection cells. Furthermore the existence of superstructures in turbulent convection is only known from direct numerical simulations (DNS) and was not experimentally confirmed so far. Against this background we investigated large scale structures in turbulent convective flow in water, applied to a Rayleigh-Bénard cell with large aspect ratio of $\Gamma = 30$ and Rayleigh numbers about $Ra \approx 1.1\times10^5 \ldots 5.0\times10^5$. Therefore, we introduced temperature field measurements under the given conditions for the first time. Hence the major aim of this work was checking the applicability of temperature field measurements and the accessible thermal resolution (minimum detectable temperature difference ΔT) in turbulent flow by laser induced fluorescence (LIF) at large aspect ratio.

Introduction

Heat and mass transfer in natural convection are directly coupled and are accessible by measuring the temperature and velocity field of thermal convection.[1,2] Commonly the velocity field of thermal convection is measured by particle image velocimetry (PIV). Therefore particles are added to the fluid requiring similar density to prevent sedimentation of the particles and permit easy follow of the convective flow of mass.[3] Thus particle imaging velocimetry is a complementary measurement of thermal convection yielding just the velocity field of mass flow. Furthermore, in fast moving flows incoherence between temperature and velocity field may appear, leading to negative flow of heat.[4] On these grounds, it is more reasonable to directly measure the temperature field, though it is experimentally harder to access. Different methods were applied to measure the thermal fields in fluids. For example laser induced fluorescence (LIF)[5,6], thermochromic liquid crystals (TLCs)[7,8,9] or thermochromic phosphor particles (TPPs)[10,11] were developed for measuring 2-dimensional temperature fields in laser light sheet irradiation. Whilst TLCs have very narrow temperature scale of several Kelvin, but high resolution, LIF and TPP provide temperature range of several decades to hundreds of Kelvin, which is important for studying turbulent flow at large temperature gradients. A further prerequisite of LIF and TPP is that no circular analysis of measured raw data is necessary to resolve the temperature field. In addition LIF is based on molecular dispersion and thus no displacement correlations between temperature tracing particles and the fluid flow of convection will take effect. For example particle based temperature measurements possibly lack of heat transport from the outer sphere to the fluorescent or phosphorescent core of the particle.

Since our study aims on investigation of turbulent flow at large aspect ratio in water, LIF is the most suitable method, simply to apply and analyze. Since the convective cell is mostly a closed system with given height, the only opportunity to change the Rayleigh number *Ra* is the variation of temperature between heated and cooled enclosure from very low to very large gradients, requiring a temperature detecting technique spanning a possibly large temperature range. A further advantage of LIF is the diversity and excellent solubility of organic dyes[12] in various fluids and the direct response to temperature change as the single molecules are in direct contact with the fluid. Furthermore, since the maximum and minimum temperature is given by the applied heating and cooling temperature the temperature gradient is easily interpolated between those values. By measuring the luminescence efficiency vs. temperature response in advance under defined conditions, interpolation functions can be determined.

Experimental

First of all we verified the temperature dependent fluorescence of rhodamine B (Alfa Aesar) by heating 2 mg/l water based solution in a closed cuvette. The cuvette holder (Avantes) was placed on an electronic heating plate (CAT MCS 66). The temperature was varied from room temperature up to 80°C. After changing the temperature the system was equilibrated for at least 15 minutes. Hence the dye was excited with a 532 nm laser module CPS532 with 4.5 mW continuous wave (Thorlabs). The temperature dependent fluorescence was detected with a fiber spectrometer (Avantes Avaspec

ULS2048). Hence the recorded spectra were integrated from 520 nm to 780 nm to calculate total emission of the dye.

For studying turbulent Rayleigh-Bénard convection in water we used a closed cell with dimension of 600 × 600 × 20 mm³ yielding an aspect ratio of $\Gamma = 30$. The transparent non-adiabatic side walls were made of 5 mm thick poly(methyl metacrylate) (PMMA). The bottom heating plate (ELKOM) had a heating power of 1550 W and contained four PT100 thermocouples (Löbach-Messtechnik GbR) controlled by a data logger (Agilent 34970A) with a 20 channel multiplexer (Agilent 34901A). The heating power was controlled with an infinitely variable power supply (RFT Stelltrafo TST 280/6). The heating power $\dot{Q}$ was recalculated with the measured voltage (U) and current (I) input at the heating plate $\dot{Q} = U \times I$. The top cooling plate was a flow-through cell containing transparent window pane plates providing optical access to the convection cell. The side walls were also made of PMMA. The cooling liquid was water, driven by a recirculating cooler (Huber Unichiller 012-MPC) with maximum 1200 W cooling power at 15°C. The inlet and outlet temperatures of the flow-through cell were measured with PT100 thermocouples (Löbach-Messtechnik GbR) connected to the data logger. The cooling water temperature was held constant at 20°C for all measurements. Thus the surface temperature of the cold enclosure was estimated by calculating the temperature gradient across the 6 mm thick glass plate, separating the convecting fluid and cooling water. For known heating power input $\dot{Q}$ at the hot enclosure the temperature drop ΔT across the glass plate was given by heat transport equation $\dot{Q} = \frac{A \cdot \lambda \cdot \Delta T}{D}$, with A: surface area λ: heat transport coefficient and D: thickness. The concentration of rhodamine B in the convective cell was 2 mg/l.

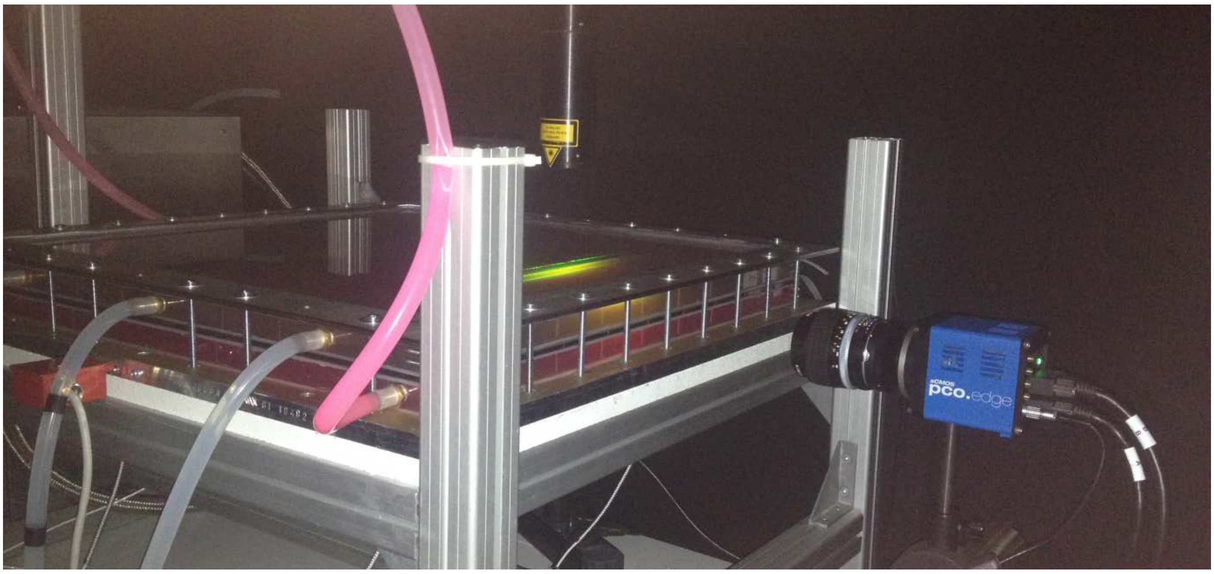

Figure 1: Experimental setup showing the Rayleigh-Bénard cell, laser module and camera.

The excitation of the dye was carried out by light sheet irradiation with a fully assembled 532 nm laser module with integrated light sheet optics (Polytec LUX-DF-H). The laser power was 100 mW continuous wave. Fluorescence images were recorded with a sCMOS camera (PCO edge 5.5), equipped with a Nikkor 35mm f/1.4 manual focus objective (Nikon), at temperature differences ΔT = 1.0 K, 1.8 K, 2.3 K, 2.6 K, 3.3 K and 4.4 K and accumulation rates *Acc* = 1, 2, 4, 8, 16 and 32 for fixed maximum possible integration time of 20 ms before saturating the CMOS detector. Data processing was performed with ImageJ (National Institutes of Health) by averaging the individual image sequence and subsequently subtracting it from the singles images. Hence the contrast was enhanced (saturated pixels set to 5% and normalization of images) yielding the final temperature field images, gray scaling from the applied cooling temperature (white) to the applied heating temperature (black). The experimental setup is depicted in Figure 1.

Results and Discussion

Spectral sensitivity of rhodamine B

The results of temperature dependent fluorescence are summarized in Figure 2. It shows the pure measured fluorescence spectra for temperatures varied from 25°C to 80°C in steps of 5 K and the calculated integral intensity of spectra.

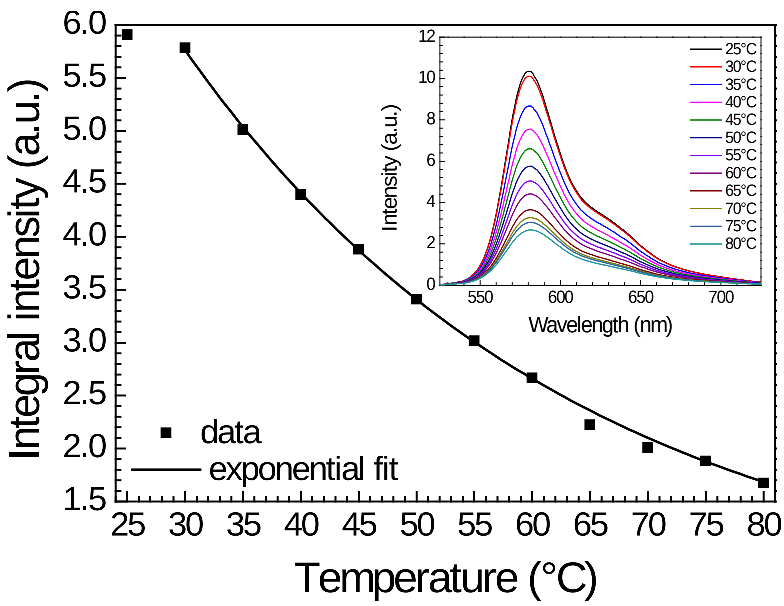

Figure 2: Spectral sensitivity and temperature dependent fluorescence of rhodamine B.

The calculated intensities were exponentially fitted without physical meaning. The inset at 25°C and values for 65°C and 70°C were not considered for fitting since the values were mismatching and leading to non-converging fit condition if taken into account. Thus the exponential fit well-followed the experimental data and hence can be considered for rescaling the temperature fields in convective flow. The extracted fit values are depicted Table 1.

Table 1: Fit values of exponentially fitted integral intensity of temperature dependent fluorescence.

	Equation	Parameter	Value	Standard Error
	$y = A_1 \times exp\{-x/t_1)\} + y_0$	y_0	46.87518	6.21336
Reduced Chi-Sqr	3.27203	A_1	1279.14348	14.0683
Adj. R-Square	0.99983	t_1	34.00249	0.75466

Temperature fields in water

Temperature fields in water were measured under varying conditions regarding the temperature gradient between hot and cold enclosure of the Rayleigh-Bénard cell. The temperature induced variation of the Rayleigh number calculated by $Ra = \alpha \Delta T g h^3 / \nu a$ was $Ra \approx 1.1\times10^5 \ldots 5.0\times10^5$, limited by the technical specifications of the heating and cooling system; α: thermal expansion coefficient, ΔT: temperature difference between hot and cold enclosure, g: acceleration due to gravity, h: height of the convective cell, ν: kinematic viscosity and a: thermal diffusivity. To investigate the applicability of rhodamine B and the accuracy for measuring temperature fields in water, the convective flow was monitored in vertical light sheet orientation for different temperature gradients and accumulation rates. The investigation of the accumulation/averaging rate is so far important since the detection limit of the CMOS is given by its lighting saturation capability due to the integration time, which was found to be 20 ms in the present case. Hence an improvement in image quality can only be achieved by internal accumulation and averaging. But this is a very delicate issue to be handled carefully. The convective flow causes permanent change in local emission which is to be detected. Thus increasing the accumulation rate results in distortion of the effective temperature field and loss of local information, especially if the temperature gradient is increased and the flow velocity rises dramatically. Hence accuracy of temperature field measurements is determined by the trade-off of flow velocity (temperature gradient) and accumulation rate. Figure 3 depicts vertical temperature fields for various temperature gradients and accumulation rates. Apparently, the detection limit of temperature variations in application of rhodamine B is downward limited to ΔT = 1.0 K, where only variations were detectable at accumulation rate of 32. But the resulted temperature field image seems to be less reliable. First ΔT = 1.8 K delivered suitable image contrast, also at lower accumulation rate, which further increased for larger ΔT due to the fact that the luminescence efficiency of rhodamine B largely depended on the applied temperature, compare Figure 2. It is also quite obvious that the accumulation rate had strong impact on the image quality, especially at small temperature gradients. Increasing the accumulation rate led to increased temperature field contrast and decreased noise of the images, despite the fact that the effective temperature field washed-out for larger temperature gradients. Consequently for the applied integration time of 20 ms frame rates varied from 50 Hz for *Acc* = 1 to 1.56 Hz for *Acc* = 32, which becomes critical for large flow velocity due to increased temperature gradient. This has to be considered when evaluating such images and judging the reliability of the resulting temperature field. Finally, it is to be advised to minimize the accumulation rate to the least suitable value to do not lose spatial resolution on smaller time scales.

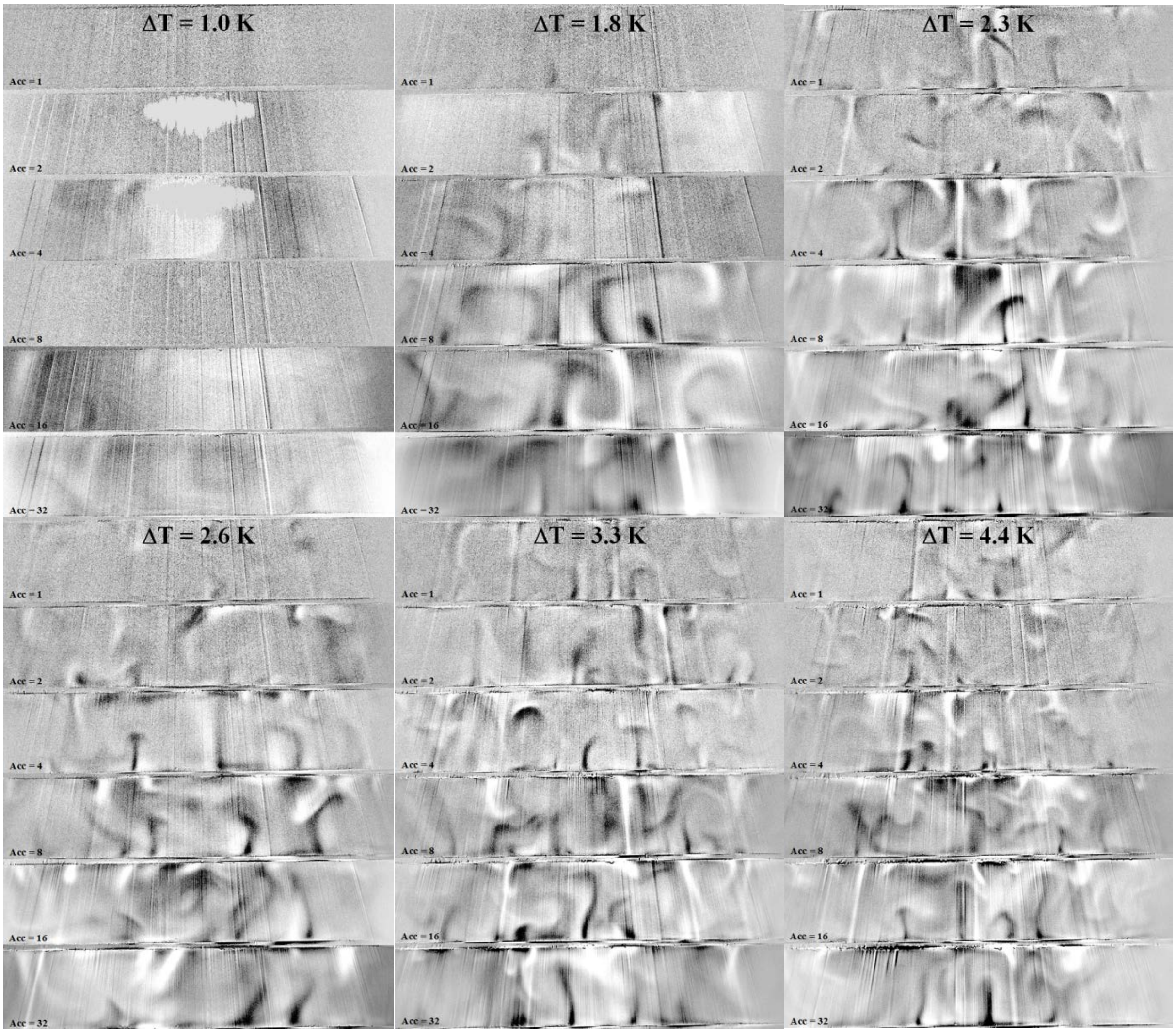

Figure 3: Vertical temperature field measurements for various temperature gradients (top left to bottom right: ΔT = 1.0 K, 1.8 K, 2.3 K, 2.6 K, 3.3 K and 4.4 K) and accumulation rates (from top to bottom of each single image: *Acc* = 1, 2, 4, 8, 16 and 32).

Summary

We demonstrated first time application of laser induced fluorescence (LIF) in large aspect ratio (Γ= 30) turbulent Rayleigh-Bénard convection in water. The applied fluorescence dye rhodamine B showed well resolvable temperature sensitivity in combination with a scientific CMOS camera, also for small temperature gradient between hot and cold enclosure of the convection cell. Whilst increasing the accumulation rate improved the image contrast and signal to noise ratio it had to be considered that the effective temperature field became distorted for increased temperature gradient due to larger flow velocity.

Acknowledgements

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