

# Structure of plumes in Turbulent Rayleigh Bénard Convection

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## Résumé :

*Cette étude porte sur la visualisation de plumes par PLIF (Planar Laser Induced Fluorescence) en convection turbulente de Rayleigh-Bénard dans une cellule cylindrique en présence ou absence de rotation. Les plumes sont des structures cohérentes de forme similaire à des champignons quand elles sont visualisées par le coté et de forme allongée quand elles sont vues par le haut. Le principe de la PLIV repose sur la dépendance en température de la fluorescence de certains colorants fluorescents. Il est possible de remonter au champ de température après calibration en mesurant la fluorescence par une caméra haute sensibilité et en utilisant des filtres appropriés. Cette technique repose fortement sur la sensibilité des colorants fluorescents.*

## Abstract :

*This project is intended to visualize the thermal plumes in a cylindrical turbulent Rayleigh-Bénard convection cell by PLIF (Planar Laser Induced Fluorescence) in absence of rotation or in rotation. The plumes are coherent structures that have a mushroom-like form, when viewed from the side and a sheet-like form when viewed from above. The PLIF technique is based on the ability of some fluorescence dyes to have a temperature dependent fluorescence. By measuring the fluorescence of the dyes with a highly sensitive camera, after a proper calibration and the use of appropriate filters, it is possible to calculate the temperature field. This technique relies strongly on the temperature sensitivity of the fluorescent dye.*

**Keywords: Rayleigh Bénard Convection, Laser Induced Fluorescence, Plumes visualization, Plume structure.**

## 1. Introduction

Rayleigh-Bénard convection can be seen everywhere in the environment - convection in the sun, in the earth atmosphere and in earth mantle between the hot core and surface of earth. Typically any region which is heated from below and cooled from the top creates Rayleigh-bénard convection. Plumes are the main way to carry heat between the hot and cold thermal boundary layers of RBC cells. Most of the temperature gradient across the cell is located in the boundary layers. Nevertheless, the dynamics of plumes and their properties are still not completely known and the problem of their extraction is still not satisfactorily solved. Plumes are defined as hot or cold blobs of fluids generated in the

boundary layers, respectively rising and sinking. Their movements are organized in a large scale circulation. The temperature difference between these hot or cold blobs of fluids and the surrounding fluid and, by that, the difference in refractive indices in these parts of the fluid compared to the bulk, make it possible to visualize the thermal plumes. The thermal plumes can be observed by shadowgraphy [1], but few information of their temperature can be obtained using this technique. The temperature of plumes can be measured by small thermistors, but they still provide only limited local information. The thermal plumes can also be visualized by thermochromic liquid crystal but only in a very limited temperature range.

The Planar Light Induced Fluorescence (PLIF) [2] has been developed to gain a better understanding of the behavior of the plumes [3]. In a few words, the PLIF technique consists of illuminating a fluid containing a fluorescence dye by a continuous laser sheet. The fluorescence depends on the temperature. The PLIF technique measures the appropriate fluorescence wavelength of the dye using a filter or multiple filters in front of a camera. By image analysis, the temperature can be calculated from the incoming light intensity. The advantages of this technique are: first, the possibility to measure the temperature fields in a complete plane with an excellent temporal resolution, and, second, the LIF-technique can be combined with other techniques like Particle Image Velocimetry (PIV).

The present study had the following goals:

- (i) to understand the behavior of the plumes in RB cells in rotation or not;
- (ii) to relate the plumes behavior to the hydrodynamical processes in the cell.
- (iii) to gain a better understanding on the implication of the thermal plumes on the heat transfer.

## 2. Experimental set-up:

The experimental set up is a 10-cm-diameter cylindrical cell of aspect ratio 1, carved into a PolyMethylMetacrylate cube of 20 x 20 x 20 cm. The external flat surfaces of the cube give a good optical access to the interior of the Rayleigh-Bénard cell (see Fig. 1). A continuous laser sheet (RayPower2000, Dantec Dynamics Skovlunde, Denmark), with a cylindrical lens set-up (Dantec Dynamics Skovlunde, Denmark) cuts vertically the slightly tilted cell in the plane of the large scale circulation. A high sensitivity camera with a high transmission optic is placed in front of the laser sheet, cutting in the RB cell in two halves (see Fig. 2).

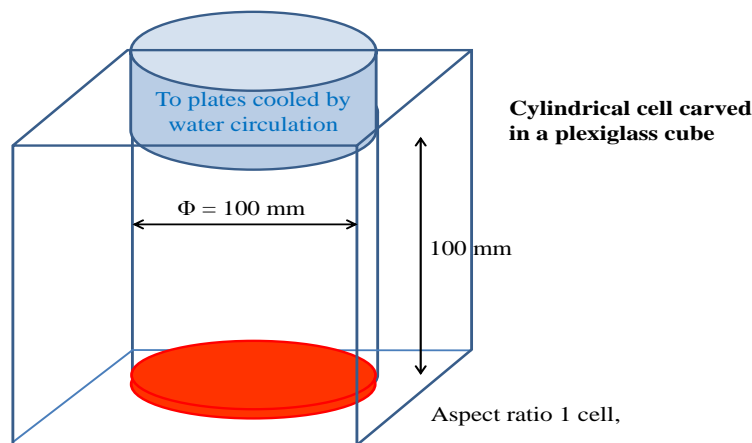


Fig. 1: Schematic representation of the Rayleigh-Bénard cell

- The oxygen free copper bottom plate is heated by joule effect by a resistive wire glued by conductive epoxy into a groove in the bottom plate (the groove sweeps equally the surface across the bottom plate). The resistance of 11 ohms of this wire is supplied with an Agilent Technologies E3634A power supply.
- The top plate of the RBC cell is a sapphire plate chosen for its high thermal conductivity. The top part of this sapphire plate is cooled down by a vigorous water flow maintained at temperature by a circulator (RTE 7, ThermoFisher Scientific).
- An image doubler from LaVision (Göttingen Germany), is used to duplicate the image so that different band pass filters can be applied to the fluorescent light. These filters let the wavelengths  $\Delta\lambda = [595, 605]$  and  $\Delta\lambda = [475, 525]$  go through respectively for the Keton Red and for the Rhodamine 560.

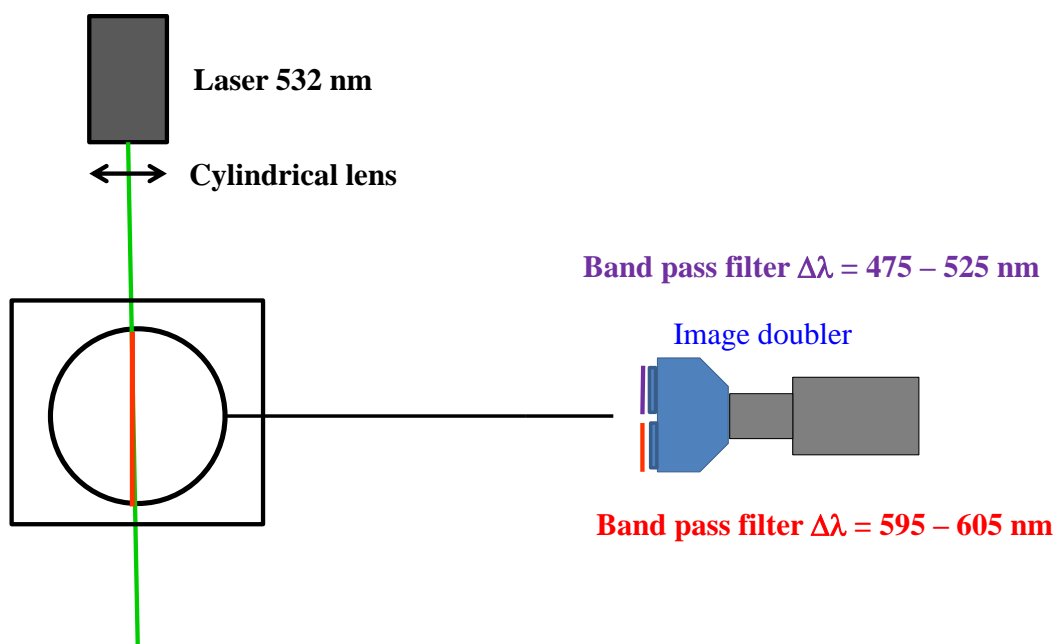


Fig. 2: Optical set-up

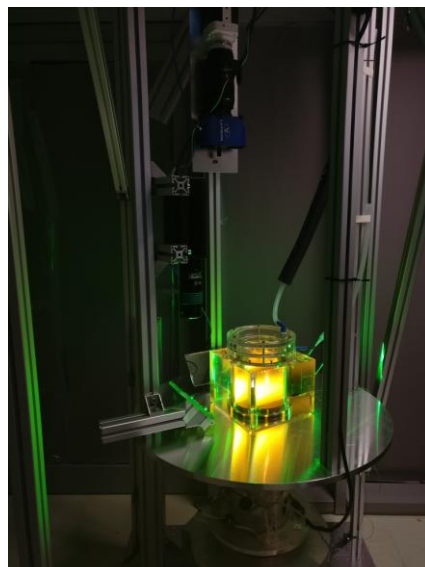


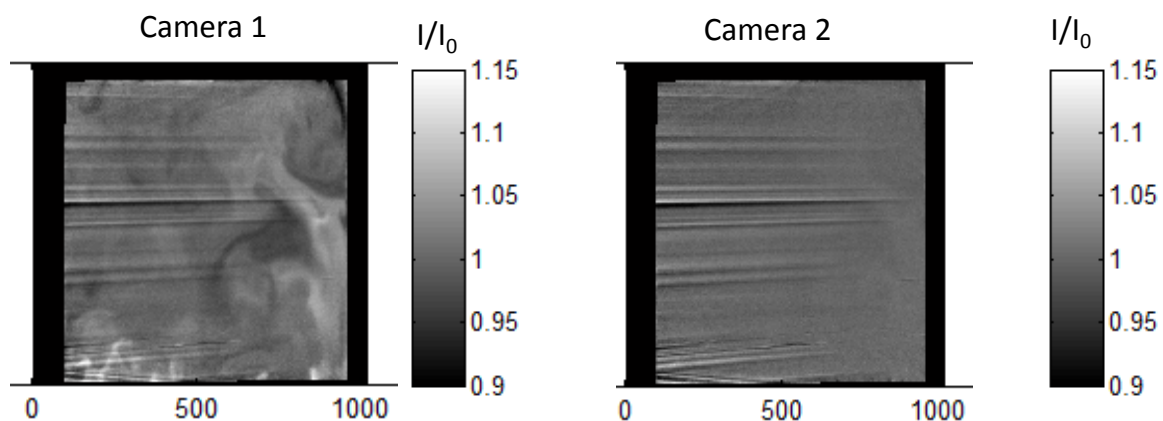
Fig. 3: experiment setup on rotating table.

### 3. Measurement technique:

The plumes are visualized by the LIF optical technique. More exactly, the 2 colors Laser Induced Fluorescence technique is used to visualize the plumes. To our knowledge, this technique has only been used previously only once for turbulent Rayleigh-Bénard convection by Sakakibara and Adrian (2004) [3].

The search for an optimal fluorescent dye (and actually dyes) was one of our major tasks. The dye: (i) has to be highly temperature sensitive (the sensitivity should be of at least a few percent per degree Celcius), (ii) the dye should have a high quantum yield, (iii) it should have a fluorescence that is not predominant in the range of wavelength of the exciting laser i.e. in the wavelength of 532nm in our case. If it would be the case, the fluorescence would decrease with the path length, which would result in fluorescence distortion. Our cell has a diameter of 100mm, what is quite long and forced us to take this factor into account, (iv) the dye should be stable with the time, and not subjected to photo-bleaching i.e. a loss of fluorescence of the molecule dye following a some exposure to the laser light.

At the beginning of our quest, we were looking for a single high sensitive dye like Rhodamine B, Sulfo Rhodamine or Fluorescein. But the slightly different index of refraction of the plumes relative to the surrounding fluid deviate the laser beam which resulted in stripes in the image (see Fig. 3). The use of two dyes allowed us to eliminate the problem of the stripes. Indeed, while in using two dyes and in dividing one image by the other, it is possible to avoid illumination problems, because only the ratio between the fluorescence of the two dyes on chosen wavelength band are taken into account for the calculation of the temperature.



Division of one image by the other → eliminate the stripes (illumination defects)

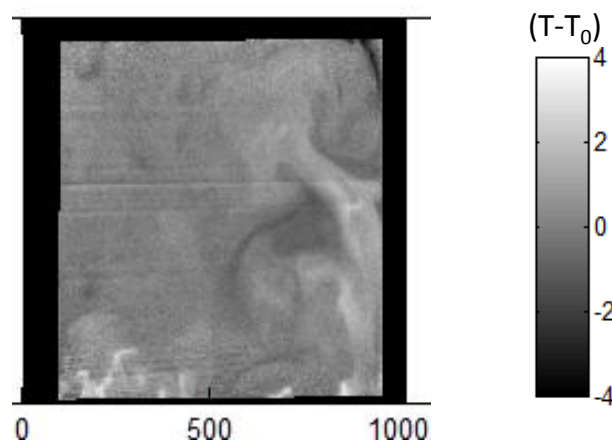


Fig. 4: Elimination of the stripes by the two dyes LIF technique

The emitted light intensity function can be expressed in function of the temperature as:

$$I_f(\lambda) = \underbrace{K_{opt}(\lambda) K_{spec}(\lambda) V_c I_0 C}_{\sim \text{constant}} e^{\frac{\beta(\lambda)}{T}}$$

Where  $\lambda$ : wavelenth,

- $K_{opt}$  : optical constant
- $K_{spec}$  : constant, spectroscopic properties of the tracer
- $V_c$  : collection volume of the fluorescence photons,
- $I_0$  : laser excitation intensity
- $C$  : concentration of the tracer
- $\beta$  : temperature sensitivity parameter,
- $T$  : temperature in °K

In practice a reference image is taken at a uniform temperature  $T_0$ .

- For the fluorescent dye 1, division by the reference frame:

$$\frac{I_{f_1}}{I_{Ref_1}} = \frac{I_0}{I_{0Ref}} e^{\beta_1(\lambda_1)\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

- For the fluorescent die 2, division by the reference frame:

$$\frac{I_{f_2}}{I_{Ref_2}} = \frac{I_0}{I_{0Ref}} e^{\beta_2(\lambda_2)\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

- By doing the ratio of these two quantities, we obtain:

$$\frac{I_{f_1}}{I_{f_2}} = \frac{I_{Ref_1}}{I_{Ref_2}} (T_0) e^{(\beta_1(\lambda_1) - \beta_2(\lambda_2))\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Therefore, knowing the intensity ratio and the reference temperature, it is possible to calculate the temperature everywhere on the image.

## 4. Experimental details

- The excitation laser was a 2.0 Watts 532 nm wavelength continuous laser. In the case of our experiment, the two dyes chosen were the Kiton Red and Rhodamine 560 at respective concentrations of  $10^{-6}$  and  $10^{-5}$  mol/l.
- The selected wavelength are  $\Delta\lambda = [595, 605]$  for the Keton Red and  $\Delta\lambda = [475, 525]$  for the Rhodamine 560 (see fig 4). Filters which allow only these wavelengths to pass through were respectively placed in front of the two opening of the image doubler (see Fig. 2).

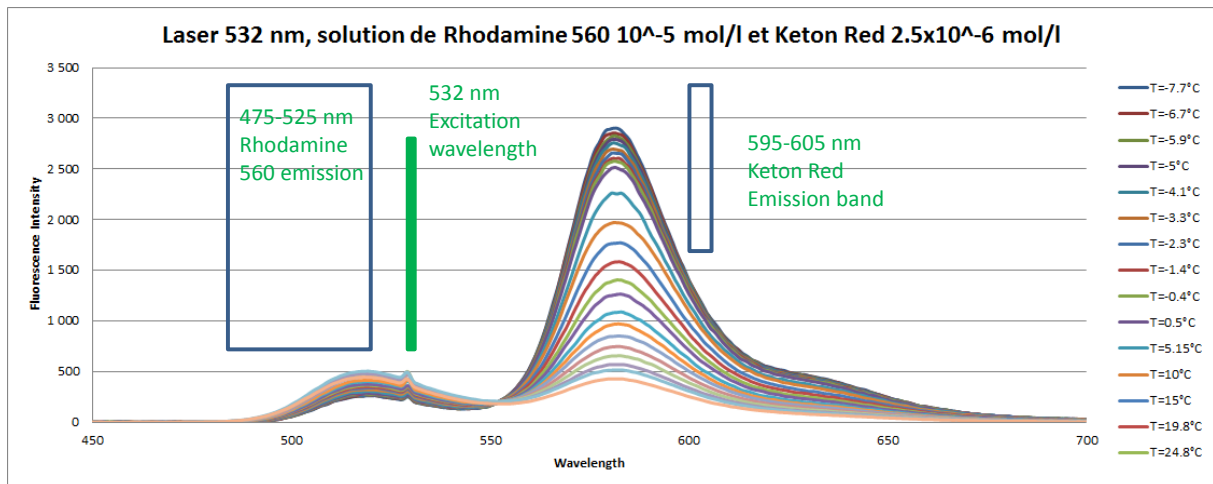


Fig. 5: Fluorescence spectra of Rhodamine 560 and Keton Red

- The cell is inclined by an angle of about 1° to force the large scale circulation into the plan of the laser.
- The first step after setting up the image doubler is to rescale the two images obtained by the image doubler, so that intensity of the second image can be precisely divided point by point by the intensity of the first image. To do that, a lattice of dots is image (see Fig. 5) and the locations of the centers of the dots are determined by image analysis. A Matlab program calculates a fitting of the geometric transformation that will be used later for rescaling the second image.

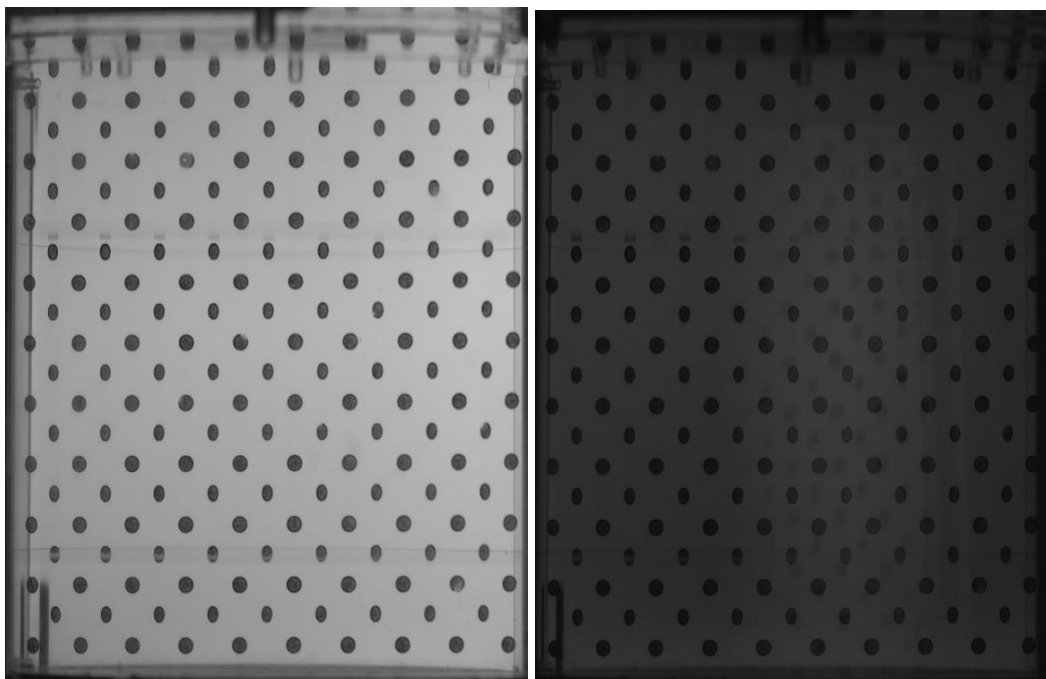


Fig. 6: Test pattern for the geometric transformation between the images seen by the image doubler

- The second step is to have a reference image at a uniform temperature. Experiments are carried out at a constant mean temperature of 40°C, so that the Prandtl number is constant for all the Rayleigh numbers investigated (the Prandtl number is the ratio of the momentum diffusivity

by the thermal diffusivity). Therefore, the reference image is taken at 40°C by having the top and bottom plate at this temperature and waiting a few hours for the thermal equilibration.

- The last step is to take images at different Rayleigh numbers, to calculate the intensity ratio between the two dyes, and to divide it by the intensity ratio of the reference image (i.e. the reference image taken at 40°C, see the calculation done in part 3, and Fig. 6 and 7). Images are taken at 24 images/s with an exposure time of 40 ms on a 12 bits depth Phantom Miro 110 Lab (Vision Research, Wayne USA). A Sigma fixed focus 150 mm F2.8 lens is used at an aperture of 2.8.

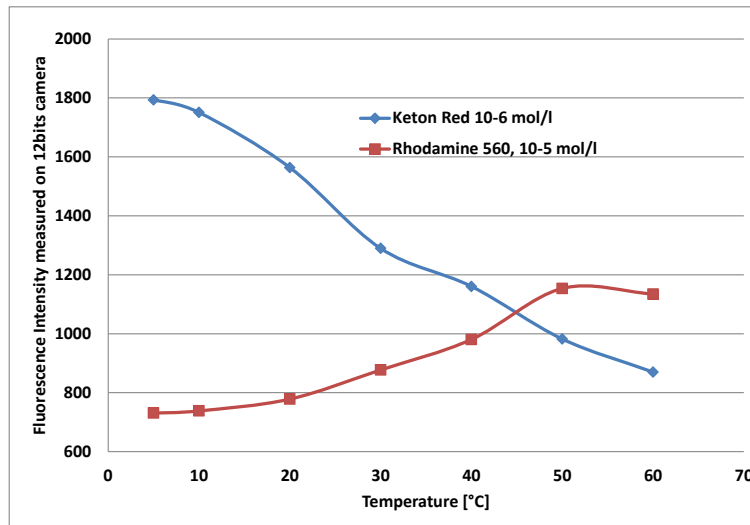


Fig. 6: Variation of the fluorescence intensity of the two dyes in function of the temperature, the intensity is measured by the Miro 12bits camera.

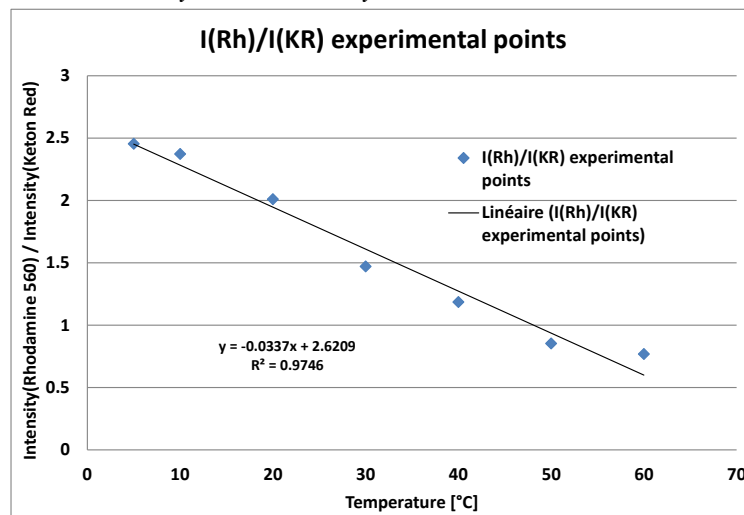


Fig. 8: Fluorescence intensity ratio  $I(\text{Rhodamine 560}) / I(\text{Keton Red})$  at respective concentrations of  $10^{-5}$  and  $10^{-6}$  mol/l in function of the temperature, the intensity is measured by the Miro 12bits camera.

## 5. Results

Without rotation, Rayleigh numbers of  $8.0 \times 10^8$  and  $1.2 \times 10^9$  have been investigated.

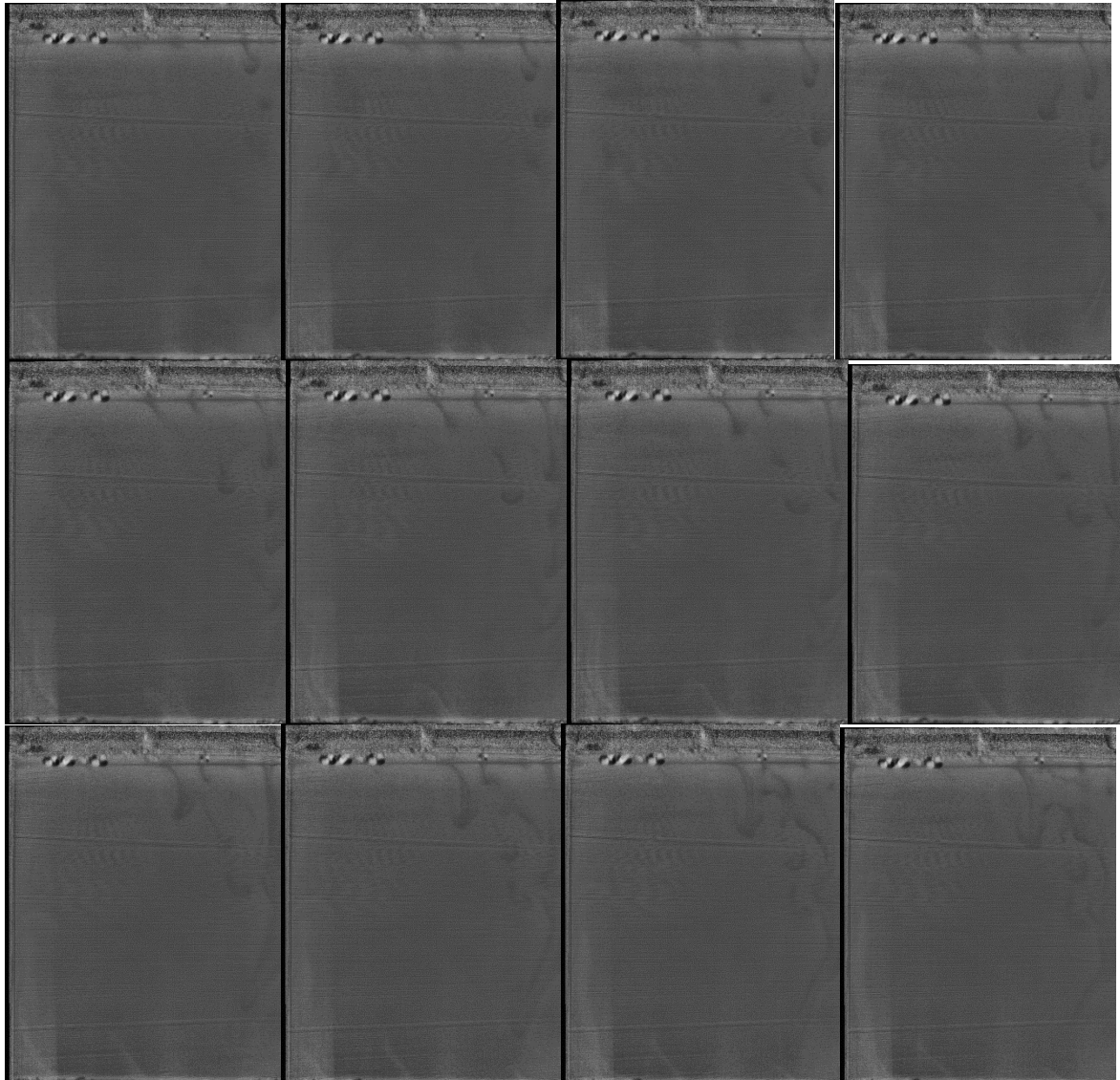
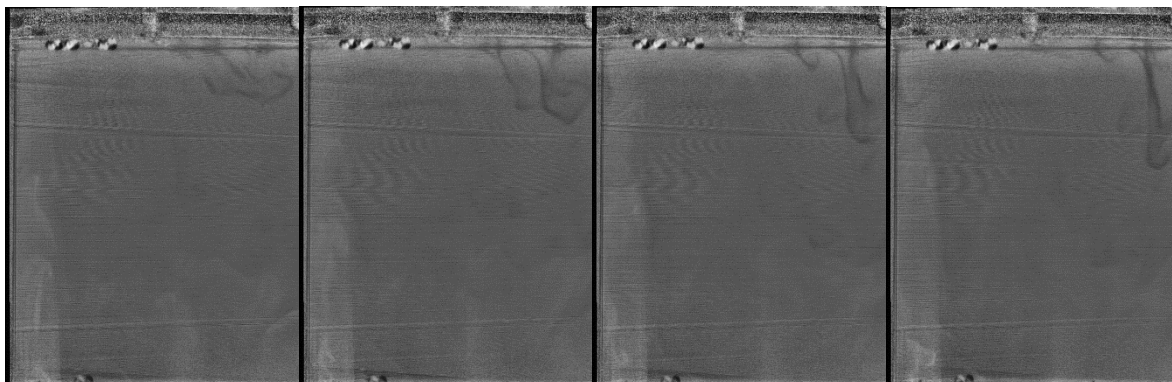
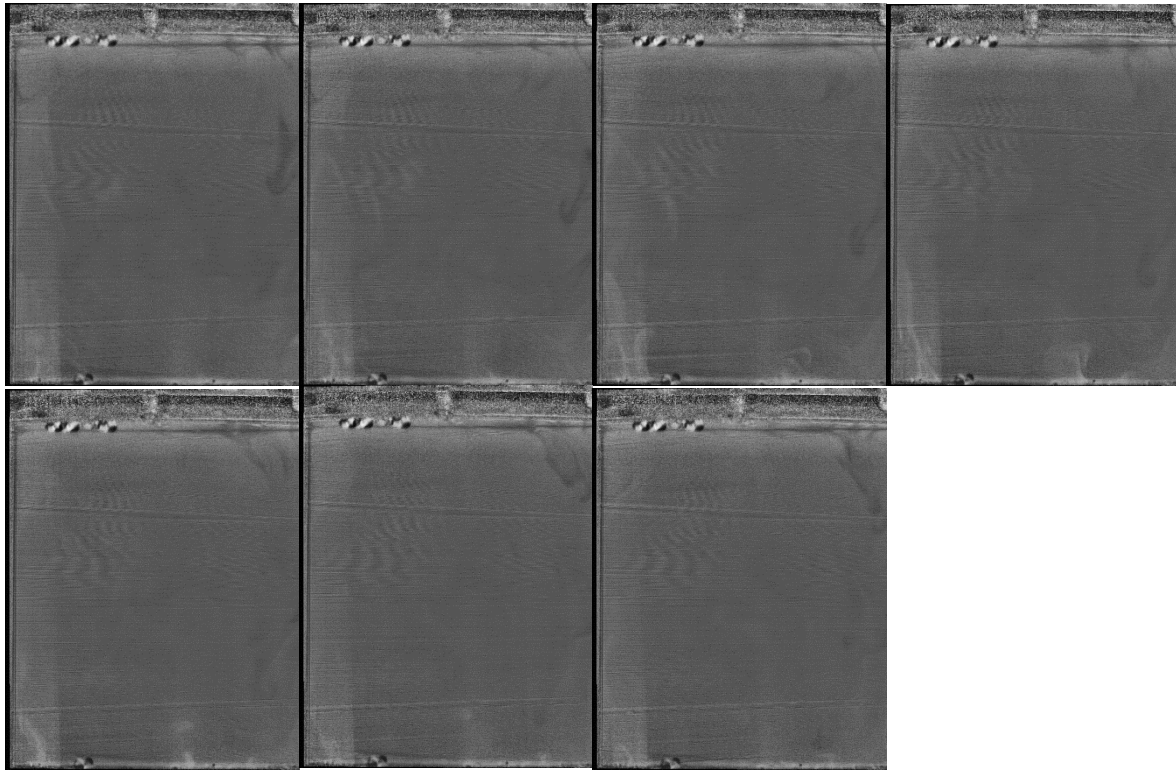


Fig. 9: Sequence of image taken 0.42 second apart. Rayleigh numbers of  $9.0 \times 10^8$ . The RBC cell is cylindrical, 100 mm diameter and aspect ratio 1.







*Fig. 10: Sequence of image taken 0.5 second apart. Rayleigh numbers of  $1.2 \times 10^8$ . The RBC cell is cylindrical, 100 mm diameter and aspect ratio 1. Hot plumes rising are white. Cold plumes falling down on the right part of the image are black. The small tilting of the cell (about  $1^\circ$ ), force the hot plumes to rise on the left part of the image, and the cold plumes to fall on the right part of the image.*

From the image, one observe that the plumes are tracing on average the large scale circulation, even though individually, a plumes can erupt anywhere and begin to rise against the large scale circulation before being catch by the large scale circulation.

The large scale circulation velocity and the number of plumes increase with the Rayleigh-number, which is not too surprising. We did not observe a growth in the size of the plumes with the Rayleigh number. Plumes do not seem to change sizes in the range of Rayleigh numbers investigated. The plumes activity is clearly not constant in the time. Sometimes a burst of activity is seen during a few seconds, before a period of relative calm is observed.

## 6. Conclusion

The LIF technique is a very interesting technique to understand the dynamics of plumes, and their role in the large scale circulation. The influence of the Rayleigh number on the dynamic of plumes has been better understood. The kinetics of heat transfer inside the cell can be clearly explained by proper visualization and analysis of the plume structures. Also the plane of circulation of hot plumes ascending from one end of the wall and of descending cold plumes on the other end can be clearly visualized. Mechanisms causing this phenomenon can be explained by further analysis of the plume structures.

## 7. Bibliography

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