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Preliminary measurements of the thermal field in a rectangular channel by the Planar Laser-Induced Fluorescence method

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Abstract. This paper describes the preliminary measurements of the temperature field in water channel by the Planar Laser-Induced Fluorescence (pLIF) method in the one-colour mode using commercial LaVision system. The aim of the work is to find suitable parameters of the experiment (concentration of fluorescent dye, laser power, arrangement of the experiment, etc.) for measuring the temperature field in a closed glass channel of rectangular cross-section with a heated bottom-wall and to verify an applicability of this method in general. The intention is to carry out measurements in the transverse plane of the duct such that the specific thermos-convective structures of the Rayleigh-Bénard-Poiseuille convection, i.e. mixed convection, are detected. For simplicity, the initial measurements were performed in the natural convection regime, i.e. the water in the channel was not driven by the circulation pump. In this case, a larger temperature gradient was created near the wall compared to the force convection case when a cold liquid flows continuously into the experimental area. The presented work serves as a methodological guide for future measurements and provides valuable experience for the design of a new channel for investigation of the thermal flow instabilities.

1 Introduction

Thermoconvective structures in ducts with heated or cooled walls are experimentally investigated for several decades. Rayleigh-Bénard-Poiseuille (RBP) flow is a specific case of convection in a parallel-plate horizontal channel with a heated bottom-wall. It is a mixed convection consisting of a primer Poiseuille forced flow [1] and a secondary flow caused by heat transfer near the wall, also known as Bénard cells [1, 2].

Many experimental studies on this phenomenon have been published since 1980s. Osborne and Incropera [3] performed an investigation of top and bottom-wall heating effect in a wide rectangular channel. Shortly afterwards, Incropera et al. [4] published a paper dealing with a specific longitudinal rolls. The work was specified in paper of Maughan and Incropera [5]. Similar works can be mentioned from the recent years, namely by Benderradji et al. [6], Mey et al. [7] and Taher and Abid [8]. Authors of the last study used the pLIF method to measure temperature fields.

The Planar Laser-Induced Fluorescence (pLIF) is a radiometric method for the measurement of temperature and concentration fields. The principle consists of measurements of the energy emission intensity I (W · m^{-3}) of a fluorescent dye, which is excited by a coherent light source according to the relationship $I = I_0 C \phi \varepsilon$, where I_0 (W · m^{-2}) is the incident light flux, C (kg · m^{-3}) is the concentration of dye in a solution, ε (m^2 kg^{-1}) is an absorption coefficient and ϕ (1) is the quantum efficiency, which is temperature dependent for some dyes (e.g., Rhodamine B has a sensitivity of 2 % per 1 Kelvin) [9]. The pLIF method, whether in one-color or two-color mode, has been more widely used in recent years to measure a variety of fluid dynamic and thermodynamic phenomena. Some of them are briefly summarized in Table 1.

Tab. 1. An overview of selected pLIF experiments.

author	**content**	**method**	**RhB concentration (µg · l^{-1})**
Xu et al. [10]	emission spectra for different concentration of RhB	1-col	2000 ÷ 10 000
Amiri et al. [11]	exchanger measurement	1-col	10
Zhang et al. [12]	effect of viscosity on fluorescence intensity	1-col	10 ÷ 50
Sakakibara and Adrian [9]	convection over a heated horizontal surface	2-col	50
Sakakibara et al. [13]	thermally stratified pipe flow	1-col	100 ÷ 1000

A relatively large variance in dye concentrations can be observed in the selected experimental studies. It should

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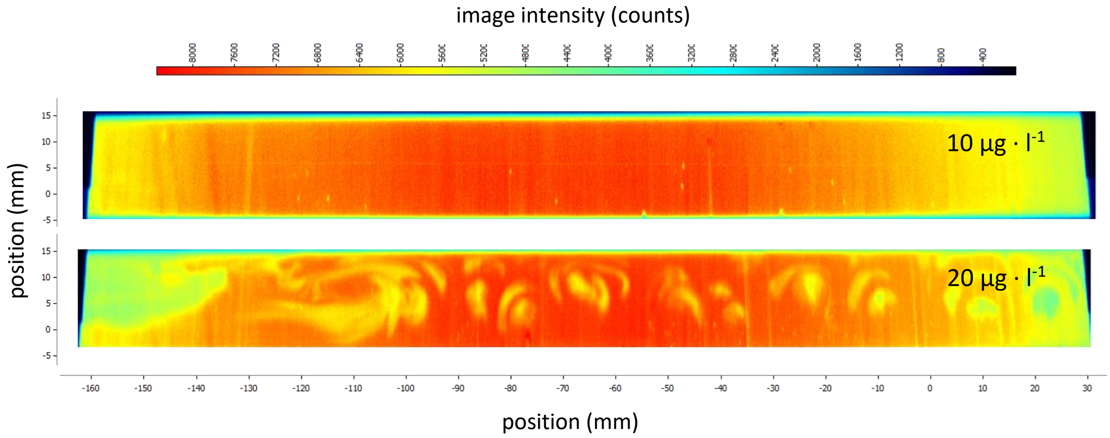

Fig. 2. Intensity response to temperature change at 10 and 20 µg · l^{-1}.

be mentioned that the fluorescence intensity increases with concentration [10], but the choice of Rhodamine B concentration depends on the power of the laser and the thickness of the measured liquid layer. The LaVision manufacturer states the recommended concentration of Rhodamine B in the range of 10 to 1000 µg · l^{-1}. This study was performed as a test measurement to find suitable parameters and arrangements and to verify its applicability for our experiment when the thermal flow instabilities will be measured at various Reynolds numbers and heat fluxes in a rectangular water channel.

2 Experimental equipment and setup

The experiment was performed using the PIV system LaVision which contains a hardware and a software extension for pLIF measurement. The pLIF system included:

- camera sCMOS 5,5 MPx, resolution 2560 × 2160 pixels, 16 bit, exposure time 15 µs to 100 ms, spectral range 370 nm to 1100 nm
- 50 mm lens f/1,4D,
- Nd:YAG double-cavity laser, 340 mJ per pulse, wavelength 532 nm, maximum repetition frequency 15 Hz, pulse duration up to 10 nm, 1,8 m optical arm,
- long-pass filter 540 nm
- software DaVis 10.

The data was recorded by single-frame mode with a frequency of 15 Hz.

In Fig. 1 there is a scheme of a current experimental setup. The measured space is a glass rectangular duct with a cross-section of 200 × 20 mm^2. On the outer surface of a bottom-wall, a resistive heating foil is placed. A constant heat flux of 13.4 W passes through 10 mm thick glass wall. A laser is positioned above the channel such that a vertical laser sheet is created in the cross-section of the channel in the space above the heated area. An sCMOS camera is placed to capture the cross-section with as little distortion as possible. A simple case study of the natural convection, i.e. with the circulation pump turned off, was investigated in this work.

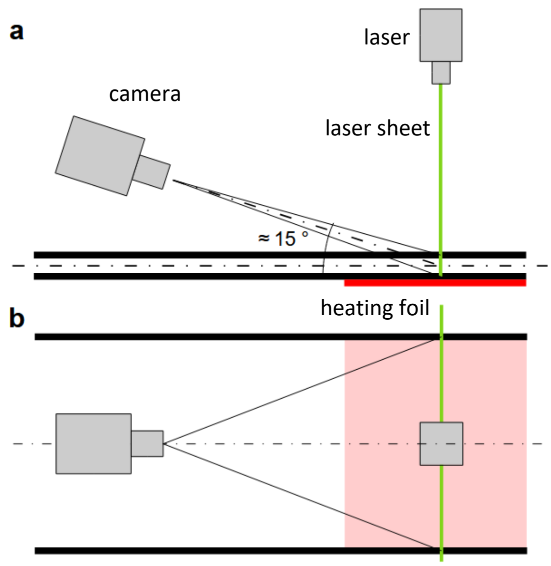

Fig. 1. Scheme of the experimental setup; ***a*** side view, ***b*** top view.

3 Analysis of suitable parameters

One of the important results of this work was to find a suitable concentration and to adjust the corresponding aperture of the camera lens. The Rhodamine B was gradually mixed into the heated experimental channel until a sufficiently strong signal response to the temperature change was found. The laser power and the lens aperture settings were also regulated for each concentration. The concentration ranging from 2.5 to 20 µg · l^{-1} was verified. Fig. 2 shows the response of the recorded image intensity to the concentrations of 10 and 20 µg · l^{-1}. The settings parameters used for the final measurement are described in Table 2.

Table 2. Final parameters for the natural convection case.

parameter	value
lens aperture	f/1.4
laser power	160 mJ per pulse
Rhodamine B concentration	20 µg · l^{-1}

4 Temperature calibration and image correction

After finding the appropriate dye concentration with the best temperature response, the temperature calibration of pLIF was performed. By gradual heating of water in the channel, five calibration data points for five different water temperatures were captured. Temperature was measured by four thermocouples located in several places over the channel cross section with a standard uncertainty of ± 0.2 K. The temperature field was continuously monitored and after its stabilization, the intensity distribution was recorded. A linear calibration curve was obtained from the temperature measurements. It should be noted that precise calibration requires many calibration points over wide temperature range in order to evaluate a second order polynomial. The linear function was selected for preliminary tests as it assures a continuously decreasing trend over the entire range.

In addition, it is necessary to record correction images namely background image (for digital noise subtraction) and sheet image (for correction of laser sheet geometry).

5 Results and discussion

The preliminary measurements were carried out in natural convection regime. The heat power of 13.4 W corresponded to the supercritical Rayleigh number for natural turbulent flow (Ra = 1,100,000 with a critical value of $Ra_{crit,turb}$ = 300,000 [1]). The data were taken with frequency 15 fps and subsequently evaluated and corrected. Fig. 3 shows 11 images each corresponding to the 10^{th} frame, i.e. a measurement sequence of 7.3 seconds.

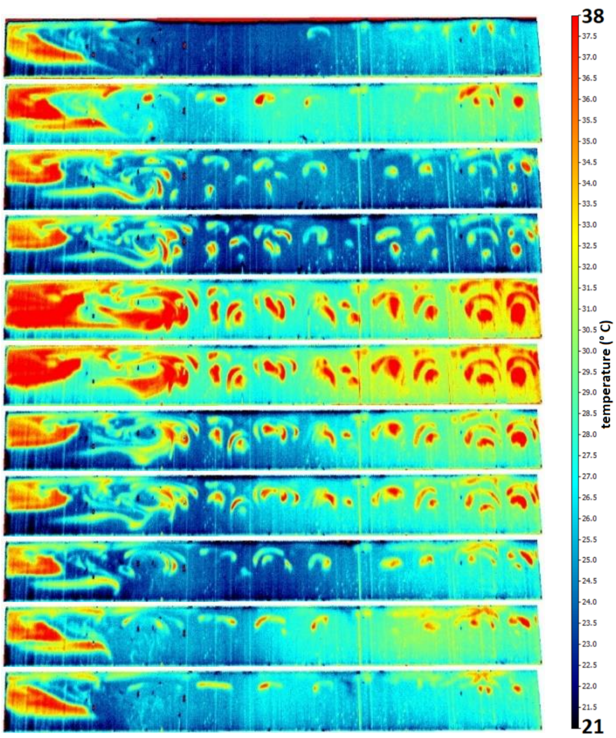

Fig. 3. 11 temperature map images over time with a constant time step of 0.66 s.

Temperature is symbolized by colour scale ranging from dark blue (21 °C) to red (38 °C). The images show thermoconvective structures caused by natural convection. Formations similar to Bénard's cells appear on the temperature map as a mushroom-shaped structures formed by a warmer liquid rising due to a density variation. The images show fluctuations in the calculated temperature in the space between the structures. This is suspected to happen due to the fluctuations of laser pulse power over time.

Fig. 4 shows the course of intensity along the horizontal axis of the channel cross-section. The upper curve represents an average value of intensity across the width of the channel. The average intensity was calculated from a section of data without visible thermoconvective structures. The lower curve shows the variance of the minimal and maximal intensity at each point. The graph indicates that the local intensity deviation is up to 25 %. The average values are related to the geometry of the laser sheet. A maximum of light intensity was in the centre of laser sheet, a minimum on the channel sides. The detected feature can be improved using the software sheet image correction. The time fluctuation requires either an energy monitor in the laser path or a two-color pLIF method. Stationary processes can also be solved by time averaging.

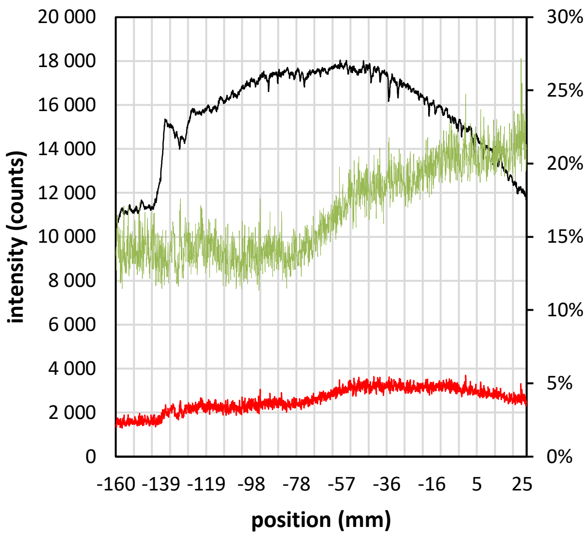

Fig. 4. Intensity along horizontal channel centreline. *The upper black curve*: average image intensity; *the lower red curve:* difference between the maximum and minimum of intensity fluctuation; *central green curve:* percentage deviation on secondary axis.

It has to be mentioned that the presented natural convention had a higher temperature gradient near the wall than it is expected for the mixed convection case. When the circulation pump is switched on, the wall cooling will be more intensive. For mixed convection regime, the pLIF system has to be set much more sensitively. The temperature calibration needs to be based on at least ten calibration points over a sufficiently wide range, which exceeds the expected temperature interval during the experiment. Due to the distortion of the image by the refraction of light at the interfaces of the channel, it was decided to modify the optical setup arrangement.

The further measurement will be performed with the two-colour pLIF and the flow will be monitored from the side-wall along central vertical plane in order to observe the growth of the temperature boundary layer. In this case, the camera views will be approximately perpendicular to all interfaces and there will be minimal flattening of the monitored space.

6 Conclusion

The natural convection pLIF test measurements in the channel of a basic geometry were performed. A wide rectangular glass channel with a bottom-wall section heated over a resistive heating foil was used. The fundamental parameters of the pLIF setup were found including the appropriate concentration of the fluorescent dye. The applicability of the method for measurement of the temperature field of the mixed convection was verified and the limits of the current arrangement and the selected one-color pLIF mode were described. In further work, pLIF will be tested in a two-color mode together with a modified side-wall arrangement of the optical setup.

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