

Investigation of Rayleigh-Bénard convection in heat transfer oils in a miniature enclosure with laser-induced fluorescence

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ABSTRACT

A Rayleigh-Bénard (R-B) Convection (Rayleigh number $Ra = 2.20 \cdot 10^7$, Prandtl number $Pr = 29.9$) of a synthetic heat transfer oil Marlotherm LH (benzyltoluene) in a miniature enclosure is characterized with a two-color laser-induced fluorescence measurement technique (2c-LIF). Therefore, a miniature convection cell with unity aspect ratio was developed, which enables temperature differences up to 120 K. The fluorescence signal is generated by dissolving the fluorophore Nile red in the heat transfer oil and exciting the mixture at 532 nm with a pulsed Nd:YAG laser. First, the 2C-LIF technique is calibrated within the convection cell under homogeneous temperature conditions. The calibration reveals a decreasing relative temperature sensitivity with increasing liquid temperatures. Second, the motion of thermal plumes within the convection cell was analyzed, while the bottom wall was heated to 360 K and the top wall was cooled to 240 K. This results in a respective temperature field of the mixture in the range of 300 K to 345 K. The time-resolved 2C-LIF measurements enable a characterization of the buoyancy driven flow in terms of 2D temperature distribution, heat flux density, thermal plume shape and plume velocity. The investigated plumes are characterized by large temperature stratification velocities and velocities in the range of 15 mm/s. Stationary large recirculation zones were not detected, which are typical for such thermal R-B convection conditions.

1. Introduction

Temperature gradient driven flows play a major role in the industrial and energy sector and many others. The present investigations focus on a diagnostic technique to study convective heat transfer in heat exchangers or immersion cooling (Pambudi et al., 2022) and energy applications such as thermal energy storages (TES) (Alva et al., 2018) or solar thermal power generation (Faddouli et al., 2024). Diagnostic techniques in combination with CFD-simulations enable an optimization of such systems.

Simplified model systems are often used for the investigation of natural thermal convection. The Rayleigh-Bénard convection (R-B convection) (Bénard, 1901; Rayleigh, 1916) is the most frequently investigated natural convection system besides horizontal convection (Sheard & King, 2011; Shishkina, 2017) and vertical convection (Ng et al., 2015; Wang et al., 2021). The convection is governed by the dimensionless Rayleigh number Ra and the Prandtl number Pr . These two dimensionless quantities allow a comparison between experiments with various convection cell sizes and liquids (Weiss et al., 2025).

The R-B convection is driven by a temperature difference between two isothermal horizontal surfaces and takes place when $Ra > 1708$. The heated fluid at the bottom of the cell moves upwards due to its reduced density, while the cooler fluid due to its higher density sinks and displaces the warmer fluid. The presence of a continuous density gradient leads to the so-called R-B convection. The miniature convection cell in the current study has an aspect ratio $\Gamma=1$ (h: 15 mm, w: 15 mm). This geometry generates a flow structure, which is present in small cooling channels. A determination of the temperature field and the plume velocities enable a characterization of the convective flow in terms of flow morphology and heat transfer.

Multiple numerical and experimental studies can be found in the literature, which analyzed the flow structures within convection cells. Therefore, a lot of optical methods like schlieren (Li et al., 2024; Srivastava et al., 2004), shadowgraphy (Dong et al., 2025; Srivastava et al., 2004), interferometry techniques (Mishra et al., 1999; Rao & Srivastava, 2016), particle image velocimetry (PIV) (Chen et al., 2014; Cierpka et al., 2019) and laser-induced fluorescence (LIF) (Kashanj & Nobes, 2023; Sakakibara & Adrian, 1999) were applied.

LIF imaging enables the visualization of the flow field and temperature within a convection cell. The fluorescence signal itself is commonly generated by doping the measurement liquid with a suitable organic tracer, which is dissolved in the liquid. A temperature dependent dye in combination with a 2-color LIF (2c-LIF) detection scheme enables a determination of the temperature field. Until now, only a few studies are available, which investigated the flow structure within convection cells with laser-induced fluorescence (Kashanj & Nobes, 2023; Sakakibara & Adrian, 2004).

The present study investigates a turbulent R-B convection in a cubic miniature convection cell (aspect ratio $\Gamma=1$) filled with the heat transfer oil Marlotherm LH ($Ra=2.20\cdot 10^7$, $Pr=29.9$). This heat transfer oil is commonly used in high power electric and electronic applications, where high heat dissipation rates are present. Marlotherm LH is also used as LOHC (liquid organic hydrogen carrier) in dehydrogenation hydrogenation reactors (Teichmann et al., 2012).

In this study, the temperature and flow morphology within a miniature convection cell are studied for a turbulent operating point with a 2C-LIF scheme. For this purpose the heat transfer oil Marlotherm LH was doped with the fluorescence tracer Nile red, providing a high temperature sensitivity (Koegl & Breitenbach, 2025; Koegl et al., 2022; Koegl et al., 2024).

The paper is structured as follows: First, preliminary spectral investigations of Nile red dissolved in Marlotherm LH are carried out in a wide temperature range at the relevant dye concentration and laser fluence. Second, the temperature dependent fluorescence intensity was recorded and the 2C-LIF technique was calibrated. Third, the turbulent flow field was analyzed in terms of temperature distribution, heat flux and plume velocity (propagation speed of the plume front). The newly developed cell allows very large temperature differences of up to 120 K. Finally a brief conclusion and an outlook is provided.

2. Description of the experiment

2.1. Preliminary experiments

A preliminary study investigating the fluorescence signal is conducted prior to the two-dimensional measurements in the convection cell. The probe volume of the convection cell (see Figure 1, right) is illuminated with a light sheet located at the center plane of the cell by a pulsed Nd:YAG laser (Q-smart 850, Quantel, France, wavelength 532 nm, repetition rate 10 Hz, pulse width: 6 ns, laser fluence at probe region: 57.4 mJ / cm²). The laser (light sheet: 15 mm x 0.35 mm) enters the chamber from the right.

A power meter (model: QE50LP-S-MB-INT-D0, Gentec Electro-Optics, Canada) ensures constant laser fluence during the measurements. The convection cell was operated under homogeneous temperature conditions with two recirculation thermostats (model: CP50, Thermo Fisher Scientific, Waltham, MA, USA). The temperature within the cell is measured with two micro thermocouples (see Figure 1, right). The temperature dependent emission signals were recorded with a UV-VIS spectrometer (model: Maya 2000-Pro, Ocean Optics, USA, wavelength range 200.5 nm–1120.4 nm, pixels 2048, slit size 25 μ m, integration time 100 ms; 50 subsequent spectra were averaged for each measurement) in front of the convection cell.

2.2. Experimental Setup for planar fluorescence measurements

The experimental setup for the two-dimensional measurements (left) and a detailed sectional view of the convection cell (right) is shown in Figure 1.

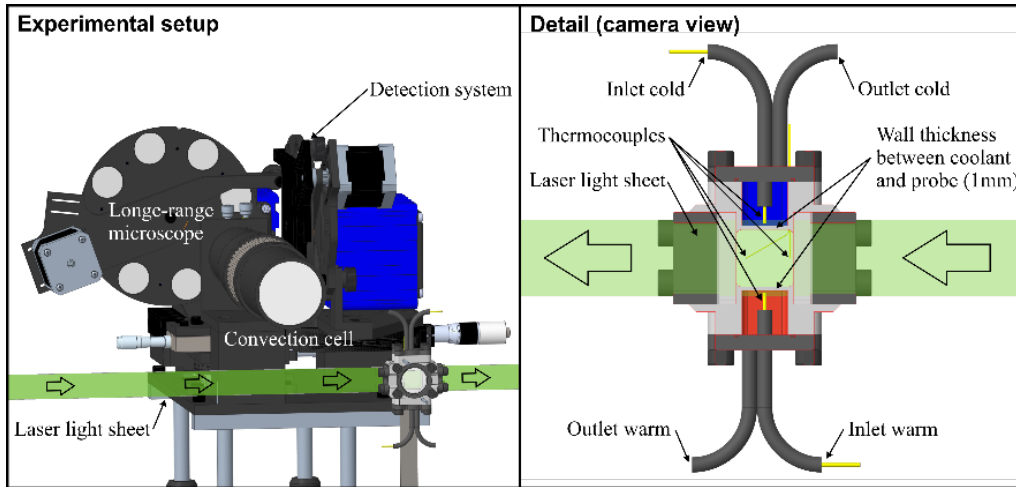


Figure 1: Experimental setup (left) with detailed sectional view of convection cell (right).

The illumination setup is already described in the previous section. The individual LIF signal intensities are recorded with a specially designed detection system, which was already applied in earlier investigations (Koegl et al., 2019; Koegl et al., 2021; Koegl et al., 2018; Koegl et al., 2020). The detection system is equipped with two identical sCMOS cameras (Imager, LaVision, Goettingen, Germany, resolution: 2560 pixel $\times$ 2160 pixel) and a long-range microscope (K2 DistaMax, Infinity, Centennial, USA; nominal pixel resolution: 81 pixel/mm). Two bandpass filters (568 nm and 632 nm, 10 nm FWHM, OD4, Edmund Optics, NY, USA), which are selected in an earlier investigation of the group (Koegl et al., 2022) enable a quantitative temperature determination of the flow field.

The R-B convection is investigated in a specially designed convection cell (see Figure 1). The optically accessible cell is made of stainless steel (1.4571) and has two 1" sapphire windows (detection) and two rectangular sapphire windows (for the laser light sheet). It has a cubic probe volume of 15 mm $\times$ 15 mm $\times$ 15 mm. The bottom and top surfaces are heated or cooled individually with two recirculation thermostats (model: CP50, Thermo Fisher Scientific, Waltham, MA, USA). The convective fluid motion in the cell was generated by cooling the top and heating the bottom surface. For the present study, the top temperature was kept at 240 K and the bottom temperature was kept at 360 K. The temperatures right in front of the conditioned surfaces (wall thickness between coolant and probe volume: 1 mm) of the cooling/heating fluids are constantly monitored by two thermocouples (type K, tc-direct GmbH, Kitzingen, Germany). For the calibration of the 2c-LIF technique, two 0.25 mm thermocouples (type K) were inserted in the middle of the measurement volume, one on the left and one on the right side (see Figure 1). These thermocouples

are only present during the calibration process. They are removed for the convective measurements to ensure an undisturbed flow.

2.3. Heat transfer fluid and tracer used

The fluorescence signal in the present study is generated by dissolving the fluorophore Nile red in the heat transfer fluid Marlotherm LH (monobenzyltoluene, Sasol Germany GmbH, Hamburg, Germany). The thermo-physical properties of Marlotherm LH are shown in Table 1.

Table 1: Thermo-physical properties of Marlotherm LH (Eastman chemical company, 2022; McClintock, 2003).

Property	Unit	Marlotherm LH
Density	g/cm^3	973.4 (322.5 K)
Heat conductivity	$\text{W/(m}\cdot\text{K)}$	0.1281 (322.5 K)
Kinematic viscosity	mm^2/s	2.305 (322.5 K)
Thermal diffusivity	mm^2/s	$7.700\cdot 10^{-2}$ (322.5 K)
Isobaric thermal expansion coefficient	$1/\text{K}$	0.000981 (473 K)

A minimum of 6.25 mg of Nile red (powdered form) was weighted with a high-precision analytical balance (Mettler Toledo XS 205, proofed repeatability 0.05 mg). Earlier investigations of the group revealed a linear fluorescence behavior up to a concentration of 6.25 mg/L for a extinction length of 15 mm (Koegl et al., 2022). The tracer was completely dissolved in the measurement liquid. The melting point of the tracer is in the range of 476 K to 479 K (Roth, 2019), which is not reached in the present study (T_{max} : 360 K).

3. Results

3.1 Preliminary investigations

For the spectral investigation of the fluorescence signal, both horizontal boundary surfaces of the convection cell were conditioned equally to achieve a homogeneous temperature distribution within the cell. The temperature within the convection cell was varied between 293 K and 353 K in 10 K steps. Photo-dissociation free measurements are ensured due to a measurement fluid exchange during operation. The normalized fluorescence signals of 6.25 mg/L Nile red in Marlotherm LH and the corresponding band pass filters (568 nm and 632 nm, 10 nm FWHM, OD4, Edmund Optics, NY, USA) for the 2C-LIF technique are shown in Figure 2. The fluorescence signals of Nile red dissolved in Marlotherm LH are characterized by single peaks. The fluorescence peak is equally shifted towards shorter wavelengths (293 K: 578.8 nm, 353 K: 572.2 nm) with increasing temperature. The right flank remains unchanged, while the left flank is shifted with increasing temperature towards shorter wavelengths. The selected band pass filters enable a

quantitative temperature determination within the convection cell after calibration with thermocouples.

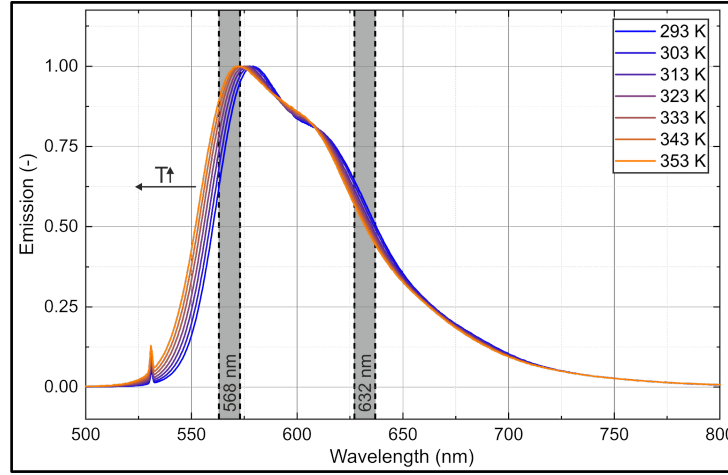


Figure 2: Normalized emission spectra of 6.25 mg/L Nile red dissolved in Marlotherm LH, 293 K and chosen BP filters for building the intensity ratio.

3.2 Temperature dependent measurements

3.2.1 Temperature calibration

For the calibration of the 2C-LIF scheme, the convection cell was operated as described in the previous section (see 3.1). A quantity of 100 images was recorded for each detection channel and operating point. An exponential approach according to Beer-Lambert was used in the post-processing routine to reduce the wavelength dependent laser absorption effect of the background corrected images. This routine leads to more uniform intensity images and significantly reduces the measurement uncertainty.

For the calibration process, the signal intensities in the area close to the two thermocouples (areas of each 76x76 pixels) were averaged and the corresponding intensity ratios were calculated. The liquid temperature T_{Liquid} can be determined by using the following polynomial fit equation ($R^2=0.9996$):

$$T_{\text{Liquid}}(K) = 7.29842 \cdot r_{\text{Signal}}^3 - 96.76558 \cdot r_{\text{Signal}}^2 + 453.25446 \cdot r_{\text{Signal}} - 438.05448 \quad (1)$$

with:

$$r_{\text{Signal}} = \frac{\sum \tau_{\text{Filter}_{568\text{nm}}} \cdot I_{\text{LIF}}}{\sum \tau_{\text{Filter}_{632\text{nm}}} \cdot I_{\text{LIF}}} = \frac{I_{\text{CH1}}}{I_{\text{CH2}}} \quad (2)$$

The signal intensity ratio r_{Signal} is defined as the quotient of the two products of the transmission curves τ of the respective band pass filters and the spectral fluorescence signal I_{LIF} , when other efficiencies of the optical setup such as efficiency of the optics, quantum efficiency of the cameras etc. are neglected. The relative thermal sensitivity S_r is defined as:

$$S_r = \left| \frac{1}{r_{\text{Signal}}} \cdot \frac{dr_{\text{Signal}}}{dT} \right| \quad (3)$$

The temperature-dependent intensity ratio is described by the following second polynomial fit ($R^2=0.9999$):

$$r_{\text{Signal}} = 2.29952 \cdot 10^{-4} \cdot T_{\text{Liquid}}^2 + 0.17756 \cdot T_{\text{Liquid}} - 28.32461 \quad (4)$$

The temperature-dependent intensity ratio curve fit as well as the relative thermal sensitivity are shown in Figure 3.

The temperature dependent intensity ratio increases with increasing temperature from 3.96 at 293 K to 5.70 at 353 K. The relative temperature sensitivity decreases from 1.08 %/K at 293 K to 0.27 %/K at 353 K.

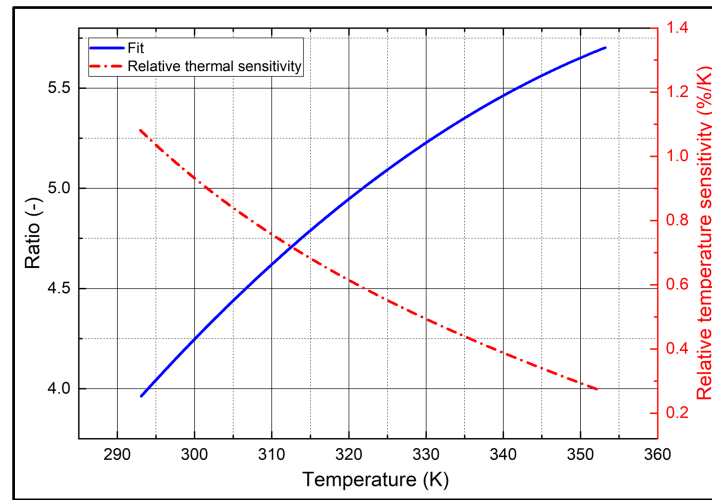


Figure 3: Temperature-dependent intensity ratio and the corresponding relative thermal sensitivity. Calibration curves are determined by using the imaging setup.

The determined average temperature sensitivity ($S = |\Delta r_{\text{Signal}} / \Delta T_{\text{Liquid}}|$) of 0.72%/K are comparable to earlier spectral investigations of the group (Koegl & Breitenbach, 2025; Koegl et al., 2022; Koegl et al., 2024) for Marlotherm LH (9.38 mg/L Nile red: 4.22%/K) and other heat transfer fluids (9.38 mg/L Nile red in Fragoltherm F12: 1.12%/K; 9.38 mg/L Eosin-Y in glycol: 1.99%/K) and studies provided in the literature (10 $\mu\text{mol/L}$ pyrromethene PM597 in ethanol: 1.2%/K (Palmer et al., 2016); 2.5 $\mu\text{mol/L}$ Rhodamine B in ethanol: 0.7%/K (Vetrano et al., 2013)).

The predominant thermal plumes in the flow cell will lead to temperature dependent refractive index variations, which can result in measurement uncertainties due to laser beam steering. Furthermore, the addition of the dye may change the optical properties of the liquid. A pre-investigative study by the group (Koegl et al., 2025) revealed that the admixture of Nile red to Marlotherm LH shows no significant impact on the refractive index.

3.2.2 Convective flow investigations

The turbulent convective flow is characterized in terms of temperature field and plume velocity. To ensure stationary conditions within the cell, the measurements were conducted after reaching

steady state (60 minutes of operation). The Rayleigh number for this operating point is $2.20 \cdot 10^7$, which indicates a turbulent flow (assumptions: thermal diffusivity, liquid viscosity and liquid heat capacity @ 322.5 K, thermal expansivity @ 473 K, temperature difference equals temperature of the conditioning fluid ($120 \text{ K} = 360 \text{ K} - 240 \text{ K}$)). The recording frequency, determined by the pulsed laser, was 10 Hz.

Multiple convective hot and cold plumes in the probe volume are responsible for the heat exchange between the hot and the cold surface. In general, the hot plumes have their origin on the lower heated surface and move towards the upper cooled surface due to a lower density in the jet in comparison to the ambient density, while the cold plumes show an opposite behavior. The higher density of the cold plumes in comparison to the ambient density leads to a motion of the cold plumes towards the lower surface. This behavior is shown in Figure 4.

The image sequence shows mainly one distinct turbulent plume of cold heat transfer oil in the center of the volume, which propagates downwards from the cold surface towards the hot surface due to higher density in comparison to the surrounding warm oil. The horizontal artefacts at 0.7 s to 1.3 s are caused by beam steering effects of a cold liquid layer located at the lateral window moving downwards.

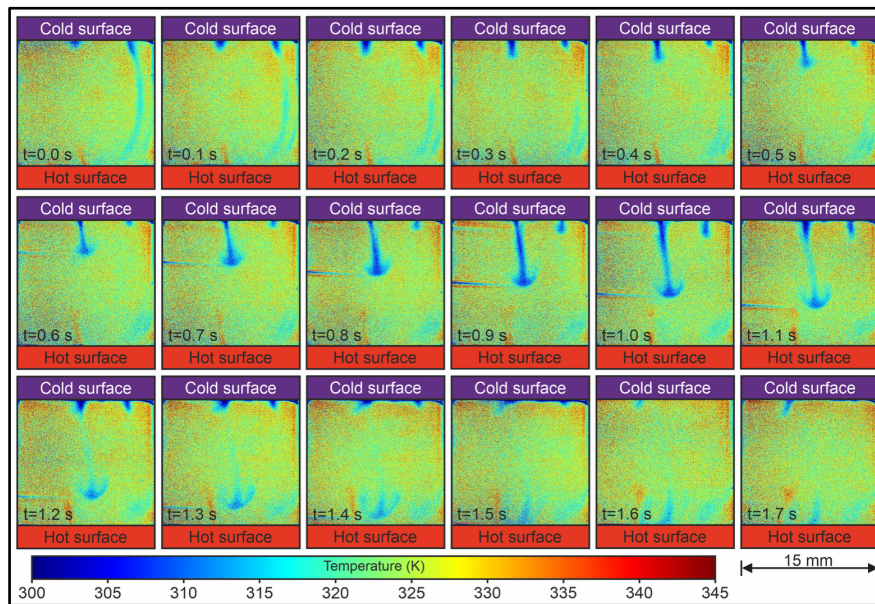


Figure 4: Turbulent Rayleigh-Bénard Convection of Marlotherm LH, top surface 240 K, lower surface 360 K.

The fluid motion of a cold plume (starting at time step 0 s, see Figure 4) is analyzed in terms of plume front velocity and penetration length. The formation of cold plumes can be explained as follows. The oil at the bottom of the convection cell is heated and rises towards the upper cold surface driven by density differences. The rising oil accumulates at the top and cools down. This leads to a formation of a cold oil plume in the center of the upper surface which propagates through the cell towards the lower heated surface. First, the plume front velocity increases with

time, while the plume separates from the accumulated cold oil volume at the upper surface. The surrounding hot oil leads to a constriction of the plume core right after the plume front. The plume front and the velocity increase with increasing penetration length up to 15 mm/s, see Figure 5. The temperature of the ambient oil near the lower hot surface led finally to a decrease of the plume front velocity, until the plume reaches the lower heated surface. At the lower surface, the cold jet dissolves and the local oil is heated again so that the process starts from the beginning.

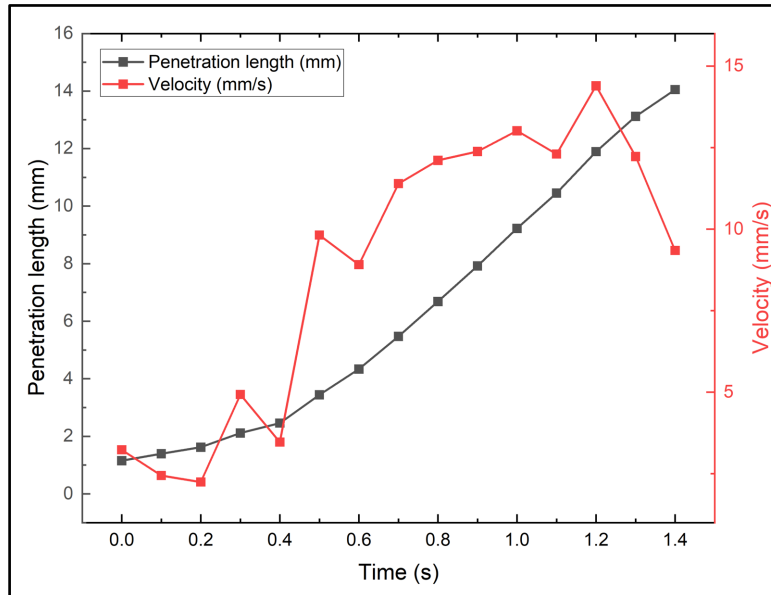


Figure 5: Velocity and penetration length of a cold oil plume.

Further details of this study including local heat transfer coefficients and Nusselt numbers can be found in reference (Koegl et al., 2025).

4. Conclusions and future work

The turbulent Rayleigh-Bénard convection of a heat transfer oil was investigated with a two-color laser-induced fluorescence scheme (2c-LIF). A miniature convection cell with unity aspect ratio was developed, which enables temperature differences up to 120 K. The fluorescence signal is generated by dissolving the fluorophore Nile red in the heat transfer oil and exciting the mixture at 532 nm by a pulsed Nd:YAG laser. A dye concentration of 6.5 mg/L ensures a linear LIF signal with laser fluence. The upper wall was cooled to 240 K and a lower wall was heated to 360 K. At these operating conditions, the respective Rayleigh number was $2.20 \cdot 10^7$ and the Prandtl number was 29.9. The 2C-LIF technique was calibrated for a wide temperature range. The calibration revealed a large temperature sensitivity of 1.1 %/K (293 K), which decreases almost linearly to 0.27 %/K at 353 K.

The detection system used enables a characterization of the convection in terms of a quantitative temperature field and plume velocities. The resulting temperature field in the center plane of the cell is between 300 K and 345 K. The chaotic formation and dissipation of cold plumes could be

well resolved with the technique. The highest analyzed single plume velocity was in the range of 15 mm/s. The technique can also be used for the investigation of other heat transfer oils and for experiments with additional forced convection or mixing of differently heated oils, which will be part of future studies.

The integration of the measurement technique in real applications is part of our future work as well.

Author Contributions:

M.K. designed the convection cell; M.K. designed the experimental setup; M.K., J.V. and L.B. performed the measurements; M.K. and L.Z. performed the data evaluation; M.K. and L.Z. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials: Data can be shared upon request.

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