5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Studies on the simultaneous measurement of velocity and temperature fields in Rayleigh-Bénard convection using thermochromic liquid crystals

Jörg König*, Sebastian Moller, Christian Cierpka

Institute of Thermodynamics and Fluid Mechanics, Technische Universität Ilmenau, Germany

*Joerg.Koenig@tu-ilmenau.de

Abstract

In this contribution, simultaneous velocity and temperature measurements using thermochromic liquid crystals (TLC) as tracer particles are discussed, with regard to measuring range, uncertainty and spatial resolution. These particles shall later be used for the characterization of the momentum and heat transfer in Rayleigh-Bénard cells with high aspect ratio. Light scattered from the TLCs is analyzed by spectrometer measurements, revealing its general scattering characteristics depending on the angle between the light sheet plane and the viewing axis. It is shown that white light sources with continuous spectral characteristic and a slightly higher fraction of light in the red wavelength range perform well, thereby a supercontinuum white light laser can be used, even though it has a cut-in wavelength of about 475 nm. Moreover, a suitable setup for both measurements exists, yielding minimum uncertainty for both quantities at the same time, on condition that an appropriate two-dimensional calibration is applied taking the variation of the observation angle over the FOV into account. In comparison with an LED-system, the white light laser used here allows for generating very thin light sheets, as ideally applied for planar PIV. Therefore, higher spatial resolution in depth-direction can be achieved, promising more detailed insights into Rayleigh-Bènard convection, particularly inside cells with high aspect ratios.

1 Introduction

The Rayleigh-Bénard convection is an important flow very often leveraged to study thermally-driven turbulence. Such turbulence occurs in many natural flows, e.g. in the earth's atmosphere, and, have not yet been fully understood. For fundamental research on this phenomenon, convection cells with high aspect ratio $\Gamma=L/H$ between lateral dimension L and cell height H are of interest, because the influence of this dimensionless quantity is much less understood, see Stevens et al. (2018). In these cells, turbulent convection might be induced due to a high temperature gradient between a heated bottom and a cooled top plate. For a detailed understanding, not only the velocity but also the temperature field has to be measured simultaneously. In general, a combination of standard techniques, namely particle image velocimetry (PIV) and laser induced fluorescence (LIF) can be applied to obtain simultaneously velocity and temperature distributions in a thin plane. For this, particles and a temperature sensitive dye are suspended and dissolved in the fluid, respectively. However, the particles interfere with the temperature measurement, causing higher uncertainty for the scalar quantity, even if two-color LIF is applied, see Funatani et al. (2004). Another technique is the application of particles doped with temperature sensitive dyes, see Massing et al. (2016). In contrast to the combination of PIV and LIF, velocity and temperature measurements do not interfere with each other, since only particles are used, and their intensity refers to the ambient temperature of the fluid that can cover the whole liquid temperature range for water from 0°C to 100°C. As a consequence of the large temperature range that can be covered, the uncertainty of temperature measurements in Rayleigh-Bénard convection is often too high as the applicable temperature difference between bottom and top plate of convection cells with high aspect ratio very often bounds to a few degrees, compare with the findings in Fujisawa et al. (2008). For measuring temperature over small ranges with comparably low uncertainty thermochromic liquid-crystals (TLCs) have been proven, see e.g. Dabiri (2009), because the temperature range, in which TLCs are sensitive to temperature changes, can be adapted to ranges between 0.5 K and 40 K. Applying an appropriate calibration procedure a standard deviation of about 1% with respect to the nominal measuring range can be achieved, see Schmeling et al. (2014). Therefore, a combination of PIV and particle image thermometry (PIT) using thermochromic liquid-crystals (TLCs) holds a lot of promise. The temperature can be determined by the color of the TLCs while illuminated with white light, the velocity distribution can be evaluated using PIV algorithms, see Schmeling et al. (2014) or Fujisawa et al. (2004). However, this technique still requires detailed investigations for the reliable temperature and velocity measurements in convection cells with high aspect ratio Γ, since the color signal strongly depends on the observation angle, the f#-number of the camera objective and the light source. Moreover, horizontal flow and temperature measurements over the entire lateral dimension of the convection cells are of vital importance, however, difficult to accomplish in cells with high aspect ratio of about $\Gamma \geq 25$, because not only a large field of view (FOV) but also high spatial resolution in depth-direction is required as the height of those cells amounts very often to a few centimeter or even less. With regard to thin light sheets needed for high spatial resolution measurement in depth-direction, the limited height of those cells makes the use of most white light sources difficult for simultaneous planar PIT and PIV measurements. For a systematic investigation on the simultaneous measurement of velocity and temperature fields using TLCs, a small cylindrical Rayleigh-Bénard cell was set up and used for calibration measurements. While driving this cell at isothermal state, different experimental parameter settings were employed, e.g. different observation angles. In addition, an LED light system with adjustable spectral behavior and a supercontinuum white light laser were used to compare incoherent and coherent light sources with each other for this application.

2 Experimental setup

The experimental setup used for the present investigations is depicted in Figure 1(a). It consists of a small cylindrical Rayleigh-Bénard cell filled with de-ionized water, in which encapsulated TLCs are suspended (type R21C5W, manufacturer LCR Hallcrest). Their nominal temperature sensitivity is within 21°C to 26°C at an observation angle of about $\varphi = 0°$, meaning illumination and observation are done from the same direction. For illuminating the particles with white light, a supercontinuum white light laser (Super K Extreme EXR-20, manufacturer NKT Photonics) with a maximum optical power of about 2 W over the entire visible spectrum, or an LED-system containing six individually tunable LEDs of different wavelength (SPECTRA X light engine, manufacturer Lumencor) were used. A "thin" light sheet was formed inside the cell using a combination of spherical and cylindrical lenses, with a small slit added to the light sheet optics in case of the LED-system. In order to investigate the dependency of the temperature-sensitive scattering of the TLCs on the observation angle φ, calibration measurements were done employing observation angles between $\varphi = 40°$ and $\varphi = 90°$, while driving this cell at isothermal state. Temperatures between 19°C and 25.2°C were applied, taking a slight shift of the nominal measuring range to lower temperatures into account due to off-axis observation ($\varphi \neq 0°$). For the detection a color-sensitive camera (sCMOS PCO edge 5.5, LaVision GmbH) and a spectrometer (Blue wave, StellarNet Inc.) were used. While the former allows for simultaneous measurement of temperature and velocity distributions within the thin light sheet, the latter permits detailed investigations on the scattering characteristic of the TLCs. Before carrying out the experiments, the two light sources were characterized in terms of their spectral characteristics. Both spectra are depicted in Figure 1(b). In contrast to the laser light, exhibiting a non-uniform but continuous spectrum with a cut-in wavelength of about 475 nm, the spectral behavior of the LED light shows four distinctive peak wavelengths corresponding to the blue, cyan, green and red channel of the LED-system. Their output power was set to approximately 100 mW, 60 mW, 100 mW and 230 mW, respectively. The violet (395/25 nm) and the near-IR LED (730/40 nm) of the LED-system were switched off.

3 Results

The spectral characteristic of the light scattered from the TLCs outside their temperature sensitive range is depicted in Figure 2 for two different observation angles. For a better comparison, the spectral behavior of the laser light used to illuminate the TLCs is depicted too. As can be seen, the scattered light at 19.3°C exhibits, almost independently of the observation angle, a much more uniform intensity distribution compared to that of the supercontinuum laser, indicating that the scattering cross-section of the TLCs is larger for smaller wavelengths. A very similar behavior was found by using the LED-system, at which the intensity of the blue and the green light scattered from the TLCs increases compared to the red part. This explains the power setting of the LED-system, using less power for the blue, cyan and green LED, as mentioned above without explanations. However, the power setting should be done carefully with respect to the spectral sensitivity of the detector, and no single dominant peaks with narrow wavelength bands should exist in the spectrum, see Segura et al. (2015).

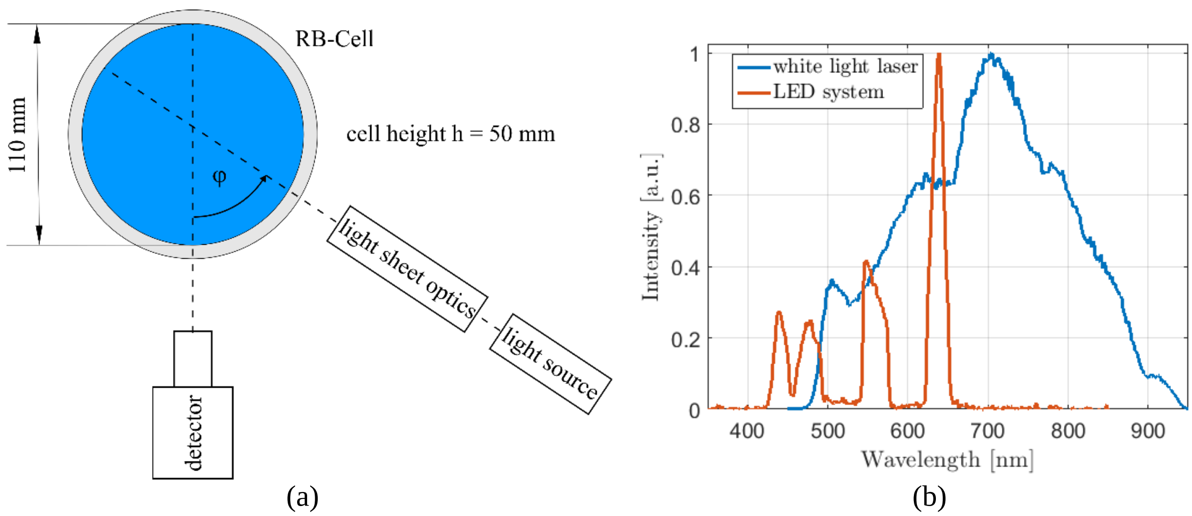


Figure 1: (a) Sketch of the experimental setup and (b) spectral characteristics of both white light sources used.

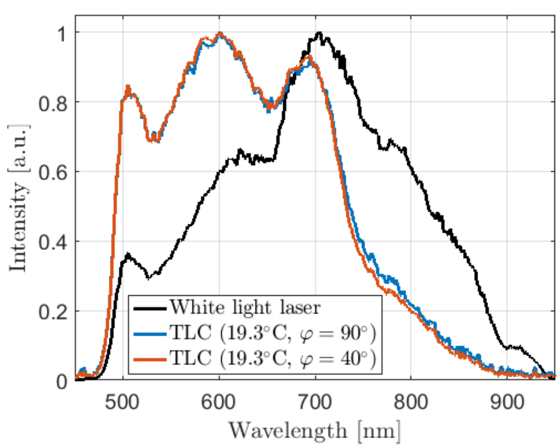
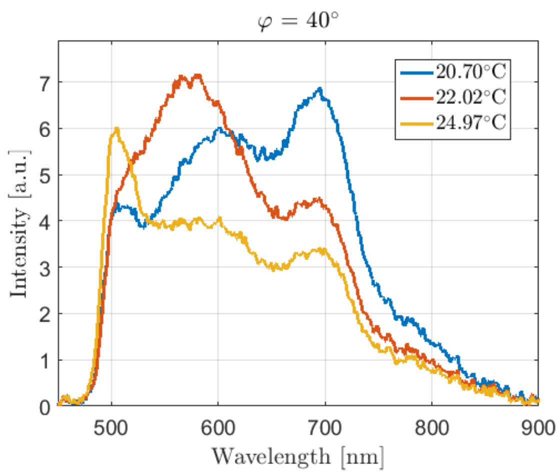
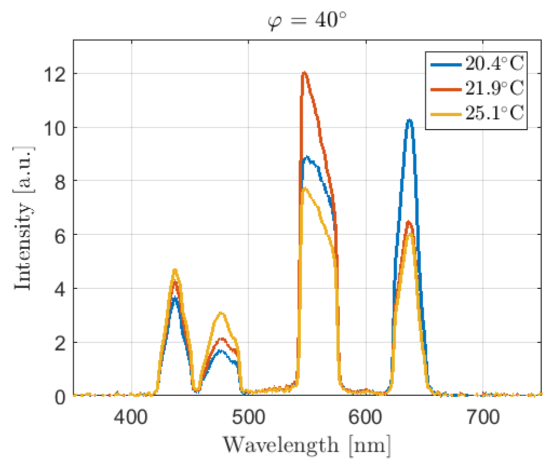


Figure 2: Spectral characteristic of the supercontinuum white light laser and of the scattered light from the TLCs.

Within the temperature-sensitive range of the TLCs, the spectral characteristic of the scattered light from the TLCs shows a significant change with increasing temperature, see Figure 3(a). While the red component of the scattered light dominates at the lower limit of the nominal temperature range of the TLCs, the intensity distribution shifts to smaller wavelengths and eventually the blue component dominates at high temperature for illumination with the white light laser. This behavior is confirmed by using the LED-system, see Figure 3(b). The maximum intensity of the red component occurs at low temperature, while the intensity of the blue part increases with temperature. The scattering characteristic also strongly depends on the observation angle, which can be seen in Figure 4. There, the normalized mean intensities of the red, green and blue part of the spectrum of the light scattered from TLCs by illuminating them with the supercontinuum laser are depicted over temperature for two different observation angles. For this, the red (R), green (G) and blue (B) 'channel' were extracted from the continuous spectrum using a top-hat filter with bandwidth of 60 nm at the central wavelengths of 660 nm, 535 nm and 480 nm, respectively. With increasing temperature, the red component of the scattered light starts to increase and reaches its maximum at about 20.8°C for an observation angle of φ = 40°. The maximum intensity of green and blue come to pass at higher temperatures, according to the behavior of the three spectra exemplarily shown in Figure 3(a). In case of an observation angle of φ = 90°, see Figure 4(b), the intensity of all three colors reaches its maximum at much lower temperatures, meaning that the measuring range shifts to lower temperatures with increasing observation angle.

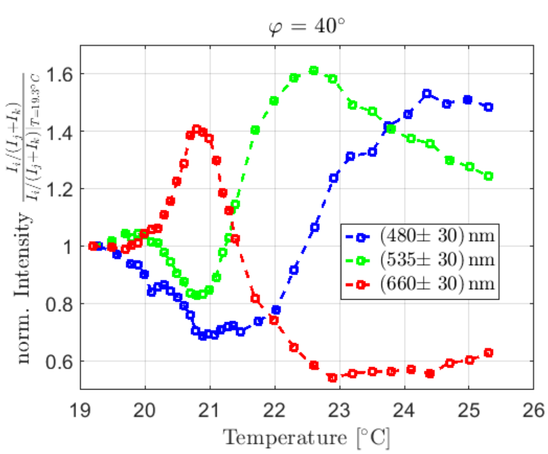


(a)

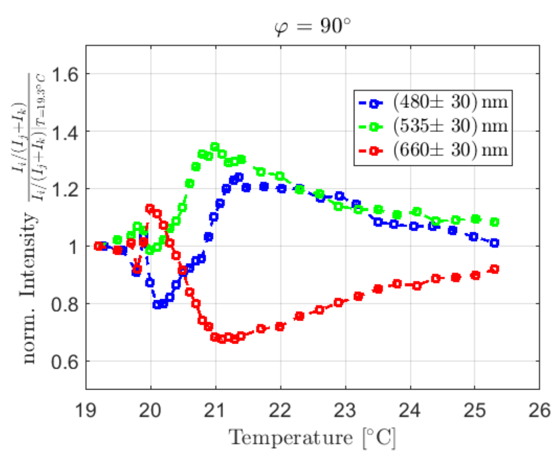


(b)

Figure 3: Spectrum of the light scattered from the TLCs by illumination with (a) the white light laser and (b) the LED-system at an angle between illumination and detection of φ = 40°, for three different temperatures.



(a)

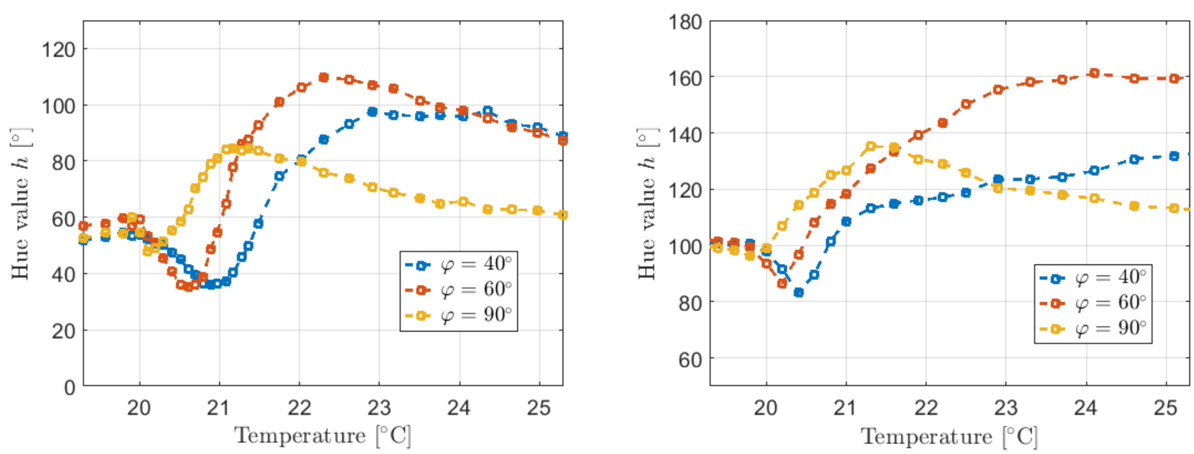


(b)

Figure 4: Normalized RGB mean intensities by illuminating the TLCs with the laser at (a) φ = 40° and (b) φ = 90°.

In addition, measuring range and intensity variation decrease here with increasing angle between illumination and detection, which can be clearly seen using the HSV color space, more common for PIT measurements. This color space is an alternative representation of the RGB model, allowing to determine the perceptual color with the Hue value *h*, independently of colorfulness (Saturation) and brightness (Value).

The Hue value *h* ranges from 0° to 360°, representing red at these values, while passing through the entire visible spectrum in between. In Figure 5(a), the Hue value *h* of the light scattered from the TLCs illuminated with the white light laser, is depicted over temperature for three different observation angles. At first, the color of the scattered light ranges only between 30° (red) and 110° (dark green), due to the use of the white light laser with a cut-in wavelength of about 475 nm. Second, while for an observation angle of φ = 40° the color passes unambiguously from red to green between 21°C and 24°C, which is almost the nominal measuring range of the TLCs for φ = 0°, this color play is limited to a smaller temperature range for larger observation angles. In case of a perpendicular detection (φ = 90°), the scattered light exhibits almost the same color at 25°C as determined for low temperatures outside the temperature sensitive range. Therefore, the larger the observation angle the smaller the measuring range, which agrees well with results published to date, see Günther et al. (2002). Similar behavior can be found using the LED-system instead of laser light (see Figure 5(b)) with except from the actual color of the scattered light that ranges approximately from 80° to 160°, due to LED light containing now also dark blue (compare the spectra in Figure 1(b)). For the calculation of the Hue value *h*, three top-hat filters with central wavelengths and bandwidth adapted to the spectral characteristic of the LEDs were used, in order to obtain the red, green and blue 'channel'. It can be further seen that the dynamic range of the color is almost the same as for laser light illumination. However, a slightly larger range of unambiguous Hue values *h* results compared to that by illumination with laser light, particularly for a smaller angle between light sheet plane and optical axis of the detection optics.



(a) (b)

Figure 5: Hue value obtained by illuminating the TLCs with (a) the white light laser and (b) the LED-system, for three different observation angles.

In case of two-dimensional measurements with a camera, the measuring range and sensitivity of the TLCs is not only dependent on the angle between light sheet plane and optical axis of the camera, since the observation angle changes within the FOV. When using Rayleigh-Bénard cells with large lateral dimension, the angle of observation can readily vary more than 15° over the entire FOV. Hence, care must be taken by choosing appropriate TLCs, usually providing the minimum uncertainty with a temperature range adapted to the temperature difference applied between bottom and top wall of the cell. In addition, refraction through optical transparent walls must be taken into account as well, as the angle between illumination and detection changes accordingly. In Figure 6, a snapshot taken from a measurement of the Rayleigh-Bènard convection using TLCs that are illuminated from the right side and observed from an angle of 70° is depicted. There, two plumes of cold water falling down near the center of the cell, indicating two counter-rotating rolls, which is confirmed by the velocity vector field. However, a superimposed significant color gradient exists from left to the right side that cannot be explained by a horizontal temperature gradient. Following the setup sketched in Figure 1(a), the observation angle increases from the left to the right side due to the numerical aperture of the detection optics.

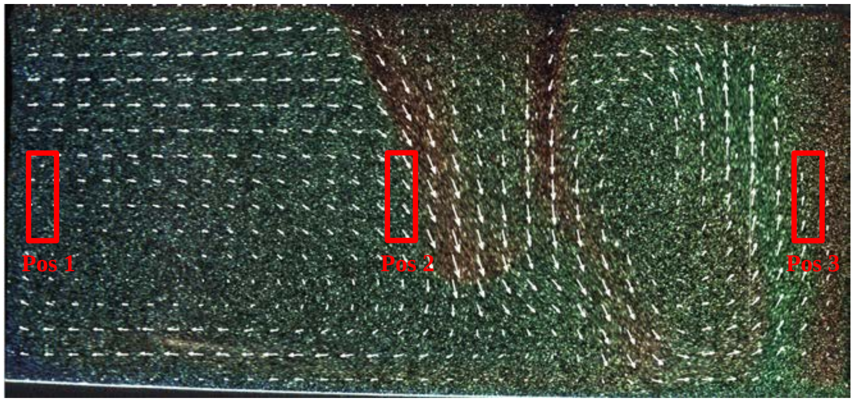


Figure 6: Exemplary snapshot of TLCs in the Rayleigh-Bénard cell showing the possibility to measure the velocity and temperature field at the same time. The three boxes mark distinctive positions needed for the discussion about the superimposed horizontal color gradient from blue to red that occurs inside the Rayleigh-Bénard cell from the left to the right, respectively.

The Hue value *h* obtained from two-dimensional calibration measurements at three different positions inside the cell (cmp. Figure 6) is depicted over temperature in Figure 7. At the far left of the cell, where the smallest observation angle has to be expected for simple geometrical consideration, the measuring range shifts to lower temperatures, while at the far right of the cell the opposite occurs. This behavior, which is in contrast to the previous finding, see Figure 5, can be explained by the refraction of light due to the curvature of the cylindrical cell used here. However, by applying an appropriate two-dimensional calibration, see e.g. Schmeling et al. (2014), this systematic deviation can be taken into account.

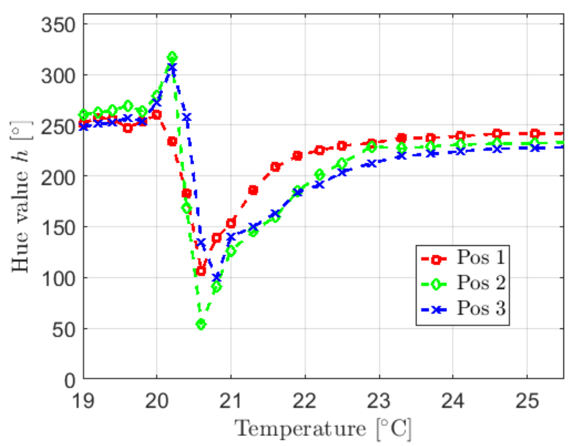


Figure 7: Hue value obtained at the three horizontal positions marked in Figure 6 for different temperatures.

4 Conclusion

The calibration measurements inside the Rayleigh-Bénard cell revealed a scattering characteristic of thermochromic liquid crystals (TLCs) that strongly depends on the angle between light sheet plane and optical axis of the detector. In accordance with findings published in literature, maximum sensitivity occurs at an angle of about 50° to 60°, while minimum sensitivity is obtained with perpendicular detection, as common for 2D particle image velocimetry (PIV). Therefore, for the combination of PIV and PIT employing TLCs as temperature-sensitive tracer particles, maximum uncertainty and minimum measuring range occur for the temperature measurement in standard planar configuration. In case of optimized temperature measurements maximum velocity uncertainty occurs due to perspective errors. Hence, for a simultaneous measurement of temperature and velocity with minimum uncertainty for both quantities, two independent cameras should preferably be used, with at least one color camera. By doing this, all three velocity components can be determined with stereo PIV. By dewarping the particle images first into physical coordinates and computing the velocity vectors subsequently, minimum uncertainty is obtained for both, temperature and velocity, because optimal observation angle for PIT and optimal camera arrangement for PIV coincide for this PIV-evaluation approach. The spectral analysis of the light scattered from the TLCs also revealed that the scattering cross-section is obviously larger for smaller wavelengths. Therefore, depending on the actual spectral characteristic of the detector used for the measurement, white light sources with slightly higher fraction of red should be used or adjusted properly, which can be realized using an LED-system of independent LEDs. In addition, a continuous spectrum yields a well-perceived color play of the TLCs over the temperature range. Therefore, another light source come into play, namely white light lasers. This type of light sources offers mostly inherently a slightly higher fraction of red light. Moreover, the supercontinuum laser used here features not only a broad spectrum of wavelengths, but also high spatial coherence that allows to generate a thin sheet of white light (~100 µm) with high intensity. For instance, the laser light sheet thickness can be less than 1 mm, within a Rayleigh-Bénard cell having lateral dimensions of about 800 mm. Therefore, high spatial resolution in depth-direction can be obtained, which is of vital importance for the experimental investigation of Rayleigh-Bénard convection in cells with high aspect ratio. However, further investigations are necessary with respect to the actual optical setup as chromatic aberrations exist, which can affect the simultaneous velocity and temperature measurements using a supercontinuum white light laser.

Acknowledgements

The authors are very grateful to NKT Photonics and Dr. Nicolai Granzow for providing the supercontinuum white light laser and technical support. Many thanks are also given to Alexander Thieme for helpful comments for the construction of the Rayleigh-Bénard cell.

References

Dabiri D (2009) Digital particle image thermometry/velocimetry: a review. *Exp. Fluids* 46: 191-241

Günther A, von Rohr R. (2002) Influence of the optical configuration on temperature measurements with fluid-dispersed TLCs. *Exp. Fluids* 32: 533–541

Fujisawa N, Nakajima T, Katoh N, and Hashizume Y (2004) An uncertainty analysis of temperature and velocity measured by stereo liquid-crystal thermometry and velocimetry. *Meas. Sci. Technol.* 15: 799–806

Fujisawa N, Funatani S, and Watanabe Y (2008) Simultaneous imaging techniques for temperature and velocity fields in thermal fluid flows. *Journal of Visualization* 11: 247-255

Funatani S, Fujisawa N, and Ikeda H (2004) Simultaneous measurement of temperature and velocity using two-colour LIF combined with PIV with a colour CCD camera and its application to the turbulent buoyant plume. *Meas. Sci. Technol*. 15: 983-990

Massing J, Kaden D, Kähler C, and Cierpka C (2016) Luminescent two-color tracer particles for simultaneous velocity and temperature measurements in microfluidics. *Meas. Sci. Technol*. 27: 115301

Schmeling D, Bosbach, and Wager C (2014) Simultaneous measurement of temperature and velocity fields in convective air flows. *Meas. Sci. Technol.* 25 :035302

Segura R, Rossi M, Cierpka C, and Kähler C (2015) Simultaneous three-dimensional temperature and velocity field measurements using astigmatic imaging of non-encapsulated thermo-liquid crystal (TLC) particles. *Lab Chip* 15: 660

Stevens R, Blass A, Zhu X, Verzicco R, and Lohse D (2018) Turbulent thermal superstructures in Rayleigh-Bénard convection. *Physical Review Fluids* 3: 041501