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Application of structured illumination to gas phase thermometry using thermographic phosphor particles: a study for averaged imaging

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Abstract Structured laser illumination planar imaging (SLIPI) is combined with gas phase thermometry measurements using thermographic phosphor (TGP) particles. The technique is applied to a heated jet surrounded by a coflow which is operated at ambient temperature. The respective air flows are seeded with a powder of $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$ (BAM) which is used as temperature-sensitive gas phase tracer. Upon pulsed excitation in the ultraviolet spectral range, the temperature is extracted based on the two-color ratio method combined with SLIPI. The main advantage of applying the SLIPI approach to phosphor thermometry is the reduction of particle-to-particle multiple light scattering and diffuse wall reflections, yielding a more robust calibration procedure as well as improving the measurement accuracy, precision, and sensitivity. For demonstration, this paper focuses on sample-averaged measurements of temperature fields in a jet-in-coflow configuration. Using the conventional approach, which in contrast to SLIPI is based on imaging with an unmodulated laser light sheet, we show that for the present setup typically ~40% of the recorded signal is affected by the contribution of multiply scattered photons. At

locations close to walls even up to 75% of the apparent signal is due to diffuse reflection and wall luminescence of BAM sticking at the surface. Those contributions lead to erroneous temperature fields. Using SLIPI, an unbiased two-color ratio field is recovered allowing for two-dimensional mean temperature reconstructions which exhibit a more realistic physical behavior. This is in contrast to results deduced by the conventional approach. Furthermore, using the SLIPI approach it is shown that the temperature sensitivity is enhanced by a factor of up to ~2 at ~270 °C. Finally, an outlook towards instantaneous SLIPI phosphorescence thermometry is provided.

1 Introduction

Combustion systems are presently irreplaceable for mobility and power generation. Dwindling fossil resources and environmental constraints impel a constant improvement of combustion technologies. One example is the novel lean combustion concepts in gas turbines, which enable much reduced emissions of nitric oxides (NO and NO_2), but require the implementation of more effective combustor cooling procedures (Behrendt et al. 2008). Film cooling is recognized as an important process in the operation of gas turbines and a key parameter for the devices' durability (Bogard and Thole 2006). Hence, the detailed investigation of combustor cooling concepts (Behrendt and Hassa 2008; Behrendt et al. 2008) as well as a thorough study of generic film cooling processes (Stephan et al. 2016; Schreivogel et al. 2016) is subject to current research. The information of both, the gas phase temperature and velocity, is considered highly relevant for further development of film cooling techniques (Schreivogel et al. 2016).

Laser diagnostics are capable of non-invasively measuring various quantities simultaneously, at both high spatial and temporal resolution. More specifically, for

The original version of this article was revised: Figure 3 is incorrect and it has been corrected.

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simultaneous measurements of gas phase temperature and velocity, several laser-diagnostic approaches have been proposed. A simultaneous use of particle image velocimetry (PIV) and filtered Rayleigh scattering (FRS) thermometry was previously demonstrated (Most et al. 2002), as well as a combination of PIV with laser-induced fluorescence (LIF) thermometry (Nebuchinov et al. 2017). Another approach consists in applying PIV along with laser-induced phosphorescence (LIP) as presented by Lee et al. (2016), Stephan et al. (2016), Fond et al. (2012), and Schreivogel et al. (2016). One advantage of this approach is that the dispersed particles serve as tracers for both thermometry and velocimetry (Lee et al. 2016). For LIP thermometry, particles made of thermographic phosphor (TGP) are used as their emission characteristics exhibit temperature-dependent changes (Fond et al. 2012; Lawrence et al. 2013). TGPs are ceramic host materials doped with rare-earth or transition metals (Brübach et al. 2013; Fond et al. 2012; Lawrence et al. 2013). Their emission spectra are often in the visible, while most of them feature broad absorption spectra in the ultraviolet spectral range (Fond et al. 2012). In the context of this study, the emission of TGPs is termed luminescence rather than phosphorescence—in accordance with the terminology by Brübach et al. (2013). Hence, the related laser-diagnostic approach is denoted as laser-induced luminescence (LIL) instead of LIP in the further manuscript. Numerous TGPs and their use are reviewed in Brübach et al. (2013) and Aldén et al. (2011).

In this study, $\text{BaMgAl}_{10}\text{O}_{17}:\text{Eu}^{2+}$ (BAM) particles are selected as TGP seeding. BAM emits in the visible spectral range at high quantum efficiencies of up to 80% (Bizarri and Moine 2005) and is typically excited by a frequency-tripled Nd:YAG laser at 355 nm (Lindén et al. 2009; Särner et al. 2008). Its luminescence emission spectrum is centered around 440 nm and broadens to lower wavelengths for rising temperatures, which is, in turn, suited for thermometry (Aldén et al. 2011; Särner et al. 2008). The use of BAM for gas phase thermometry measurements is presented in various studies within the literature (Fond et al. 2012; Lawrence et al. 2013; Lee et al. 2016; Schreivogel et al. 2016; Stephan et al. 2016; van Lipzig et al. 2013). Lee et al. (2016) as well as Fond et al. (2012) have been using BAM particles for simultaneous gas phase thermometry and velocimetry in a canonical flow configuration (jet-in-coflow). Stephan et al. (2016) and Schreivogel et al. (2016) applied such simultaneous measurements to a jet in a crossflow, which is suited to investigate film cooling processes relevant for gas turbine combustion. Furthermore, van Lipzig et al. (2013) performed gas phase thermometry measurements with BAM within a heated high-pressure cell, which was able to operate under combustion-related conditions. In this context, an erroneous influence originating from

multiply scattered luminescence emission was observed in several studies (Lee et al. 2016; Stephan et al. 2016; van Lipzig et al. 2013). To compensate for the negative impact of multiple scattering, Lee et al. (2016) as well as van Lipzig et al. (2013) suggested the use of structured laser illumination planar imaging (SLIPI).

SLIPI was first introduced by Berrocal et al. (2008) and Kristensson et al. (2008), who demonstrated its capability in removing the bias due to multiple scattering processes in spray systems. The technique is based on using laser light sheets whose light intensities are spatially modulated in sine waveforms. In the detected images, multiply scattered light does not preserve this modulated structure, whereas the single light scattering does. By recording several sub-images—originally three—with different spatial phase, it is possible to reconstruct an image corresponding to the amplitude of the modulation, which is the direct signature of single light scattering. On the contrary, the non-modulated component which can be removed, corresponds to the multiply scattered light from outside of the incident light sheet. Over the years, several designs of the technique have been developed. The common SLIPI approach uses three averaged images that were recorded one by one (Berrocal et al. 2008). To capture and freeze the motion in dynamic flow systems a more complex setup was presented by Kristensson et al. (2010), using three single-shot sub-images recorded in rapid succession. In order to reduce the complexity of the optical layout, a design using only two sub-images is shown in Kristensson et al. (2014) and more recently in Storch et al. (2016). Finally, the recording of a single modulated sub-image was demonstrated by Berrocal et al. (2012). Since its introduction, SLIPI has been combined with other optical diagnostics for improving quantitative measurements. A few examples are the SLIPI–LIF/Mie ratio to deduce droplet Sauter mean diameters (Mishra et al. 2014), the SLIPI–Rayleigh thermometry (Kristensson et al. 2015; Kempema and Long 2014) for temperature measurements in flames, and the SLIPI two-color LIF for temperature measurements in liquid solutions and sprays (Mishra et al. 2016).

In this study, SLIPI is applied to gas phase LIL thermometry using solid TGP particles (BAM) seeded to a canonical flow configuration. The first objective of the article is to investigate the influence of both the particle-to-particle multiple scattering and the influences of diffuse wall reflections on temperature measurements and to assess the feasibility of the technique. The second objective is to quantify the sensitivity of the measurement and to compare the results with the conventional laser sheet illumination. The third objective is to reconstruct two-dimensional mean temperature fields of the jet-in-coflow configuration.

2 Optical measurement techniques

In this study, the LIL technique used for two-color ratio gas phase thermometry is merged with the SLIPI approach to reduce multiply scattered light. The fundamental functionality of both techniques is outlined briefly in the following.

2.1 Two-color ratio LIL thermometry using TGP particles

For thermometry, this study uses a time-integrated method, in which the transient luminescence signal is temporally integrated. This is experimentally realized by recording two time-integrated luminescence images from two different spectral emission ranges for calculating a temperature-dependent two-color ratio (Brübach et al. 2013), where several dependencies of the luminescence emission cancel as they are equal in both detected signals. The two-color ratios are related to temperatures by an in situ calibration procedure (Lee et al. 2016).

2.2 Structured laser illumination planar imaging

Structured laser illumination planar imaging (SLIPI) is a laser-optical approach for removing the light intensity contribution from multiple light scattering and any undesired light not originating from the incident light sheet. For this purpose, several spatially intensity-modulated laser light sheets with different spatial phases are acquired. Using these modulated sub-images, the amplitude of the modulation can be locally extracted and a SLIPI image (I_{SLIPI}) can be reconstructed. This final image contains the light information from the signal emitted at the location of the illuminating light sheet only, suppressing any surrounding unmodulated light signals. Using three or more sub-images (I_j and I_k ; $n \geq 3$), the spatial resolution can be fully preserved and the SLIPI image is reconstructed by:

$$I_{\text{SLIPI}} = \frac{\sqrt{2}}{n} \times \left\{ \sum_{j=1}^{n-1} \sum_{k=j+1}^n (I_j - I_k)^2 \right\}^{1/2}, \quad (1)$$

where the spatial phase of the modulation pattern is shifted by $2\pi/n$ for each sub-image (Berrocal et al. 2012). Whereas a three-pulse approach, i.e., the recording of three SLIPI sub-images, is commonly used (Berrocal et al. 2008; Kristensson et al. 2008, 2010), this study applies a two-pulse SLIPI approach to reduce the experimental complexity (Kristensson et al. 2014; Storch et al. 2016). In this case, two modulated sub-images (I_0 and I_π)

with a phase shift of half a spatial period (π) are required to reconstruct the SLIPI image (Berrocal 2016)

$$I_{\text{SLIPI}} = \frac{\sqrt{2}}{2} \times \left\{ (I_0 - I_\pi)^2 \right\}^{1/2}. \quad (2)$$

A so-called conventional image (I_{conv}) can be reconstructed by:

$$I_{\text{conv}} = \frac{1}{2} \times (I_0 + I_\pi). \quad (3)$$

The conventional image equals the image which would be recorded using a conventional laser light sheet without any spatial intensity modulation. The consistency of I_{conv} to an image recorded using an unmodulated laser light sheet has been checked within this study. Thus, the conventional image provides a straightforward benchmark for the SLIPI image, as both I_{SLIPI} and I_{conv} can be calculated from an identical set of sub-images (I_0 and I_π). For convenience, I_{SLIPI} is also termed SLIPI reconstruction while I_{conv} is denoted as conventional reconstruction. Even though the two-pulse concept is more convenient for its experimental realization, other challenges arise. The SLIPI reconstructions resulting from Eq. (2) feature unwanted residual line structures of twice the spatial ground frequency ($\tilde{\nu}$) of the initial modulation pattern, which have to be removed (Kristensson et al. 2014). Following Kristensson et al. (2014), this can be achieved by low-pass filtering the spatial frequencies of I_{SLIPI} applying a cutoff frequency $\tilde{\nu}_c$. This procedure is executed in the Fourier domain. If $\tilde{\nu}_c$ is close to the resolution limit of the imaging system ($\tilde{\nu}_{\text{max}}$), the spatial resolution of the filtered I_{SLIPI} is only affected marginally, as only minor data are discarded in the Fourier domain. In theory, there is no resolution loss for $\tilde{\nu} = 0.5 \times \tilde{\nu}_{\text{max}}$. In practice, this limit is hard to reach as sufficient pixel sampling is required to resolve the modulated pattern with high contrast. The appropriate choice of the modulations' ground frequency $\tilde{\nu}$ as well as a description of the low-pass filtering procedure is described in detail by Kristensson et al. (2014).

3 Experimental setup

A canonical flow arrangement consisting of a circular jet ($d = 16$ mm) and a concentric coflow ($d = 140$ mm) is investigated. The identical configuration was previously used and investigated by Lee et al. (2016). A sketch of this jet-in-coflow device is embedded in Fig. 1. The jet flow is electrically heated (OSRAM SYLVANIA Inc., part number 068464 and Niggeloh GmbH, customized) whereas the coflow is operated at ambient temperatures. Both flows consist of air at atmospheric pressure seeded with TGP particles of BAM (Phosphor Technology Ltd., part number

Fig. 1 Optical setup for performing the mean SLIPI measurements. Schematic sketches of both the frequency cutter and the jet-in-coflow arrangement are embedded

KEMK63/UF-P2). Customized fluidized bed seeders are used to disperse the powder of BAM particles in both air flows. Seeding densities are quantified in the discussion of the experimental results in Sect. 5. For the purpose of demonstration, the test rig and the analyzed configuration are operated at steady state. Thus, the jet flow is laminar at a Reynolds number of $Re_{jet} = 1800$ and the bulk velocity of the co-flow is approximately 0.2 m/s ($Re_{coflow} = 1620$, based on the hydraulic diameter). Steady-state operation is ensured by monitoring the jet core temperature with a thermocouple (type K, $d = 1.5$ mm, tip at jet center), whereas the flow rates are controlled using mass flow controllers (Bronkhorst High-Tech).

The optical setup for excitation and recording of the luminescence of BAM particles dispersed in the gas phase is outlined in Fig. 1. The mean SLIPI setup used in this study consists of a two-pulse SLIPI approach (Kristensson et al. 2014) combined with a time-averaging (or rather sample-averaged) concept (Berrocal et al. 2008). This approach is realized by generating the two final SLIPI sub-images $\bar{I}_0$ (SLIPI path 1) and $\bar{I}_\pi$ (SLIPI path 2) by sample averaging (the overbar denotes the

sample-averaged value). Single sub-images (I_0 , I_π) are recorded independently and consecutively for each SLIPI path by blocking either path 2 or path 1, respectively. A pulsed Nd:YAG laser (Spectra-Physics, Quanta-Ray PIV series, PIV 400, only one cavity used) operating at the third harmonic output (355 nm) at 10 Hz repetition rate is used as an excitation source of the luminescence of BAM particles. A combination of $\lambda/2$ -plate and polarized beam splitter cube is employed to control the laser pulse energy (P-polarized beam transmitted). To generate the spatially intensity-modulated SLIPI light sheets, general design rules of Kristensson (2012) and specific aspects for a two-pulse realization of Kristensson et al. (2014) are followed. At first, the laser beam is expanded using a telescope and passes a rectangular aperture to select a region with an approximately homogeneous intensity distribution. Subsequently, a 50/50 beam splitter (CVI, energy separating) guides the remaining laser radiation to both SLIPI paths, each one using a Ronchi grating (Edmund Optics, 5 line pairs/mm) to generate an individual diffraction pattern. Both diffraction patterns are overlapped using a second 50/50 beam splitter. The

spatial phase shift between both modulated SLIPI light sheets is determined and fine adjusted by vertical shifting of the Ronchi grating in SLIPI path 1. In this study, the approach of fringe projection (Kristensson 2012) is used to generate the spatial sine structure of the SLIPI light sheets by interference of two coherent beams which are extracted from diffraction patterns created by the Ronchi grating. For this purpose, the diffraction patterns are focused onto a spatial beam filter device called frequency cutter designed in accordance with Kristensson (2012). A sketch of the frequency cutter functional principle is embedded in Fig. 1 with the incident beam on the left-hand side and the resulting interference pattern on the right-hand side. The frequency cutter is employed to extract the ± 1 st diffraction order components. All other orders (0th, ± 3 rd,...) are blocked. The ± 1 st diffraction orders diverge after passing the frequency cutter, intersect, and finally interfere, thus creating a sinusoidal intensity modulation of the laser light sheet. The laser sheet thickness is shaped using a positive cylindrical lens, whereas the period of spatial modulation is aligned by an adjustable telescope which additionally collimates the beam. In the field-of-view (FOV) the final modulated laser light sheets feature a thickness of $200 \pm 20 \mu\text{m}$, a spatial modulation period of 240–300 μm , and a mean pulse energy of 0.25–0.33 mJ with a standard deviation of 9–16 μJ (energy values derived from 500 single laser pulses). The emitted luminescence signal is collected by an achromatic lens, separated by a dichroitic beam splitter (Chroma Technology Corp., T425LPXR, $\lambda_{\text{center}} = 425 \text{ nm}$) and recorded by two cameras (PCO AG, sensicam qe double shutter, 1376×1040 pixels, 6.45 μm pixel size) operating in fast shutter mode with 5 μs exposure time at 5 Hz frame rate. The 5 μs exposure is ~ 2.5 times the luminescence lifetime of BAM (2 μs at ambient temperature (Lindén et al. 2009)) such that practically the entire signal upon pulsed excitation is recorded. The upper spectral range of the transmitted luminescence emission is denoted as red signal ($\lambda > 425 \text{ nm}$), whereas the reflected signal is termed blue signal and contains the lower spectral range of the

emission ($\lambda < 425 \text{ nm}$). In addition, interference filters are located in front of each camera objective (f-number $f_{\#} 1.4$, focal length $f = +85 \text{ mm}$) to more accurately specify the red (Chroma Technology Corp., ET470/40X, $\lambda_{\text{center}} = 470 \text{ nm}$, $\Delta\lambda = 40 \text{ nm}$) and blue (Chroma Technology Corp., ET400/40X, $\lambda_{\text{center}} = 400 \text{ nm}$, $\Delta\lambda = 40 \text{ nm}$) signal. The investigated FOV extends by $x \times y = 41.8 \times 31.6 \text{ mm}^2$ (horizontal $\times$ vertical) and is intersecting the symmetry axis of the jet at $z = 0 \text{ mm}$. One single pixel on each camera chip corresponds to a $30.35 \times 30.35 \mu\text{m}^2$ area. A digital delay pulse generator (Quantum Composers Inc., 9520 series pulse generator) is used to trigger and synchronize laser and cameras.

For reproducible measurements, the test rig is prepared in a defined process. Prior to each measurement day all plastic hoses, which are contaminated with remaining BAM powder, are replaced to avoid agglomerations and the fluidized bed seeders are cleaned. The BAM powder is dried at 120 $^{\circ}\text{C}$ for about 4 h to reduce moisture. The SLIPI light sheet optics are iteratively aligned using a beam monitor (DataRay Inc., WinCamD) equipped with a UV converter and monitoring the fluorescence signal of a cuvette filled with a dye tracer (Coumarin 307 solved in ethanol, recorded by red camera channel). For this purpose, both the beam monitor and the dye cell are alternatingly placed within the FOV and the signal is monitored during the fine adjustments (phase shift, light sheet overlap, modulation depth).

4 Post-processing methodology

Data post-processing can be divided into three major parts: (1) Conditioning and structuring of raw data, (2) SLIPI post-processing, and (3) Thermometry post-processing. A flow chart of the entire post-processing methodology is outlined in Fig. 2. The procedure is optimized for analyzing the mean SLIPI results. The post-processing steps are implemented and performed using MATLAB R2016a (The MathWorks, Inc.).

Fig. 2 Flow chart of the post-processing methodology. The data flow is characterized by arrows

4.1 Conditioning and structuring

The first post-processing step is the conditioning and structuring of the recorded raw data. During the test rig operation, temporal seeding density of both the jet and coflow fluctuated. As both SLIPI sub-images $\bar{I}_0$ and $\bar{I}_\pi$ are derived by sample averaging, the single raw images I_0 and I_π need to be comparable regarding their seeding conditions. Otherwise averaging is affected by these fluctuations. Thus, a proper conditioning of the recorded single raw images I_0 and I_π with respect to a roughly constant seeding density appeared imperative for a reliable implementation of the mean SLIPI approach. This issue is addressed in the data post-processing by applying an intensity threshold-based particle counting algorithm to all raw images. To identify a single particle, this algorithm considers all connected pixels with an intensity exceeding the local mean background by 30 counts on the red camera channel. Notice, that this procedure provides an apparent particle density—referred to as seeding density in the following—and might be biased by the optical resolution of the imaging system as well as by the modulated illumination of the probed area. However, this procedure has shown to be a sufficient measure to distinguish different low, medium, and high seeding density cases. All available raw images are classified regarding to both the jet and coflow seeding density. In a subsequent step, a structuring algorithm accesses the computed seeding density information and composes a statistic database with N samples of appropriate raw images I_0 and I_π . In this study, $N = 50$ samples are typically taken out of 1000 available raw images. Finally, their sample average is calculated to obtain the SLIPI sub-images $\bar{I}_0$ and $\bar{I}_\pi$. In this procedure, saturated pixels are excluded ($I = 4095$) and a mean background subtraction is performed to avoid a bias by static background and ambient light. The sample-averaged sub-images $\bar{I}_0$ and $\bar{I}_\pi$ are calculated independently for both the red and blue camera channels. An example for the sample-averaged sub-image $\bar{I}_0$ is shown in appendix A.

4.2 SLIPI post-processing

The second step in data analysis is the SLIPI post-processing which is applied to $\bar{I}_0$ and $\bar{I}_\pi$ of both the red and blue camera channels. For further clarification, the Appendix section A provides a detailed visualization of the SLIPI post-processing steps by showing interim processing results.

In a first step, intensity fluctuations between the sub-images $\bar{I}_0$ and $\bar{I}_\pi$ are corrected (Kristensson 2012). This process compensates for temporal and spatial intensity fluctuations of the exciting laser radiation as well as for temporarily varying seeding densities, which is also causing intensity differences in the recorded sub-images. The

second step consists of the reconstruction of both the SLIPI ($\bar{I}_{\text{SLIPI}}$) and conventional image ($\bar{I}_{\text{conv}}$) from the two sub-images $\bar{I}_0$ and $\bar{I}_\pi$ according to Eqs. (2) and (3), respectively. In the third step, a low-pass filtering in the Fourier space is performed to remove distracting residual lines of twice the ground frequency of the light sheet modulation in the SLIPI reconstructed images (Kristensson et al. 2014). For this purpose, the reconstructed images are transferred to the Fourier domain using a fast Fourier transformation (FFT). For illustration, Fig. 3 shows an arbitrary $\bar{I}_{\text{SLIPI}}$ image processed by FFT. Intensities of the Fourier spectrum F are presented in a normalized logarithmic magnitude $\log(|F|) \in [0, 1]$. The look-up table of Fig. 3 is adapted to a range of $[0.5, 1]$ to point out the prominent components in the spectrum. In addition, predominant points are marked and a profile of the spectrum in $\tilde{v}$ -direction is shown (averaged over 11 pixels in $\tilde{u}$ -direction centered at $\tilde{u} = 0 \mu\text{m}^{-1}$). Number ① denotes a component of the spectrum that is centered at the origin. It represents an averaged intensity (Gustafsson 2005). The frequency component position of the initial laser sheet modulation corresponds to the spatial ground frequency ($\tilde{v}$) which is marked by ② whereas $2\tilde{v}$ is identified by ③. As expected, only minor residuals of the $\tilde{v}$ line structure are observed (see Fig. 3, ②). In a perfect SLIPI reconstruction, however, amplitudes of the $\tilde{v}$ line structure would have been removed entirely (Kristensson et al. 2014). This imperfection is attributed to both local intensity and seeding differences between $\bar{I}_0$ and $\bar{I}_\pi$ that remained from the intensity correction procedure (see Fig. 9, appendix A). These minor residuals are considered negligible in this study. However, as stated in Sect. 2.2, the more distinct $2\tilde{v}$ residuals (see

Fig. 3 Fourier spectrum of an $\bar{I}_{\text{SLIPI}}$ image prior to low-pass filtering. Intensities are shown as normalized logarithmic magnitude $\log(|F|)$. Parameters $\tilde{u}$ and $\tilde{v}$ denote the coordinates in the frequency domain. ①–③ identify prominent frequency components. The $\tilde{v}$ - and BLPF-profile is shown at centerline $\tilde{u} = 0 \mu\text{m}^{-1}$. Red camera channel shown at ambient flow temperature. Statistics based on 50 samples

Fig. 3, ③) need to be removed. For this purpose, a Butterworth low-pass filter (BLPF) is applied to $\bar{I}_{\text{SLIPI}}$ in the Fourier domain. A BLPF is suited to attenuate or even avoid the distracting influence of so-called ringing effects which can result from the application of ideal top-hat low-pass filters or higher-order BLPF (Gonzalez and Woods 2002). In this context it is noted that no significant ringing is observed when processing the mean SLIPI images based on ensemble averaging, i.e., $\bar{I}_{\text{SLIPI}}$ and $\bar{I}_{\text{conv}}$, using a top-hat low-pass filter. This is attributed to the smooth intensity gradients resulting from averaging. For a single-shot SLIPI application with inherently steeper intensity gradients due to local fluctuations of seeding density, top-hat filtering most likely results in significant ringing. To attenuate ringing and preserve spatial resolution, a 5th order BLPF with relatively abrupt cutoff frequency range is applied in this study. The qualitative $\tilde{\nu}$ -profile of the BLPF applied in this study is superimposed to the profile of the spectrum in Fig. 3. As the BLPF features no single sharp cutoff frequency $\tilde{\nu}_c$, the locations of two characteristic cutoff frequencies at $\tilde{\nu}_{c,50\%} \approx (180 \mu\text{m})^{-1}$ and $\tilde{\nu}_{c,10\%} \approx (150 \mu\text{m})^{-1}$, retaining 50 and 10% of the corresponding frequency component, are outlined. Here, the residuals at $2\tilde{\nu}$ are located beyond $\tilde{\nu}_{c,10\%}$. Using this approach, no influence of any residuals is apparent in the images after filtering (see Fig. 9, zoomed profile after low-pass filter). The application of the BLPF is accompanied with a reduction of the spatial resolution. Based on resolution test target recordings (Newport Corporation, USAF-1951), the final spatial resolution after application of the BLPF is estimated to be approximately $180 \mu\text{m}$, which corresponds well to the cutoff frequency $\tilde{\nu}_{c,50\%} \approx (180 \mu\text{m})^{-1}$. This is larger by a factor of 2 than the resolution limit of the detection optics of $90 \mu\text{m}$ that was determined from the unfiltered resolution test target images and shown as dashed line in Fig. 3. After filtering, the image is transferred back to the spatial domain using an inverse FFT (filtered SLIPI image is termed $\bar{I}_{\text{SLIPI}}^*$).

4.3 Thermometry post-processing

The final step is the thermometry post-processing, which utilizes the reconstructed images ($\bar{I}_{\text{SLIPI}}^*$ or $\bar{I}_{\text{conv}}^*$) of both the red and blue camera channels to calculate a two-color ratio image. To ensure an accurate calculation of the two-color ratio, red and blue images of $\bar{I}_{\text{SLIPI}}^*$ and $\bar{I}_{\text{conv}}^*$ are matched pixel-by-pixel (Lee et al. 2016). This is done in two steps. The first step applies a dewarping procedure, which spatially dewarps the images using calibration polynomials calculated in DaVis 8.1.5 (LaVision GmbH) deduced from images of a calibration target (LaVision GmbH, 058-5). The second step utilizes a matching algorithm that bases on image warping procedures provided by MATLAB R2016a.

Prior to calculating a temperature from the dewarped images, pixels with negative gray-scale values (resulting from subtraction of background) as well as pixels exceeding the spatially averaged intensity by 10 times, most likely representing agglomerates, are removed from the dataset for the following analysis (removed pixels are allocated as not-a-number, NaN). Subsequently, a 6×6 binning operation is performed to provide interrogation windows of $180 \times 180 \mu\text{m}^2$, corresponding to the estimated spatial resolution after application of the BLPF. A 5×5 averaging filter is applied after the binning procedure. This additional filter lowers the final spatial resolution of the two-dimensional ratio and temperature fields to $\sim 1 \text{ mm}$. Finally, the desired two-color ratio is computed by dividing the resulting blue by the red image pixel-by-pixel.

Once the two-color ratio is calculated, a flat-field correction (FFC) is applied (Lee et al. 2016). In doing so, the two-color ratio image is divided by a sample-averaged two-color ratio image at ambient temperature, which is additionally processed by a 5×5 averaging filter. The quantification of two-color ratios in terms of temperatures is finally performed using an in situ calibration procedure. For this purpose, two-color ratios are measured at different jet core temperatures. The temperature is measured by placing the tip of a calibration thermocouple on the centerline of the jet directly above the nozzle exit. After removing the thermocouple, for each reference temperature, a spatial mean and standard deviation of the two-color ratio is calculated within the area of the thermocouple tip (45×30 pixels, see ① in Fig. 7a). Finally, these ratio values are correlated to the corresponding thermocouple temperatures resulting in calibration curves.

5 Results and discussion

5.1 Impact of multiple light scattering to the luminescence emission

At first, major differences between the conventional and the SLIPI technique in the reconstructed luminescence intensity are discussed. It is emphasized here that the SLIPI image and its corresponding conventional image are calculated from an identical set of sub-images (I_0 and I_π) and thus base on the same raw images. Intending to investigate the occurrence of multiple scattering of the apparent luminescence, a test case was applied in accordance with Lee et al. (2016). In this test case, the coflow is seeded with TGP particles ($2\text{--}4 \times 10^{10}$ particles/ m^3), whereas the jet flow remains unseeded. Thus, any signals apparent within the jet region can be attributed to multiply scattered light originating from the coflow area located in front or behind the jet flow. The results of the test case are shown in Fig. 4

Fig. 4 2D mean count images of the red luminescence channel ($Re_{jet} = 1800$) are shown for both the conventional (a) and SLIPI reconstruction (b) in the center plane ($z = 0$ mm). Vertically averaged count profiles (averaging range $y > 0$ mm) are shown in addition (c).

for a laminar jet ($Re_{jet} = 1800$) intersected at its center plane ($z = 0$ mm). For illustration, the exit of the jet nozzle ($-8 \text{ mm} < x < 8 \text{ mm}$) is shown at the bottom of the xy -plane. Only the intensities in the red camera channel are shown as the blue camera channel exhibits a similar behavior. The conventional (Fig. 4a) and SLIPI reconstruction (Fig. 4b) are shown next to each other for comparison. In addition, vertically averaged mean count profiles are presented for both reconstructions to further emphasize the differences (Fig. 4c).

The surface of the jet tube is partially covered with BAM particles. Accordingly, an area near the jet nozzle exhibits high luminescence intensities (see ① in Fig. 4a) originating from high BAM particle densities at the surface. To investigate the capability of the SLIPI technique to cope with this ‘diffuse wall luminescence and reflection’ in enclosed flow devices seeded with TGPs, the incident laser beam was intentionally hitting the nozzle. This causes an increased and spatially blurred intensity distribution within the conventionally reconstructed image (Fig. 4a) within region ①. This influence is almost entirely removed within the SLIPI reconstructed case (Fig. 4b). The entire intensity field in the coflow region appears much more homogeneous in the SLIPI reconstructed cases. This is confirmed by inspecting the profiles shown in Fig. 4c when comparing the signal in the left and right coflow region. Consequently, the SLIPI technique has shown its capability to remove the influences of ‘diffuse wall luminescence and reflection’ and thus its application appears beneficial in enclosed flow geometries or could even enable the measurement of wall-near quantities.

Another striking zone is located on the left boundary between jet and coflow (see ② in Fig. 4a). Within the actually unseeded region, a signal is detected in the conventionally reconstructed image (Fig. 4a). As no seeding is present

The jet flow is unseeded but heated with the jet core at 187°C . Statistics based on 50 samples. Numbers ①–⑤ and dashed areas denote specific regions that are discussed in the text. The laser beam enters the flow from the left-hand side

in the jet, the signal along this line-of-sight is attributed to multiple scattering events in the seeded coflow area. The erroneous signal in this zone is entirely removed in the SLIPI reconstructed case (Fig. 4b). Thus, the SLIPI technique is successfully eliminating multiply scattered light in the seeded gas phase. When observing this boundary, the reader has to keep in mind that additionally seeding the jet flow would increase multiply scattered light and would finally cause an even more severe blurring. The multiply scattered light originating from the luminescing nozzle (see ① in Fig. 4a) is expected to contribute to zone ②. As this is not the case on the right boundary layer between jet and coflow, a zone similar to ② is not observed there.

In the conventionally reconstructed mean image, multiply scattered light is not observed within the entire region of the unseeded jet (Fig. 4c). For $-2 \text{ mm} < x < 8 \text{ mm}$, the signal is in the order of magnitude of the noise floor. This is attributed to the sample-averaging step in the post-processing where the influence of multiple scattering is smoothed.

The comparison of the conventionally and SLIPI reconstructed luminescence signal of BAM particles seeded to a gas phase flow demonstrates the capability to drastically reduce systematic errors by multiple scattering in the mean SLIPI approach.

In a next step, the contribution of multiply scattered light to the recorded luminescence signal is determined quantitatively. The quantification bases on a comparison of the intensities of both reconstructions, i.e., $\bar{I}_{SLIPI}^*$ and $\bar{I}_{conv}^*$. For this purpose, Eq. (4)

$$\phi_{MS,i}(x,y) = \frac{\bar{I}_{conv,i}^*(x,y) - \bar{I}_{SLIPI,i}^*(x,y)}{\bar{I}_{conv,i}^*(x,y)} \quad (4)$$

is utilized (Kristensson et al. 2011). The index i represents red and blue camera channels, respectively, whereas

$\phi_{MS,i}$ can be interpreted as a multiple scattering degree. A vanishing ratio represents a signal that does not contain any multiply scattered light ($\phi_{MS,i} = 0$, no multiple scattering), whereas a ratio of unity corresponds to a signal that entirely consists of multiply scattered light ($\phi_{MS,i} = 1$, only multiple scattering).

$\phi_{MS,i}$ is assessed and compared in two different regions, each extending by 200×200 pixels. The first area is selected in the bulk coflow (see ④ in Fig. 4a) where single and multiple scattering in the gas phase but no influence of diffuse wall luminescence and reflection is expected. The second region is near the jet nozzle (see ⑤ in Fig. 4a) which is additionally affected by the aforementioned emissions that originate from walls. For both camera channels the analysis is performed for varying apparent seeding densities in the coflow ($3\text{--}5 \times 10^{10}$ particles/m³), i.e., different degrees of multiple scattering. The results of this analysis are shown in Fig. 5. It is observed that $\phi_{MS,i}$ exceeds 40% for all analyzed cases and features values up to 75% in a region near the wall. In area ④, with increasing seeding density different slopes of $\phi_{MS,red}$ and $\phi_{MS,blue}$ are observed. The red channel features a higher multiple scattering degree with elevated seeding densities. Evaluating area ⑤, it is clearly recognized that the red channel exhibits much higher $\phi_{MS,i}$ than the blue. This originates from the fact that the local intensities of the red and blue channel are differently affected by the diffuse wall luminescence and reflection from the nozzle. In the red channel, the influence of the nozzle is clearly observed within area ⑤ (see Fig. 4a).

Fig. 5 Evaluation of multiple scattering degree $\phi_{MS,i}$ within zones ④ and ⑤ (spatially averaged $\phi_{MS,i}$) shown in Fig. 4 with respect to different coflow seeding densities. Statistics based on 50 samples

However, in the blue channel the increased and blurred intensity does not propagate as far into the bulk coflow as in the red channel and thus does hardly reach area ⑤. This might be due to preferential absorption (Lee et al. 2016) of the blue photons on their way from the nozzle to area ⑤. From these observations we conclude that multiply and wall scattered luminescence influences the two-color ratios differently at different locations. Especially in flows where multiple scattering or covering of walls by luminescent particles is unavoidable this causes systematic errors that cannot be accounted for by a conventional calibration procedure.

5.2 Quantification of luminescence signal and temperature sensitivity

Although the presence and influence of multiply scattered luminescence emission is discussed in Sect. 5.1, the impact of multiple scattering and related biasing effects (e.g., diffuse wall luminescence/reflection) on calibrating the two-color ratio needs a more quantitative analysis. The two-color ratios of the luminescence signal are calibrated typically against thermocouples. In this study, for calibration a homogeneous region in the jet center close to the nozzle is selected (see ① in Fig. 7a). Calibration curves are then applied to the entire FOV and for several consecutive measurements. As shown below, in case of conventional imaging multiple scattering and related effects cause a severe bias.

This analysis is performed for both the SLIPI and conventionally reconstructed results. By varying the seeding density of the coflow, the degree of multiple scattering is changed. Apparent seeding densities for the coflow are classified as: low: $2\text{--}4 \times 10^{10}$ particles/m³; medium: $4\text{--}6 \times 10^{10}$ particles/m³; high: $6\text{--}8 \times 10^{10}$ particles/m³. The jet flow seeding is fixed between $1.5\text{--}5 \times 10^{10}$ particles/m³. The results are shown in Fig. 6. Data points represent the spatial average (μ) of the two-color ratios within the area of the calibration thermocouple tip and the error bars denote the corresponding spatial standard deviation (σ). For the sensitivity analysis towards varying apparent coflow seeding densities (colored curves in Fig. 6), two-color ratios are extracted from zone ① shown in Fig. 7a, which represents the calibration thermocouple tip location. To investigate local influences (black curves in Fig. 6), two-color ratios are furthermore extracted from a region downstream the jet centerline at $y = 22$ mm (see zone ② in Fig. 7a).

For the conventionally reconstructed images (Fig. 6a) the two-color ratio shows a distinct sensitivity to varying coflow seeding densities. The calibration curve flattens with increasing coflow seeding density, i.e., multiple scattering. Thus, the two-color ratio appears to be a function of both the temperature and the degree of multiple scattering. In

Fig. 6 Calibration curves for both the conventional (a) and SLIPI reconstruction (b). For sensitivity analysis, the curves are presented at different apparent coflow seeding density cases (low, medium, high; colored curves; extracted from zone ② in Fig. 7a) and extracted from a region downstream the jet centerline at $y = 22$ mm (black curves;

extracted from zone ② in Fig. 7a). Data points: spatial average μ within region of thermocouple tip; error bars corresponding spatial standard deviation σ (shown: $\mu \pm \sigma$). Temperature points correspond to 21, 49.5, 99.5, 195, 268 °C. Statistics based on 50 (coflow low), 45–50 (coflow medium) and 11–29 (coflow high) samples

contrast, this effect is much less pronounced in the SLIPI reconstructed calibration curves (Fig. 6b). All calibration curves feature similar slopes (sensitivities) and absolute values, independently of the coflow seeding density. Here, the two-color ratio appears to be merely a function of the temperature. This observation confirms that the differences in the calibration curves in the conventional case (Fig. 6a) are caused by multiple scattering. Notice, that the cases coflow medium (45–50 samples) and coflow high (11–29 samples) feature reduced sample sizes. To ensure a more robust statistical analysis, further analysis is focused on the seeding density case coflow low, which provides at least 50 samples.

The temperature sensitivity of the SLIPI approach is almost independent of coflow seeding density, whereas in the conventional approach the sensitivity decreases with increasing coflow seeding density. At highest seeding densities investigated here for 268 °C the decrease is up to a factor of 2 between the SLIPI and conventional reconstruction. This is due to the fact that multiply scattered light is intermixing information from spatial regions of different temperature.

To assess local influences upon the calibration curves, Fig. 6 additionally outlines curves extracted from an area downstream the nozzle at $y = 22$ mm (see zone ② in Fig. 7a) for the low coflow seeding density case. This analysis requires the assumption of constant jet core temperature along the centerline, which is valid for the near nozzle region (here $x/D < 1.5$). Calculating the two-color ratios from the downstream region in the conventional reconstruction (Fig. 6a) results in an increased temperature sensitivity compared to the upstream region.

However, in the SLIPI case the downstream curve matches well to the original upstream curves (Fig. 6b). This observation underlines the potential local dependency of conventionally measured calibration curves and again suggests a higher robustness of the SLIPI approach.

Signal-to-noise ratios (SNR) are included to the two-color ratios underlying the calibration curves in Fig. 6. For this purpose, noise has been calculated from the spatially averaged intensity within zone ③ in Fig. 4. For the conventional cases presented in Fig. 6, the red channel features a SNR of 8.4–30.4, while the blue channel has a SNR of 1.2–3.6. In the SLIPI reconstructions, the SNR value ranges are 3.7–15.7 for the red and 1.2–2.9 for the blue channel. SLIPI features lower SNR values compared to the conventional case. This is attributed to the signal loss accompanied with the SLIPI reconstruction, as the SLIPI image ($\bar{I}_{\text{SLIPI}}$) results from subtraction of the SLIPI sub-images. In contrast, $\bar{I}_{\text{conv}}$ features a higher but biased signal as is originates from the sum of the SLIPI sub-images.

5.3 Two-dimensional mean two-color ratio and temperature distributions

In a final analysis, two-dimensional mean ratio and temperature fields are derived. Two-dimensional mean ratio distributions are shown for both the conventional (Fig. 7a) and the SLIPI reconstruction (Fig. 7b) within the center plane of the jet/coflow arrangement at $z = 0$ mm. The jet core is heated to 195 °C. Seeding conditions equal the coflow low case introduced in the previous section. y -profiles of both the ratio and the mean counts of the red camera channel

Fig. 7 2D mean ratio (**a**, **b**) and temperature fields (**d**, **e**) for both the conventional (**a**, **d**) and SLIPI reconstruction (**b**, **e**) within the center plane ($z = 0$ mm). For quantitative comparisons, y -profiles of both the ratio and the mean counts of the red camera channel are extracted along the jet centerline at $x = 0$ mm (**c**). Furthermore, polynomial fitted x -profiles of the temperature at $y = 15$ mm are shown (**f**). Zones

① and ② mark regions where ratios are extracted for calibration curves in Fig. 6. The case of low apparent coflow seeding and the corresponding calibration curves are used here. Jet core temperature is 195 °C (measured with thermocouple in zone ①). Statistics based on 50 samples. The laser beam enters the flow from the *left-hand side*

are extracted along the jet centerline at $x = 0$ mm (Fig. 7c). It is observed that the conventionally reconstructed two-color ratio field (Fig. 7a) features an asymmetrical distribution with respect to the jet centerline. Despite flat-field corrections, a bias originating from the jet nozzle is leading to an underestimation of the ratio on the left-hand side of the FOV. In contrast, this is not observed in the SLIPI ratio (Fig. 7b), which appears symmetrically with respect to the jet centerline and thus represents the expected physical behavior of a laminar heated jet. As a drawback, the SLIPI case possesses less spatial homogeneity in the ratio compared to the conventional approach and locally appears noisier. Observations in the two-dimensional ratio fields become manifested in the corresponding temperature distributions. The conventionally reconstructed field (Fig. 7d) features deficient symmetry to the jet axis and underestimates the temperature on the left-hand side, in contrast to the SLIPI case (Fig. 7e). In addition, the conventional field overestimates the jet temperatures for $y > 15$ mm. This observation originates from decreasing mean count values in the red channel with increasing y -direction (see Fig. 7c), while the count values on the blue camera channel are nearly constant (not shown). The decreasing count value on the red count profile is attributed to a decreasing

nozzle influence with increasing distance from the nozzle. However, this is not the case in the SLIPI reconstruction and accordingly results in a more homogeneous temperature along the jet centerline. Furthermore, assuming a constant jet core temperature along the centerline, the average ratio on the centerline shown in Fig. 7c is additionally used to calculate a spatial mean value and standard deviation along the profile. For the conventional case, this results in $\bar{T} = 222 \pm 62$ °C, while SLIPI features $\bar{T} = 182 \pm 39$ °C (here twice the standard deviation is given as error). Accordingly, the SLIPI approach reproduces the temperature as measured by a thermocouple (195 °C) with higher accuracy and precision. The above findings are equally observed for radial temperature profiles at $y = 15$ mm (Fig. 7f).

From the evaluation of two-dimensional ratio and temperature fields, it is emphasized that the SLIPI approach in combination with gas phase phosphor thermometry is more robust against systematic errors originating from multiple scattering and related effects.

As a penalty, the above analysis points out that the SLIPI results exhibit a reduced spatial homogeneity compared to the conventional approach. As aforementioned in Sect. 5.2, the subtraction required in the SLIPI reconstruction reduces

Fig. 8 2D instantaneous count images of the red luminescence channel ($Re_{jet} = 6400$) are shown for both the conventional (a) and SLIPI reconstruction (b) in the center plane ($z = 0$ mm) using a quasi-

instantaneous SLIPI setup. The jet flow is unseeded but heated with the jet core at 182°C . Laser beam enters the flow from the left-hand side

SNR. In the post-processing of mean SLIPI data, the required sample averaging prior to the calculation of two-color ratios blurs the luminescence signal to a certain extent. High signal levels in a voxel of an individual sub-image are mixed with weak or background signal of other sub-images during sample averaging. This is a primary drawback which is inherent to thermometry based on particle seeding. Particularly in cases with too low seeding densities, this can contribute to erroneous ratios, i.e., temperatures, as occasionally observed in the temperature fields. Independent of conventional or SLIPI reconstruction, this in turn is expected to lower the SNR values in general. To overcome the shortcomings resulting from sample averaging inherent to a mean SLIPI approach, a quasi-instantaneous SLIPI setup can be used, where sample averaging follows the two-color ratio calculation. A pathway towards this approach is presented in the following section.

6 Towards single-shot SLIPI thermometry

As aforementioned, applying a quasi-instantaneous SLIPI approach is expected to yield less erroneous mean temperatures. For turbulent flows this requires measurement of the sub-images I_0 and I_π at time scales shorter than Kolmogorov times.

For a proof of principle, a quasi-instantaneous SLIPI TGP setup is experimentally realized by including a second frequency-tripled pulsed Nd:YAG laser. The additional laser beam path is equipped with a separate beam expanding telescope and aperture for selecting a most homogeneous part of the intensity profile. By firing both lasers sequentially with a separation of $\Delta t = 18 \mu\text{s}$, the two single-shot SLIPI sub-images I_0 and I_π are recorded quasi-

instantaneously. To avoid any crosstalk of sequential excitation, the separation of $\Delta t = 18 \mu\text{s}$ is chosen well above the luminescence lifetime of BAM at ambient temperature of approximately $2 \mu\text{s}$.

Similar to results presented in Sect. 4.1, only the coflow is seeded whereas the central jet remains unseeded. Preliminary results of the red camera channel are shown in Fig. 8 for a turbulent jet flow ($Re_{jet} = 6400$). Comparing conventional images with those reconstructed by the SLIPI approach reveal similar properties as for the sample-averaged mean data. Blurring due to ‘diffuse wall luminescence and reflection’ in the conventionally reconstructed image and multiple scattering in the gas phase (Fig. 8a) is eliminated within the SLIPI reconstruction (Fig. 8b). In the mixing layer located at the left boundary of the turbulent jet, the SLIPI approach greatly removes multiply scattered signal from vortices. Overall, the evolving shear layer is observed more clearly and without any interruptions due to multiply scattered light. In addition, the locally different contribution of multiply scattered light is clearly apparent in the unseeded jet core. This first demonstration implies to use the quasi-instantaneous SLIPI thermometry approach when possible. A more detailed analysis of this quasi-instantaneous data will be the scope of our future research.

7 Summary

In this study, a sample-averaging mean SLIPI technique was applied to gas phase LIL thermometry using TGP particles. To the authors’ knowledge, this application is demonstrated here for the first time. The technique was implemented to perform measurements on a steady-state

canonical jet-in-coflow configuration with a heated laminar jet flow and a coflow operated at ambient temperature conditions.

The SLIPI technique is capable to almost entirely remove the contribution of multiply scattered light within the bulk gas phase and originating from walls covered by luminescent particles. It was shown, that the contribution of multiply scattered light to the total recorded luminescence signal is considerable (40–75%) and reveals a spatial and spectral dependency, i.e., is different in the red and blue camera channels. Therefore, multiple scattering can cause a bias due to a spatially dependent two-color ratio that is not accounted for in the conventional calibration curves. Thus, high levels of multiple scattering impacts calibration curves. Using a conventional reconstruction the two-color ratios are sensitive to varying coflow seeding densities. Removal of multiple scattering by means of SLIPI, in contrast, yielded calibration curves independent of the coflow seeding density. These findings underline that the common calibration procedure in combination with a conventional reconstruction is not suitable for fluid flows with significant levels of multiple scattering, especially when seeding densities strongly fluctuate. In contrast, the SLIPI approach features a high robustness regarding the bias by multiply scattered light and related effects. Furthermore, it was shown that the temperature sensitivity is enhanced considerably using the SLIPI technique. By analyzing two-dimensional mean ratio and temperature fields, it was observed that the results derived from the SLIPI technique appear to be more physical compared to conventionally attained results and feature an improved precision and accuracy in the temperature quantification. In view of these observations the combination of SLIPI and LIL thermometry represents a robust approach and enables investigations of complex flow configurations such as film cooling processes. However, the SLIPI results exhibit lower SNR values and possess slightly noisier two-dimensional ratio and temperature fields. This drawback can be partly overcome by utilizing a quasi-instantaneous instead of a mean SLIPI approach. An outlook towards the realization of a quasi-instantaneous SLIPI approach applied to gas phase LIL thermometry using TGP is briefly introduced and will be the scope of our future research in this field.

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Appendix A: Visualization of the SLIPI post-processing routine

This appendix section outlines a stepwise visualization of the SLIPI post-processing procedure applied in this study. The major processing steps are shown in Fig. 9 in terms of two-dimensional mean count images and horizontally averaged local count profiles. The horizontal averaging in the zoomed profiles is performed to provide more distinct profiles and to close seeding free gaps in the images.

An example for initial raw data (0.) entering the SLIPI post-processing is presented in Fig. 9, showing a sample-averaged sub-image $\bar{I}_0$ and a zoom of horizontally averaged local profiles of $\bar{I}_0$ (blue line) and $\bar{I}_\pi$ (red line). In the zoomed profiles the spatial phase shift of half a period between both SLIPI sub-images is clearly visible. Furthermore, an intensity difference between both sub-images is observed. As aforementioned, this is due to both laser intensity fluctuations and varying seeding densities. Thus, the purpose of the first processing step intensity correction is to locally compensate for these differences. The enhancement of the signal-equalization by this processing step is demonstrated in Fig. 9 (1.). The subsequent image reconstruction (2.) is demonstrated in terms of $\bar{I}_{\text{SLIPI}}^*$. In both the two-dimensional image and the zoomed profile, the aforementioned line structure of twice the spatial ground frequency is apparent. By application of the low-pass filtering step, these residuals are significantly reduced and smoothed (3.). This finally results in the filtered image $\bar{I}_{\text{SLIPI}}^*$, which is the output data of the entire SLIPI post-processing algorithm. Note that the spatial average intensity of the image is retained in this filter procedure, while local intensity peaks are attenuated and local signal gaps are filled. Thus, there is no global signal loss in the integrated intensity of the full image, but a local smoothing of intensities. This can be observed in the zoomed profiles in step ‘3. low-pass filtering’ shown in Fig. 9.

In the present study the final spatial resolution of the filtered image $\bar{I}_{\text{SLIPI}}^*$ is 180 μm , two times larger than the optical resolution limit of the detection optics used ($\tilde{\nu}_{\text{max}}^{-1} = 90 \mu\text{m}$). Here, the final spatial resolution corresponds well to the inverse cutoff frequency $\tilde{\nu}_{\text{c},50\%}^{-1}$, and is thus fixed in the low-pass filter operation. In the two-pulse SLIPI approach, the cutoff frequency $\tilde{\nu}_c$ has to satisfy the requirement $\tilde{\nu}_c \leq 2\tilde{\nu}$. If a resolution closer to the optical limit is aimed for, the laser sheet modulation $\tilde{\nu}^{-1}$ must be reduced accordingly. For example, if a resolution of 100 μm is envisaged then the laser sheet modulation $\tilde{\nu}^{-1}$ must not exceed 200 μm . This can be achieved by changing the angle of the two interfering beams and is simply realized

Fig. 9 Outline of the major SLIPI post-processing steps of intensity correction, image reconstruction, and low-pass filtering. All values shown are mean count values. The zoomed profiles represent horizontally averaged mean count values extracted from the 200×200 pixel

regions marked with the red frames, respectively. *Red* camera channel shown at ambient flow temperature. Statistics based on 50 samples. Laser beam enters the flow from the *left*-hand side

by shifting the movable telescope shown in Fig. 1. Notice, that by this enhancement of the spatial resolution the area of the intersecting laser beams will be reduced (smaller FOV).

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