

Simultaneous 3D temperature-velocity measurements in fluid flow using shake-the-box and phosphor thermometry

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ABSTRACT

This contribution implements algorithmic improvements for improved simultaneous three-dimensional temperature and velocity measurements in turbulent gas flows based on seeded sub-micron sized thermographic phosphor particles. Such instantaneous measurements of multiple flow parameters are valuable for direct investigations of non-isothermal turbulent flows and to validate numerical models. The present study focuses on improving our initial implementation of the concept, by implementing state-of-the art algorithms for camera calibration and particle tracking, and refining the processing of particle luminescence images. To investigate the benefit of improved algorithms on the overall performance of the measurement concept, the same image raw data as for the initial concept implementation is evaluated. Using volume self-calibration for the camera calibration leads to a more than twentyfold reduction of remaining errors in the camera models. Combined with two-pulse shake-the-box for 3D particle tracking, the number of successfully tracked particles is increased by a factor of ten. To obtain temperature results from individual particle luminescence emissions, the segmentation of the recorded luminescence images is improved by introducing a two-step masking scheme. Combined with a 3D flat-field correction scheme, this results in more than doubling the number of successfully processed temperature data points, while maintaining the same level of temperature error. This is a further step towards resolving non-isothermal 3D flow structures from individual instantaneous single-shot recordings.

1. Introduction

This contribution covers the integration of state-of-the-art two-pulse shake-the-box (TP-STB) with phosphor thermometry to provide simultaneous three-dimensional (3D) temperature-velocity measurements in turbulent gas flows. As turbulence is a complex and inherently 3D phenomenon (Pope, 2015), numeric modelling is challenging due to the wide range of time- and length-scales involved, and sub-models are regularly used to maintain an acceptable level of computational complexity. Therefore, experimental data remains to be valuable to either validate such sub-models

or to investigate flow phenomena on its own. To obtain complete information about turbulent flow fields, instantaneous 3D measurements of all relevant quantities are required. In case of non-isothermal flows, this involves velocity and temperature distributions to gain insights into the coupled heat and mass transfer (Warhaft, 2000; Pasinato, 2011).

1.1. Particle-based 3D flow velocimetry and thermometry

For 3D flow velocity measurements, several tracer particle-based techniques have been established. They rely on small tracer particles that are seeded into the flow being studied, where they are imaged using cameras from different perspectives. From this 2D image data, their 3D position can be reconstructed and tracked over time with techniques such as tomographic particle image velocimetry (PIV) (Elsinga et al., 2006; Scarano, 2013), 3D particle tracking velocimetry (PTV) (Maas et al., 1993; Fuchs et al., 2016; Cornic et al., 2020), or STB (Schanz et al., 2013; Novara et al., 2022).

To measure the flow temperature using the same seeded tracer particles is very appealing. It limits the complexity of the measurement setup and eases the association of temperature and velocity results as they are obtained at the same particle locations. While particle-based flow thermometry techniques are less established than their velocimetry counterparts, there has been considerable progress over the past years using different kinds of tracer particles (Li et al., 2023). After all, several combined temperature-velocity measurements were reported using different kinds of tracer particles: thermochromic liquid crystals (TLCs) (Massing et al., 2018; Schiepel et al., 2021), dye-filled polymer particles (Massing et al., 2016; Deng et al., 2022), and thermographic phosphors (Omrane et al., 2008; Abram et al., 2013; Stelter et al., 2023).

All of the mentioned measurement concepts assume negligible difference in velocity and temperature between the seeded tracer particles and surrounding fluid elements. In other words, the particles' response times to temperature and velocity changes in their direct vicinity must be short to infer the flow state by observing the tracer particles. If the density of the fluid is high, solid tracer particles of tens of micrometers in diameter often offer short enough response times to changes in flow temperature and velocity. However, if turbulent gas flows are investigated, particles exceeding a few micrometers in diameter react too slowly to changes in flow temperature and velocity and would not provide a truthful representation of the flow field. Additionally, the targeted temperature range also influences the choice of tracer particles. While TLCs offer a very fine temperature resolution, their range is limited to a few Kelvin (Massing et al., 2018). Dye-filled polymer particles are suitable for a larger temperature range, but are limited by the material properties of the polymer. In comparison, thermographic phosphor particles show great potential for application in harsh reactive environments, temperature ranges exceeding those accessible by TLCs and dye-filled polymer particles, and a broad range of turbulent gas flows (Stelter et al., 2023).

1.2. Phosphor thermometry

In general, thermographic phosphors are a class of inorganic solids that are commonly produced as powders with nano- to micrometer particle sizes and emit temperature dependent luminescence upon suitable excitation as reviewed in (Allison & Gillies, 1997; Abram et al., 2018). As these inorganic compounds commonly have high melting temperatures on the order of 2000 K and are often chemically inert and insoluble, they can be used in a variety of reactive and non-reactive environments (Aldén et al., 2011; Sposito et al., 2021). As many thermographic phosphors exist and both the luminescence lifetime and spectrum are material dependent, it is often possible to select a phosphor with favourable characteristics for the planned application. Within past years, combined pointwise (Ojo et al., 2015), 2D (Omrane et al., 2008), and 3D (Stelter et al., 2023) temperature-velocity measurements have been demonstrated in gas flows using thermographic phosphor tracer particles. In the present contribution, phosphor thermometry is now integrated with state-of-the-art TP-STB, to increase the number of samples retrieved per unit volume and therewith increase the usefulness of these combined measurements compared to the initial demonstration of the concept by Stelter et al. (2023).

1.3. Two-pulse shake-the-box

STB was introduced several years ago as an advanced particle tracking scheme that uses particle images recorded from multiple perspectives (commonly 3-4) to reconstruct and track particles in 3D space over time. Compared to 3D-PTV, STB enables Lagrangian particle tracking over extended periods of time and at high particle seeding densities up to 0.1 particles per pixel (ppp) (Schanz et al., 2013, 2014, 2016). This is achieved by leveraging both a calibrated optical transfer function from VSC to aid the 3D reconstruction process (Schanz et al., 2012) and incorporating temporal information to find the most probable pairing of particles across time-steps and suppressing reconstruction artefacts in an iterative process. More recently, the STB concept was expanded to multi- and two-pulse recordings that can be recorded using commonly available double-frame CCD or sCMOS cameras (Novara et al., 2018, 2019, 2022). This expansion of the STB concept enables its integration with single-particle phosphor thermometry measurements.

2. Experimental setup and camera calibration

The data used for the present contribution was recorded in Stelter et al. (2023) and is re-evaluated here to investigate the impact of improved camera calibration, 3D reconstruction, 3D tracking, and particle image segmentation algorithms on the results. A turbulent heated free jet of air originating from a circular nozzle of 4 mm in diameter is used as test case. At a bulk velocity of 34 m s^{-1} ($\text{Re} = 4600$) and a nozzle exit temperature of 433 K, it is surrounded by an isothermal co-flow at

ambient temperatures and 0.2 m s^{-1} . Sub-micrometer ZnO particles with a luminescence lifetime below 1 ns were selected as tracer particles and seeded into both flows.

To provide the combined temperature-velocity measurements, a double-frame single-exposure imaging sub-system consisting of four CCD cameras is combined with a single-frame single-exposure imaging sub-system of two sCMOS cameras as shown in fig. 1. A double-pulse green laser (532 nm , 8 mm diameter, 95 mJ cm^{-2}) is used to illuminate the seeded ZnO particles and the Mie scattered light is recorded by CCD cameras P1-4 (LaVision Imager Pro X) to provide data for reconstruction of particle locations and velocimetry. At the same time, a UV laser (355 nm , 8 mm diameter, 280 mJ cm^{-2}) is spatially overlapped with the first green laser pulse and used to excite a luminescence emission from the same particles. These emissions are recorded in different spectral regions using cameras T1 and T2 (LaVision Imager sCMOS), equipped with $387\text{-}11 \text{ nm}$ and $425\text{-}50 \text{ nm}$ spectral filters for ratiometric thermometry.

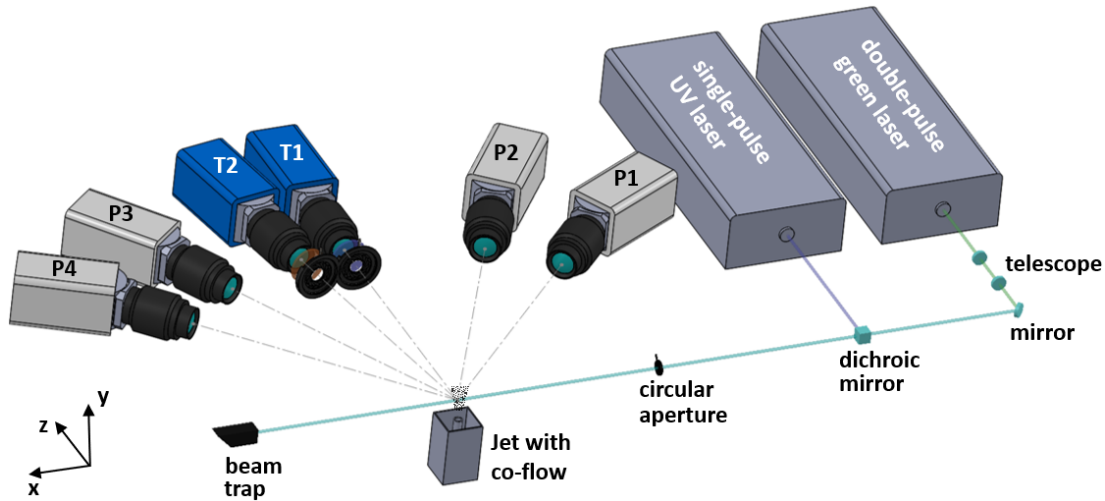


Figure 1. Schematic of the experimental setup for 3D temperature-velocity measurements, including six cameras, two lasers, optical components and a jet nozzle with co-flow. Adapted from Stelter et al. (2023) (CC-BY 4.0).

The temperature dependent emission spectrum of ZnO is shown in fig. 2 where it is plotted for three different temperatures. The spectra are superimposed with the transmission profiles of the spectral filters mounted on cameras T1 and T2, forming two colour channels. By integrating the emissions collected within each colour channel for each particle and forming the ratio between these integrated intensities, a temperature dependent luminescence intensity ratio (LIR) is formed. Upon calibration this LIR is used to infer the temperature of individual ZnO particles.

Snapshot measurements are recorded every 200 ms as a set of six particle views (four Mie scattering and two luminescence) at the first laser pulse time and another set of four Mie scattering views after a $9 \mu\text{s}$ delay. To enable the association from velocity and temperature results in 3D space from 2D camera recordings, the cameras have to be calibrated perspectively. A two-step process is used for this. First, a target image based calibration is performed as described in Stelter et al. (2023).

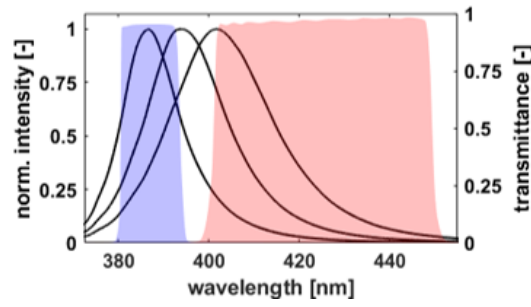


Figure 2. Normalized ZnO luminescence emission spectra at three temperatures superimposed with normalized transmission profiles of filters for cameras T1 and T2. Adapted from Stelter et al. (2023) (CC-BY 4.0).

Once all cameras are mapped to the same 3D coordinate system using this initial calibration, VSC is applied to refine the initial camera models (Wieneke, 2008). Using the implementation of VSC in DaVis 11, particle images recorded with all six cameras are used to reduce the remaining average calibration errors across all six cameras from 0.5 pixel to 0.02 pixel, as shown in fig. 3a.

3. Image data processing

3.1. Mie scattering image processing

Once the cameras are calibrated, Mie scattering images recorded using cameras P1-4 during the first and second laser pulse time are pair-wise processed. For each particle, the 3D location at the first and second laser pulse time is reconstructed using triangulation before tracking it between the time-steps. The implementation of TP-STB in DaVis 11 is used to both reconstruct and track individual particles in 3D space. Compared to the earlier custom implementation of a non-iterative tomographic reconstruction scheme with nearest neighbour pairing for 3D tracking in Stelter et al. (2023), the number of particles reconstructed and tracked from the same image data is increased more than tenfold as visualized in fig. 3b. Using the camera model for cameras T1 and T2 from VSC, the 3D position of each particle reconstructed from Mie scattering data is projected into the image space of the luminescence imaging cameras. This allows for association of the velocity results with computed temperature values in the next step.

3.2. Luminescence image processing

Once the 3D particle locations are projected into the corresponding luminescence images, the luminescence images are screened for local intensity maxima that indicate an imaged particle. If a local intensity maxima is found within a 3 pixel radius around a projected 3D position, a match is established. As the average distance between local intensity maxima in luminescence images and 3D projections is 0.94 pixel in the present data, compared to more than 12 pixel of average distance

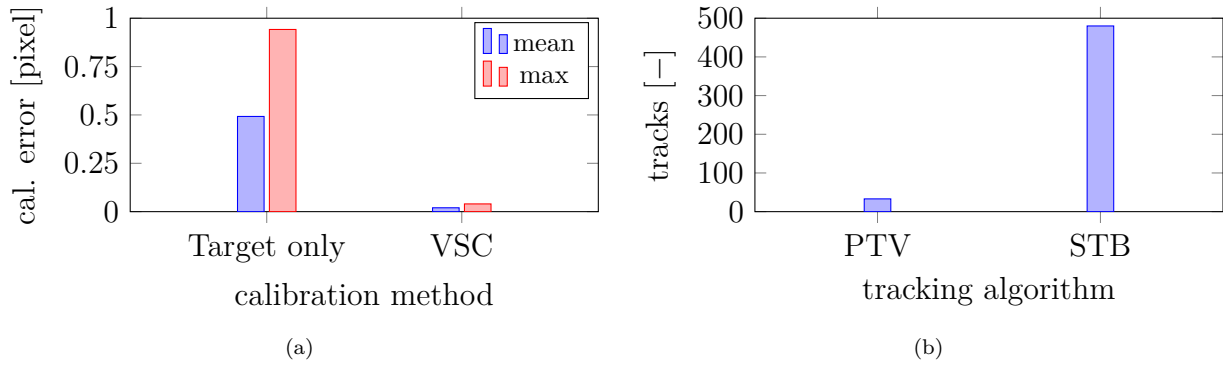


Figure 3. (a) Remaining camera calibration errors after target image-based calibration and VSC. (b) Number of reconstructed and tracked particles for single-shot result shown in fig. 7 depending on reconstruction and particle tracking algorithm.

between local intensity maxima, this approach is suitable to establish a 3D-2D pairing with the present data with a low probability for false pairing as supported by Malik et al. (1993).

After establishing pairing, individual luminescence particle images are segmented from the camera recordings to calculate the recorded image intensity per particle. This is done by combining a region growing algorithm (RGA) (Pal & Pal, 1993) with a 2D Gaussian fit. The RGA is used to mask the pixels corresponding to individual particle images while discriminating any other close-by particle images as shown in fig. 4a and b. To finally obtain the collected luminescence intensity per particle, the pixel patch segmented using the RGA is fitted with a generalized 2D Gaussian function appropriate for diffraction limited imaging (cf. fig. 4c). The fitted Gaussian is then integrated numerically to obtain the imaged intensity. By dividing these values obtained for the same particle from both cameras' (T1 and T2) images, the temperature dependent LIR is computed.

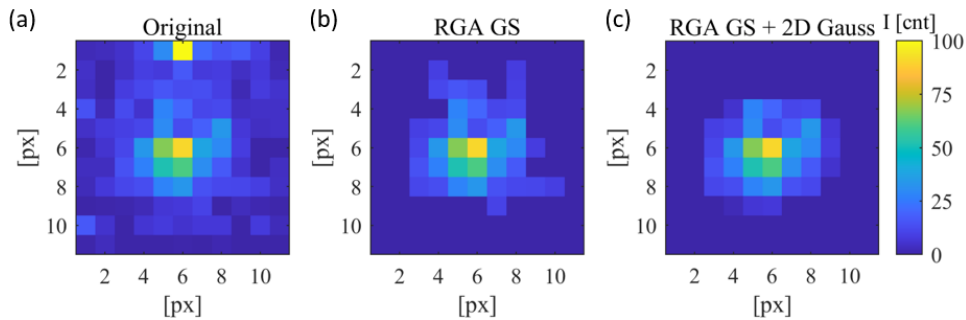


Figure 4. Particle luminescence image recorded by camera T1, after background subtraction (a), segmentation using the region growing algorithm (b), and fitting of a 2D Gaussian (c). Adapted from Stelter (2025) (CC-BY 4.0).

To convert this LIR to temperature, a calibration function is needed. To obtain such a calibration function, dedicated 3D measurements of particle LIR are conducted within a gas flow at known temperatures as detailed in Stelter et al. (2023), forming individual calibration points. Fitting a power law to multiple such calibration points results in a continuous calibration function to con-

vert arbitrary LIRs to temperature as shown in fig. 5.

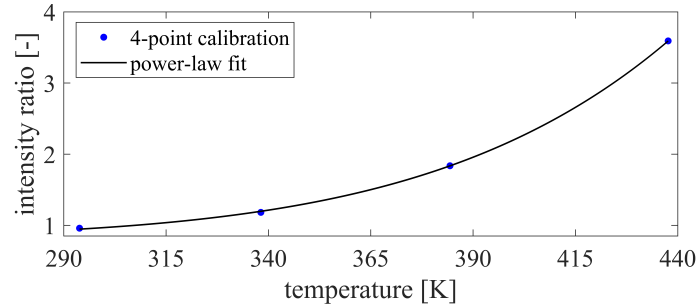


Figure 5. Calibration function obtained from dedicated 3D measurements to convert measured LIRs to temperature values, adapted from Stelter et al. (2023) (CC-BY 4.0).

As Abram et al. (2015) found that the LIR obtained from ZnO is not only dependent on temperature but also on local excitation fluence and potential angular collection non-uniformities of the spectral interference filters mounted on the detectors for radiometric phosphor thermometry, a 3D flat-field correction (FFC) scheme was developed in Stelter (2025) to compensate for these effects. To generate the 3D correction field, dedicated 3D measurements are conducted in the same jet flow as described above but without heating. Hence, LIRs are computed from isothermal flow at ambient temperature where changes in LIR are attributed directly to local laser fluence differences and angular effects in filter transmission. Correction values are computed by combining a 2D FFC within the beam cross-section (yz-plane) to account for laser fluence inhomogeneities with a 1D FFC along the beam propagation direction (x-axis) to account for angular collection non-uniformities. 2D correction values in the yz-plane are shown in fig. 6a, while 1D correction values along the x-axis are shown in fig. 6b. As the jet covers only the central part of the camera field of view, no strong angular effect on the filter transmission profiles is expected with the present data.

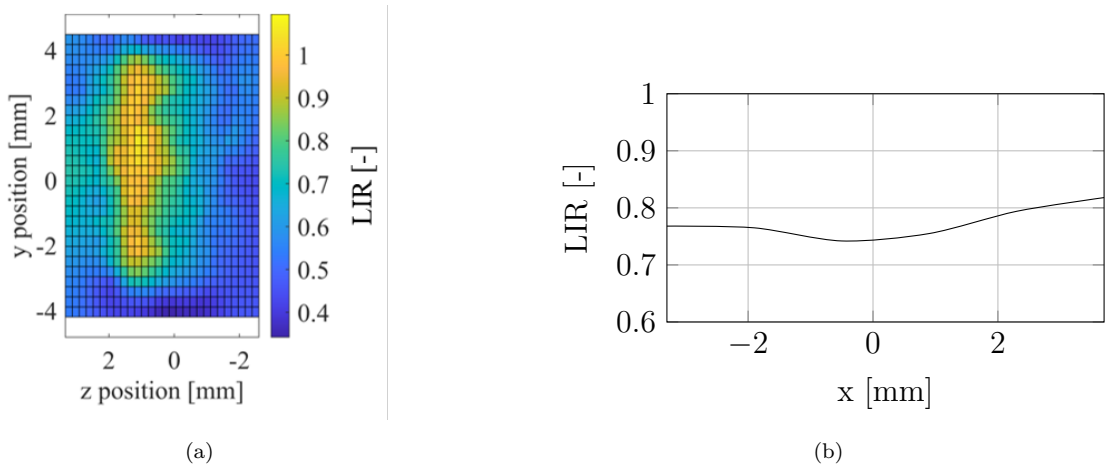


Figure 6. 2D correction field to compensate for spatial laser fluence inhomogeneities (a) and a 1D correction to compensate for angular collection non-uniformities (b). Adapted from Stelter (2025) (CC-BY 4.0).

4. Heated jet measurement results

Results of single-shot and time accumulated measurements in the turbulent gas jet using the improved processing pipeline are shown below in fig. 7 and fig. 8. To obtain these results, images with a low particle seeding density of 0.004 ppp were used. The measurement volume starts one nozzle diameter (4 mm) above the nozzle exit, has a diameter of 8 mm equal to the laser beams' diameters, and stretches the width of the camera image. However, as consistent seeding of both jet and co-flow proved challenging, the results shown here are centred on a small volume above the jet nozzle exit. In the following plots, particles are either plotted in false colours according to their temperature or their axial velocity as this is the predominant velocity component for the chosen jet flow. While more particles could be reconstructed and tracked from Mie scattering images than were available from luminescence images due to different scattering and luminescence cross-sections, here only particles are shown where both temperature and velocity results are available.

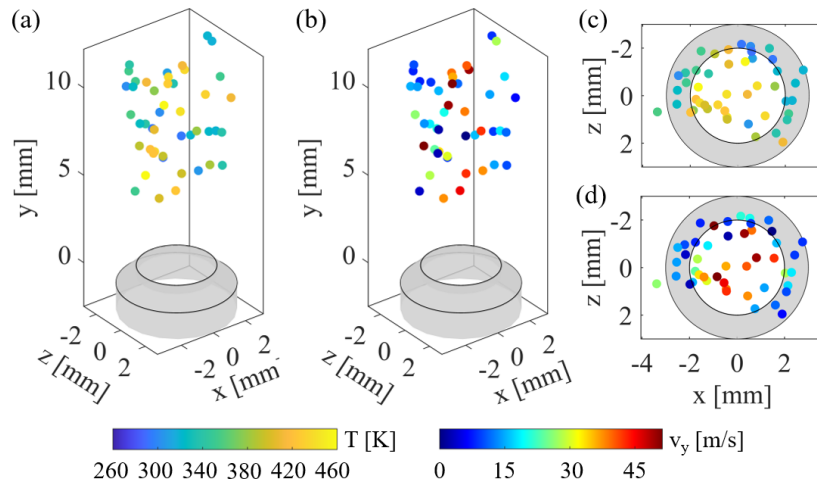


Figure 7. Single-shot temperature (a,c) and velocity (b,d) results, reproduced from Stelter (2025) (CC-BY 4.0).

For the single-shot result shown in fig. 7, 46 individual particles were reconstructed and tracked in a volume of 89 mm^2 . In fig. 7a and c the particles are coloured according to their temperature measured from their luminescence emissions while sub-figures b and d indicate their axial velocity components. As would be expected, particles in the centre of the heated jet are associated with the highest temperature and velocity values. Close to the jet axis, particles are close to the nozzle exit temperature of 433 K and approximately 25 % faster than the bulk velocity.

By accumulating several single-shot results it is possible to obtain time-averaged temperature and velocity distributions within the jet. Such results are plotted in fig. 8, where 6950 individual particle data points are distributed in a volume of $5.6 \times 8 \times 5.6 \text{ mm}^3$. To allow insights into the core structure of the jet flow, the 3D plots of temperature and velocity results in fig. 8a and b are cut-open by showing only particles at positive x -positions, as indicated by green boxes. The ry -plane scatter plots in fig. 8c and d show the expected rotational symmetry in the flow field. The shear

layer between the hot and fast jet and the slower co-flow at ambient temperature is visible at a radial distance from the jet axis of 1.9 mm. As investigated in Stelter (2025), these results are in line with the theoretical flow velocity profile predicted by the 1/7th power-law from Chant (2005). To estimate the temperature and velocity uncertainty in the presented measurements, the root mean squared deviation of both quantities is calculated within a 2.5 mm diameter potential core region around the jet axis, identified as a region with almost constant temperature and velocity, resulting in 28.48 K and 6.14 m s^{-1} , compared to 27.4 K and 4.5 m s^{-1} , respectively, obtained in our original study (Stelter et al., 2023). While both measures increased it should be noted that they include actual turbulent fluctuations of temperature and velocity in the flow.

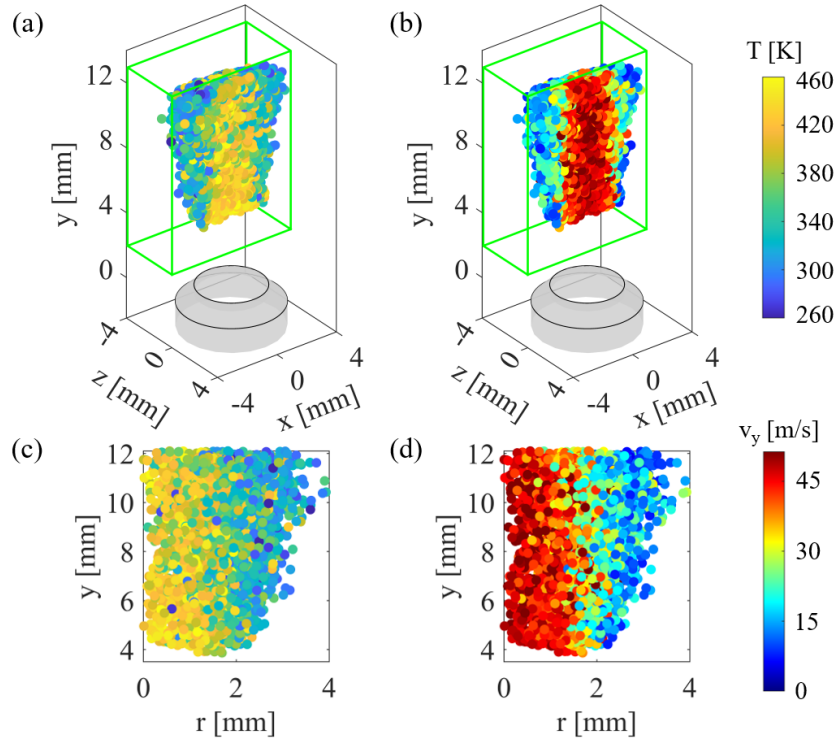


Figure 8. Cumulative temperature (a,c) and velocity (b,d) results, only particles at positive x -position are plotted in (a,b) to reveal the gas jet's internal structure. Reproduced from Stelter (2025) (CC-BY 4.0).

To facilitate a direct comparison of cumulative temperature and velocity results obtained either with the original or with the improved processing pipeline, their temperature and velocity results are plotted side by side in fig. 9. While the number of individual temperature and velocity data points was increased from 3100 to 6950, the qualitative average jet temperature and velocity profiles are similar. However, using the new processing pipeline, the size of the potential jet core in both the temperature and velocity results appears noticeably smaller. Also, slightly higher peak velocities were computed using TP-STB compared to our simpler implementation of 3D-PTV that was used earlier. As TP-STB does not rely on an initial guess from the average flow field for its velocity determination, its results are expected to be a better representative of individual particle velocities. Coming back to the comparison of estimated velocity precision, the apparent increase

when using TP-STB instead of 3D-PTV might be representative of physical velocity fluctuations within the flow, warranting further investigation in upcoming research.

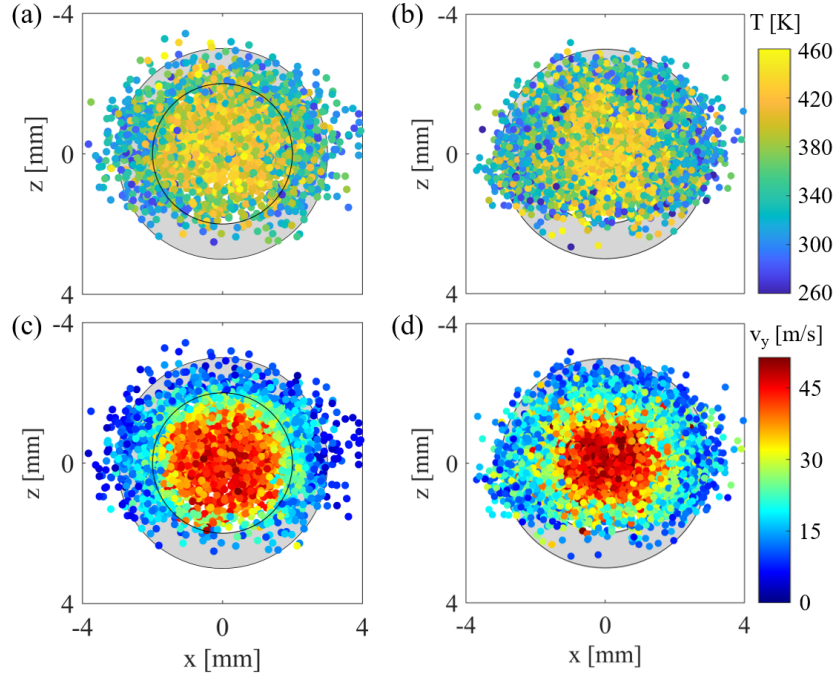


Figure 9. Cumulative temperature (a,b) and velocity (c,d) results, obtained from the same raw data but using either the original processing pipeline from Stelter et al. (2023) (a,c) or the improved processing pipeline (b,d), reproduced from Stelter (2025) (CC-BY 4.0).

5. Conclusions

Simultaneous temperature-velocity measurements in a turbulent gas jet are presented using a combination of state-of-the-art particle reconstruction and tracking using two-pulse shake-the-box and single-particle based phosphor thermometry. Sub-micron ZnO particles are seeded into the flow and act as tracers for both flow properties. Single-shot and cumulative results show the expected temperature and velocity distributions for this rotationally symmetric flow. Compared to earlier results obtained from the same raw data in Stelter et al. (2023), the number of particle data points could be increased by a factor of 2.2 thanks to algorithmic enhancements in data processing, encompassing camera calibration, 3D reconstruction, 3D tracking, and luminescence image segmentation. Yet, for only a quarter of the particles that were reconstructed and tracked a temperature result could be computed, too. This opens up possibilities for future improvements where the number of individual temperature-velocity measurements per snapshot should be increased by increasing the particle seeding density past the current value of approximately 0.004 ppp and equalizing the sample number for temperature and velocity results.

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