

# Phosphorescence-PTV: Simultaneous 3D Temperature and Velocity Measurement

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## ABSTRACT

The simultaneous measurement of temperature and velocity fields is essential for understanding thermo-fluidic systems in which heat transfer and flow structures are strongly coupled. Conventional approaches often rely on separate tracers, intrusive probes, or planar optical measurements, which limits their capability to resolve the three-dimensional and transient interaction between thermal and momentum transport. This work presents a phosphorescence particle tracking velocimetry (Phosphorescence-PTV) methodology for simultaneous three-dimensional temperature and velocity measurement in liquids. The method integrates three technical developments: density-matched phosphorescent tracer particles, decay-based particle intensity reconstruction for lifetime thermometry, and spatial three-dimensional calibration and correction for volumetric measurements.

The tracer particles are phosphorescent PDMS-based microspheres with embedded inorganic phosphor. Their apparent density is adjusted by controlling the particle matrix, phosphor loading, and low-density glass microsphere fillers, enabling improved density matching with liquid working fluids while reducing the particle diameter to 30–50  $\mu\text{m}$ . For temperature retrieval, the phosphorescence lifetime method is adopted rather than a pure intensity-ratio method. A phosphorescent-decay particle tracking strategy reconstructs particle position, spot radius, and intensity from high-speed image sequences. A neural-assisted implementation further improves the extraction of two-dimensional particle position, spot size, and intensity in each camera view.

To extend the method to volumetric measurements, a refractive multi-camera calibration framework is developed for transparent flat-walled vessels with known geometry. The calibration accounts for air–glass–liquid refraction using Snell’s law and joint optimization of camera, vessel, and refractive parameters. In the present flat-wall vessel demonstration, the optimized oil refractive index is  $n = 1.4655$ , with a light-corner distance RMS of 0.02 mm, a maximum reprojection error of 0.19 pixels, and a three-dimensional particle reconstruction RMS below 0.1 mm. A spatial intensity-correction procedure based on the relationship among lens focusing distance, defocus distance, particle spot radius, and recovered intensity is then used to correct particle decay sequences before lifetime fitting. Preliminary measurements of a central high-temperature injection flow in a large cavity demonstrate simultaneous volumetric temperature and velocity reconstruction over a measurement region exceeding  $60 \times 60 \times 80$  mm. The results show that the proposed Phosphorescence-PTV framework is a promising route toward quantitative three-dimensional thermo-velocimetry in liquid flows.

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## 1. Introduction

Temperature and velocity are two of the most fundamental variables in thermo-fluid dynamics. In many natural and engineering flows, neither field can be considered independently. Temperature gradients modify fluid density, viscosity, buoyancy, and local transport properties, while the velocity field determines the convective transport of heat and the deformation of thermal structures. This bidirectional coupling is central to turbulent heat transfer, natural and mixed convection, thermal mixing, rotating-machinery cooling, microfluidic transport, and biological flows. Measurements that capture only one of the two fields, or that acquire temperature and velocity sequentially under non-identical conditions, may miss the instantaneous coupling mechanisms and can lead to incomplete physical interpretations.

Optical diagnostics have played a central role in the development of quantitative flow measurements. Particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are now widely used for non-intrusive velocity measurements, while optical thermometry has been developed through fluorescent dyes, thermographic phosphor materials, and temperature-sensitive particles. Thermographic phosphor thermometry is particularly attractive because phosphorescent emission can provide temperature information through spectral response, intensity ratio, or decay lifetime. The principles, materials, and applications of phosphor thermometry have been reviewed extensively for both high-temperature and fluid-dynamic measurements (Khalid & Kontis, 2008; Yi & Kim, 2014; Abram, Fond, & Beyrau, 2018; Someya, 2021).

Early simultaneous temperature–velocity measurements using phosphorescent tracers were mainly demonstrated in gas-phase or planar configurations. Omrane et al. (2008) demonstrated simultaneous two-dimensional flow velocity and gas temperature measurements using thermographic phosphors. Abram et al. (2013) further showed high-speed planar thermometry and velocimetry using thermographic phosphor particles. Fond et al. (2012) extended this concept to simultaneous temperature, mixture fraction, and velocity imaging in turbulent flows, while Fan et al. (2017) demonstrated two-camera two-dimensional gas-phase temperature and velocity measurements with ZnO tracers. Lee et al. (2016) used BAM:Eu<sup>2+</sup> phosphor thermography combined with PIV to evaluate turbulent heat flux in a round jet. These studies established the feasibility of phosphor-based simultaneous measurement, but most of them were still limited to planar imaging or gas-phase applications.

In liquid flows, the particle requirements become more restrictive because tracer density, particle size, temperature response, and dispersion stability directly influence both thermal and velocity measurements. Someya et al. (2009) reported combined velocity and temperature measurements in oil based on the phosphorescent lifetimes of seeded particles, and Someya et al. (2011) applied temperature-sensitive particles to natural convection measurements. Vogt and Stephan (2012) used microencapsulated temperature-sensitive particles for simultaneous temperature and velocity measurements, providing another route to particle-based thermo-velocimetry. Kim et al. (2017) demonstrated simultaneous measurement of temperature and velocity fields using thermographic phosphor tracer particles. More recently, Cai et al. (2022) developed an adaptive-window lifetime-based thermographic PTV method using a single camera, and Cai et al. (2025) reported fluid density-matched phosphorescent microspheres for liquid-flow temperature-velocity measurement. These studies indicate that particle-based thermometry can be coupled with velocity measurement, but they also reveal the difficulty of balancing phosphorescent signal strength, flow-following performance, and measurement robustness.

Tracer-particle material development is therefore one of the key challenges. ZnO thermographic phosphor particles have been used for high-precision flow temperature imaging (Abram, Fond, & Beyrau, 2015), and BAM:Eu<sup>2+</sup> particles have been characterized as tracers for thermographic PIV (Fond, Abram, & Beyrau, 2015). Xuan et al. (2023) further demonstrated high-spatial-resolution fluid thermometry in boundary-layer measurements using individual phosphor tracer particles. However, many inorganic phosphor particles have densities much larger than those of common liquid working fluids. In low-speed liquids, density mismatch can cause sedimentation, particle slip, and biased velocity reconstruction. This motivates the development of density-adjustable phosphorescent tracer particles that can provide sufficient phosphorescence intensity while maintaining acceptable flow-following behavior.

A second challenge is the recovery of phosphorescence decay curves from moving particle images. The phosphorescence lifetime method is attractive because it determines temperature from the temporal decay rate rather than from an absolute intensity level, and it can therefore be less sensitive to excitation and detection non-uniformity than pure intensity-based approaches (Fuhrmann, Brübach, & Dreizler, 2013). However, lifetime thermometry requires an accurate intensity-time history of the same particle. When a particle moves across a pixel grid, the maximum pixel value fluctuates with sub-pixel position even if the true phosphorescence intensity follows a smooth exponential decay. Fan et al. (2021) proposed a high-resolution velocimetry technique based on decaying streaks of phosphor particles, showing that the decay process itself can be exploited for particle tracking. Luan et al. (2025) developed a phosphorescent-decay particle

tracking method based on Gaussian intensity optimization to reconstruct particle position and intensity more accurately for simultaneous temperature and velocity measurements.

A third challenge is volumetric reconstruction. Three-dimensional particle tracking has advanced rapidly through double-frame and time-resolved PTV methods, including non-iterative double-frame tracking (Fuchs, Hain, & Kähler, 2017), high-seeding-density tomographic PTV (Cornic, Leclaire, Champagnat, & Le Besnerais, 2020), and open-source particle-tracking implementations such as Part2Track (Janke, Schwarze, & Bauer, 2020). For phosphor-based thermo-velocimetry, Massing et al. (2018) demonstrated volumetric temperature and velocity measurement in microfluidics based on phosphorescence lifetime imaging, and Stelter et al. (2023) reported thermographic three-dimensional PTV for turbulent gas flows. These studies show that volumetric phosphor-particle measurements are feasible, but macroscopic liquid measurements through transparent tank walls require additional treatment of refraction, defocus, and spatial intensity variation.

Despite this progress, a general route toward macroscopic three-dimensional simultaneous temperature–velocity measurement in liquids remains challenging. The present work addresses this gap by integrating density-matched phosphorescent tracer particles, decay-based particle intensity reconstruction, neural-assisted particle characterization, refractive multi-camera calibration, and spatial intensity correction. The objective is not simply to attach a temperature value to conventional PTV tracks, but to establish a consistent processing chain in which the same phosphorescent particle provides three-dimensional position, velocity, phosphorescence decay history, and temperature.

## 2. Measurement Principle of Phosphorescence-PTV

The proposed method is based on temperature-sensitive phosphorescent tracer particles. After pulsed ultraviolet excitation, a particle emits phosphorescence whose intensity decays with time. For a single-exponential approximation, the decay can be written as

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right) + I_b \quad (1)$$

where  $I(t)$  is the measured phosphorescence intensity,  $I_0$  is the initial intensity after excitation,  $I_b$  is the background intensity, and  $\tau$  is the phosphorescence lifetime. The lifetime  $\tau$  depends on temperature through a calibration relation,

$$T = f(\tau) \quad (2)$$

where the exact calibration function depends on the phosphor material and the working temperature range. Once the lifetime is determined from the decay sequence of an individual particle, the particle temperature can be obtained from the calibration curve. Meanwhile, the

motion of the same particle provides its velocity. If the three-dimensional particle position is denoted by  $X(t)$ , the particle velocity can be estimated by finite differences or by higher-order trajectory differentiation when longer track segments are available.

The central advantage of this concept is that temperature and velocity are obtained from the same tracer particle. In conventional combined PIV–scalar thermometry measurements, the scalar and velocity information may come from different tracers or different optical signals. In Phosphorescence-PTV, the particle trajectory and its decay sequence are linked directly. This makes the method suitable for studying local heat transport, thermal plume evolution, and transient mixing where the correlation between temperature and velocity is essential.

The processing workflow is shown in **Figure 1**. Phosphorescent particles are excited by pulsed ultraviolet light and imaged by multiple high-speed cameras. In each camera view, particles are identified and their two-dimensional position  $(x, y)$ , spot radius  $\sigma$ , and intensity  $I$  are extracted. Planar particle tracks are formed in each camera view using motion prediction. Each two-dimensional track is tagged with its intensity and spot-radius sequence. Multi-view matching and refractive ray reconstruction are used to obtain three-dimensional tracks. Each three-dimensional track is associated with intensity and radius sequences from multiple camera views. The relationship among focusing distance  $L$ , defocus distance  $d$ , spot radius  $\sigma$ , and intensity  $I$  is used to correct view-dependent intensity sequences. Exponential fitting is applied to corrected decay sequences, and temperatures reconstructed from reliable views are averaged after consistency checking. For visualization, particle-level temperatures and velocities can be displayed as color-coded scatter plots, spatial arrow plots, or voxelized fields obtained by moving-window Gaussian averaging. This preserves the Lagrangian nature of the measurement while enabling field-level interpretation.

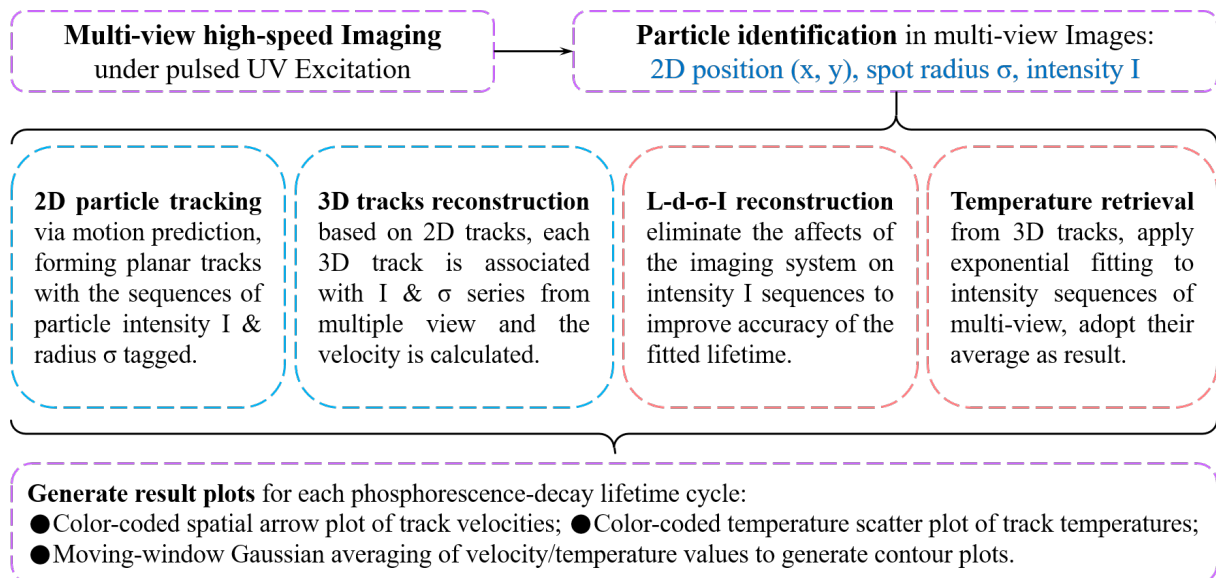


**Figure. 1** Processing workflow for volumetric Phosphorescence-PTV.

### 3. Development of Density-Matched Phosphorescent Tracer Particles

Tracer particles for simultaneous temperature and velocity measurement must satisfy stricter requirements than conventional PIV tracers. For velocity measurement, the particle should follow the flow with minimal slip. This requires a small particle diameter, low inertia, and density close to that of the working fluid. For temperature measurement, the particle must emit a sufficiently strong phosphorescence signal, exhibit a repeatable temperature-dependent lifetime, and respond rapidly to local fluid temperature changes. For three-dimensional measurements, the particle must also be optically detectable from multiple directions and should remain well dispersed over the duration of the experiment.

Inorganic thermographic phosphors such as ZnO, BAM:Eu, YAG-based phosphors, and MFG-based phosphors have been used for temperature measurement in gases and liquids (Abram et al., 2015; Fond et al., 2015; Kim et al., 2017; Xuan et al., 2023). However, many inorganic phosphor powders are significantly denser than liquid working fluids. In low-speed liquid flows, direct use of such powders can lead to gravitational settling and poor flow tracking. This is especially problematic for volumetric PTV, because particle trajectories are used not only to visualize flow structures but also to assign temperatures to moving fluid parcels. Density mismatch would therefore bias both the velocity and temperature interpretation.

To address this issue, Cai et al. (2025) developed density-matched phosphorescent microspheres based on a PDMS matrix containing inorganic phosphor material, as shown in **Figure 2**. The present work builds on that strategy and further extends it for volumetric Phosphorescence-PTV. The particle concept uses PDMS as a mechanically stable and optically compatible matrix, while Mg<sub>4</sub>FGeO<sub>6</sub>:Mn phosphor is incorporated as the temperature-sensitive component. The effective particle density can be adjusted by changing the matrix composition, phosphor loading, and low-density inclusions. The resulting particle can act as both a flow tracer and a temperature-sensitive probe.

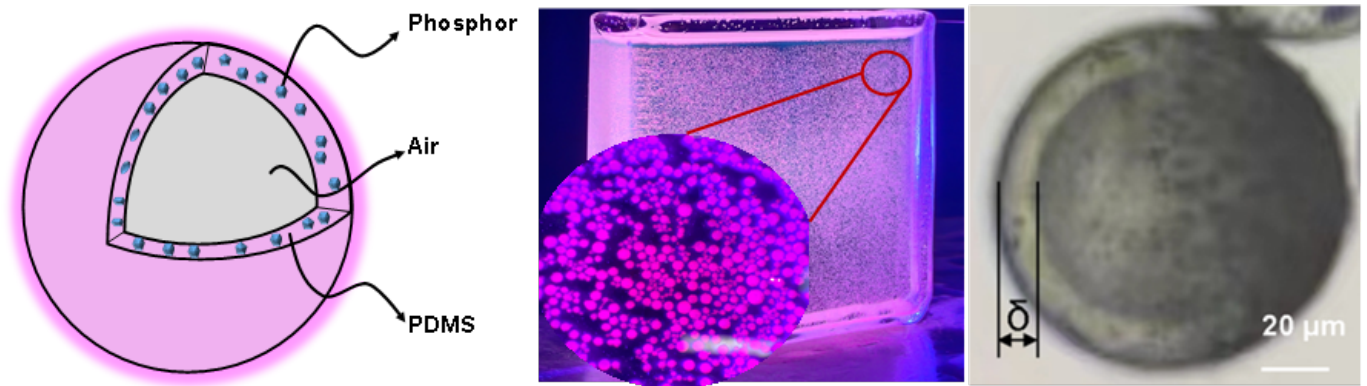


**Figure. 2** Characterization of the prepared phosphorescent tracer particles.

The microspheres are prepared through an emulsion-based process combined with thermal curing. A mixture containing PDMS and phosphorescent material is emulsified into droplets and subsequently cured. The final particle size and density depend on emulsification time, stirring speed, curing condition, and material formulation. This preparation route is flexible and can produce particles suitable for liquid working fluids such as oils used in thermal mixing experiments.

Experimental studies on the preparation process show that increasing emulsification time reduces the average particle diameter. For example, when the emulsification time was increased from 10 min to 100 min, the mean particle diameter decreased from 119.20  $\mu\text{m}$  to 65.92  $\mu\text{m}$ . Similarly, increasing stirring speed from 2000 rpm to 3000 rpm reduced the mean diameter from 112.08  $\mu\text{m}$  to 87  $\mu\text{m}$ . Under a representative condition of 2500 rpm and 30 min, the mean particle diameter was 93.15  $\mu\text{m}$  and the estimated average density was 0.919 g/cm<sup>3</sup>.

The previously reported density-adjustable phosphorescent microspheres had diameters of 57–120  $\mu\text{m}$  and theoretical average densities ranging from 0.58 to 3.2 g/cm<sup>3</sup>, covering the density range required for many liquid working fluids (Cai et al., 2025). The working temperature range was 0–200 °C, and numerical heat-transfer analysis indicated a temperature response time within 1.41 ms. In a hot–cold liquid mixing demonstration, the average temperature error relative to thermocouple measurements was 1.575%, indicating that the particles can provide temperature information while maintaining flow-tracing capability in low-speed thermal liquid flows.

In the current development, low-density glass microsphere fillers are introduced to further improve density regulation and reduce particle size. This modification preserves the general emulsion-curing route but increases the flexibility of density control. Using this strategy, the particle diameter has been reduced to 30–50  $\mu\text{m}$  while maintaining the density-matching concept. This size range is more suitable for three-dimensional PTV because smaller particles have lower inertia, reduce image overlap, and improve the probability of resolving individual particles in multi-camera images. At the same time, the particles remain sufficiently bright for lifetime-based

phosphorescence measurement when combined with high-speed imaging and optimized excitation.

The development of these particles is essential for the proposed method. Density matching improves the physical validity of the reconstructed velocity field, while the phosphorescence signal provides temperature information. The smaller particle size also supports volumetric measurements with a larger number of trackable particles and reduces the risk that particle inertia distorts the coupled temperature–velocity interpretation.

#### **4. Decay-Based Temperature Reconstruction and Neural-Assisted Particle Characterization**

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Phosphorescence-based temperature measurement can be performed using intensity-ratio methods or lifetime methods. Intensity-ratio methods are experimentally convenient, but they remain sensitive to spatially varying excitation, view-dependent collection efficiency, optical-path changes, and camera response. These effects become more severe when particles move in a three-dimensional volume. In contrast, the phosphorescence lifetime method determines temperature from the temporal decay rate of the phosphorescent signal. Since the lifetime is obtained from the shape of the decay curve, it provides a more self-referenced basis for temperature retrieval, provided that the intensity sequence of the same moving particle can be accurately reconstructed (Fuhrmann et al., 2013; Luan et al., 2025).

A phosphorescent-decay particle tracking (PDPT) method was previously developed to address this problem (Luan et al., 2025). The method treats the particle image as a discretized two-dimensional Gaussian light spot. Instead of assuming that the maximum pixel value is the particle intensity, the pixel intensity is modeled as the integral of a Gaussian distribution over the pixel area. The unknown parameters include the particle center ( $x, y$ ), the spot radius  $\sigma$ , and the particle intensity  $I$ . By minimizing the residual between measured pixel values and the integrated Gaussian model, the method reconstructs particle parameters more accurately than simple maximum-intensity extraction. Comparison of PDPT intensity tracking with other methods are shown in **Figure 3**.

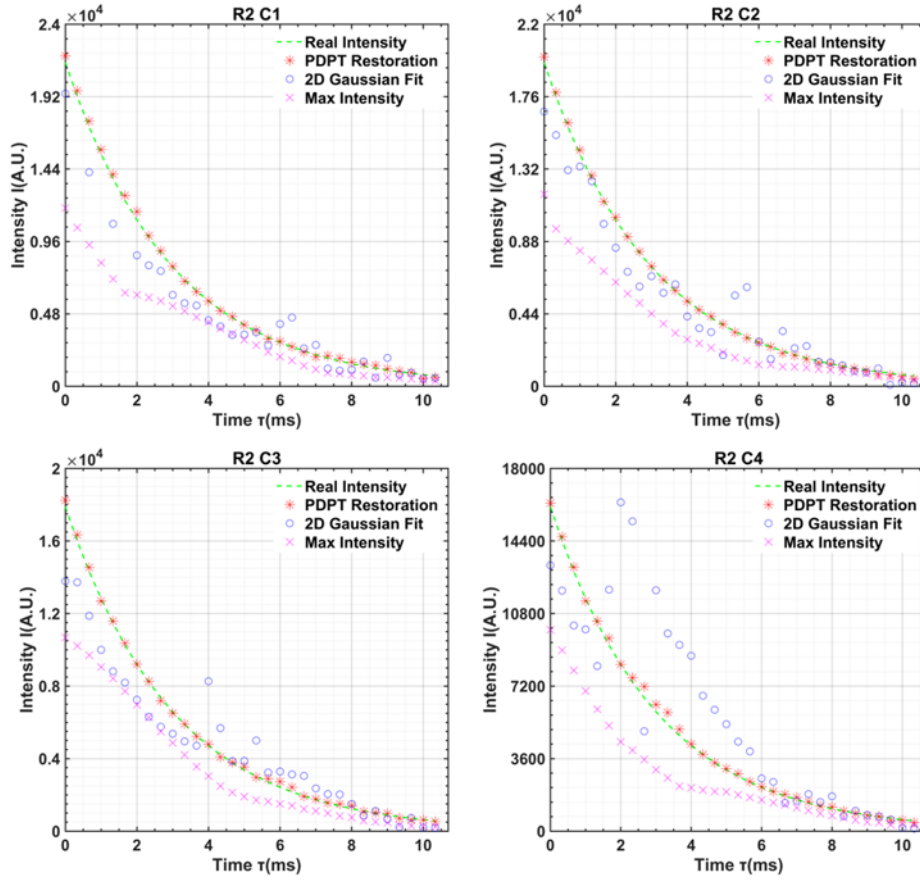


**Figure. 3** Representative intensity-time plot of different phosphorescent particles with varying initial intensity.

The reconstructed intensity sequence is then linked across frames using particle tracking. For each particle, the method obtains a sequence of positions and intensities during one phosphorescence decay event. The position sequence provides particle motion, while the intensity sequence is fitted by an exponential decay function to determine the phosphorescence lifetime. This approach combines PTV and lifetime thermometry at the single-particle level.

The previously reported validation showed that the method significantly reduces both position and intensity errors. In numerical tests, the relative trajectory error remained below 0.25% at a particle velocity of 200 pixel/s. For temperature reconstruction at 473 K, the relative temperature error was below 0.05%, while conventional two-dimensional Gaussian fitting and maximum-intensity extraction produced larger errors. In a hypothermal injection-flow experiment, the method also provided more tracked particles and more uniform temperature and velocity distributions than conventional methods (Luan et al., 2025). These results demonstrate that accurate intensity reconstruction is essential for lifetime-based particle thermometry.

For three-dimensional measurements, particle identification must be performed in multiple high-speed camera views over many frames. A purely iterative nonlinear optimization for every particle in every view can become computationally expensive. In addition, the optimization may become

unstable when particle images overlap or when signal-to-noise ratio is low. To improve efficiency and robustness, a neural-assisted particle characterization procedure is introduced.

The current implementation uses small particle image patches, typically 5×5 pixels, as input. A convolutional neural network is trained on synthetic particle images generated using the same Gaussian-integral imaging model as the physics-based reconstruction. The network predicts the particle center coordinates and spot radius. In its basic form, the model can also output intensity, but for the present processing chain a more physically constrained approach is adopted: the network is used mainly to estimate the nonlinear geometric parameters  $(x, y, \sigma)$ , while the intensity is subsequently solved by least squares.

This separation is advantageous because intensity enters the image model linearly once  $x$ ,  $y$ , and  $\sigma$  are known. Let  $g_i$  be the background-corrected gray value of the pixel  $i$  in a particle patch, and let  $\Phi_i(x, y, \sigma)$  be the normalized Gaussian integral over that pixel. The image model can be written as

$$g_i = I\Phi_i(x, y, \sigma) + b + \varepsilon_i \quad (3)$$

where  $b$  is a local background term and  $\varepsilon_i$  is residual noise. With  $x$ ,  $y$ , and  $\sigma$  fixed,  $I$  and optionally  $b$  can be obtained from linear least squares:

$$(I, b) = \arg \min \sum_i [g_i - I\Phi_i(x, y, \sigma) - b]^2 \quad (4)$$

This strategy combines the speed of neural-network inference with the physical consistency of Gaussian-integral intensity reconstruction. It also avoids requiring the neural network to learn absolute intensity under all possible noise and background conditions.

A further improvement is applied to the spot radius  $\sigma$ . In real particle tracks, the frame-by-frame estimate of  $\sigma$  may fluctuate because of noise, defocus, and partial overlap. Since the spot radius should vary smoothly along a track, it can be stabilized using a trajectory-level procedure. One option is to compute a brightness-weighted radius from the track. Another option, used in the current processing workflow, is to supply an externally determined framewise  $\sigma$  sequence and solve the intensity for each frame with that  $\sigma$ . In this case, the method does not force all frames to share a single locked spot radius; instead, the framewise radius is used directly in the least-squares intensity reconstruction. This is important for three-dimensional measurements because  $\sigma$  also contains information about defocus.

In the volumetric system, each camera view first produces its own two-dimensional particle detections, denoted by  $(x, y, \sigma, I)_k$ , where  $k$  is the camera index. These detections are linked into planar tracks by motion prediction. Each planar track contains a sequence of positions, intensities, and spot radii. The tracks are then combined across views to form three-dimensional trajectories. For temperature retrieval, the intensity sequence must be corrected for spatial optical effects before lifetime fitting. After correction, the intensity sequence in each reliable camera view is fitted by the

exponential decay model. If multiple camera views provide valid decay sequences for the same three-dimensional track, the fitted temperatures are averaged after outlier rejection.

## 5. Spatial Three-Dimensional Calibration, Correction, and Processing

Extending phosphorescence lifetime thermometry from a plane to a three-dimensional volume introduces several optical challenges. In a planar measurement, the particles are usually close to a fixed imaging plane and the optical response can be approximated as constant over a limited region. In a volumetric measurement, particles move through depth and are viewed from multiple directions. The measured intensity of a particle is therefore not determined solely by its phosphorescence decay. It is also affected by defocus, lens focusing distance, excitation non-uniformity, camera sensitivity, wall refraction, and optical path geometry.

Compared with conventional volumetric PTV, phosphorescence-based volumetric measurement requires that each reconstructed particle track also carries a reliable optical decay history. Existing three-dimensional PTV methods mainly focus on geometric reconstruction and trajectory formation from multi-view images (Fuchs et al., 2017; Cornic et al., 2020; Janke et al., 2020). For phosphor-particle thermometry, the reconstruction problem is coupled with temperature retrieval because the particle image intensity and spot size vary with defocus and viewing geometry. Previous volumetric phosphor-particle measurements in microfluidic and gas-flow environments demonstrate the feasibility of this direction (Massing et al., 2018; Stelter et al., 2023), but measurements in macroscopic liquid tanks require explicit treatment of refraction through transparent walls and position-dependent intensity correction.

For lifetime thermometry, although it is less sensitive to absolute intensity than a single-frame intensity method, a decay curve can still be distorted if the particle moves significantly during the decay period and its apparent intensity changes because of imaging geometry. This is especially important when particles are tracked in three dimensions over a large measurement volume.

The present method therefore introduces a hierarchical correction strategy. First, each camera image is processed to reconstruct particle position, spot radius, and intensity using the neural-assisted Gaussian-integral approach. Second, the particle tracks are reconstructed in three-dimensional space using refractive multi-camera calibration. Third, the relationship among lens focusing distance  $L$ , defocus distance  $d$ , particle spot radius  $\sigma$ , and particle intensity  $I$  is used to correct the intensity sequence. Fourth, exponential lifetime fitting is applied to corrected intensity sequences from multiple views, and the final particle temperature is obtained by averaging reliable view-level temperature estimates.

A key part of the spatial correction is the experimental relationship among particle intensity, spot radius, and defocus optical distance. The particle image is approximated as a Gaussian spot. When the particle moves away from the focal plane, the image spot radius increases and the peak intensity decreases. For particles near the focal plane, the relationship between spot radius and defocus optical distance can be described by a quadratic function:

$$\sigma = A(L)d^2 + B(L) \quad (5)$$

where  $d$  is the particle defocus distance relative to the focal plane,  $L$  is the lens focusing distance, and  $A(L)$  and  $B(L)$  are calibration parameters. The intensity variation with defocus can be described by a Gaussian-type function:

$$I = C(L) \exp \left[ -\frac{d^2}{2D(L)^2} \right] \quad (6)$$

where  $C(L)$  is the in-focus intensity coefficient and  $D(L)$  characterizes the width of the intensity-defocus response.

Experiments with a Nikon AF 60 mm F/2.8 lens, operated at F/5.6 in the present measurements, show that the spot radius follows the quadratic defocus relation close to the focal plane, while the intensity follows the expected Gaussian-type decay with defocus. The dependence of intensity on focusing distance is comparatively weak over the current working range; a 20 mm change in focusing distance leads to less than 5% intensity variation. Therefore, for the present experimental configuration, the dominant correction is associated with defocus rather than with long-range propagation loss. Additional checks indicate that particle phosphorescence is sufficiently close to isotropic for the present correction model and that visible-light absorption in the oil over the experimental path length is negligible.

The corrected intensity can be conceptually written as:

$$I_{corr}(t) = \frac{I_{raw}(t)}{G[L, d(t)]} \quad (7)$$

where  $G$  is the calibrated spatial response function. In practice,  $d(t)$  can be estimated from the reconstructed three-dimensional particle position and camera geometry. The raw intensity distribution with a fixed  $L=400\text{mm}$  and the  $d(t)$  represented as  $\Delta z$  is shown in **Figure 4**.

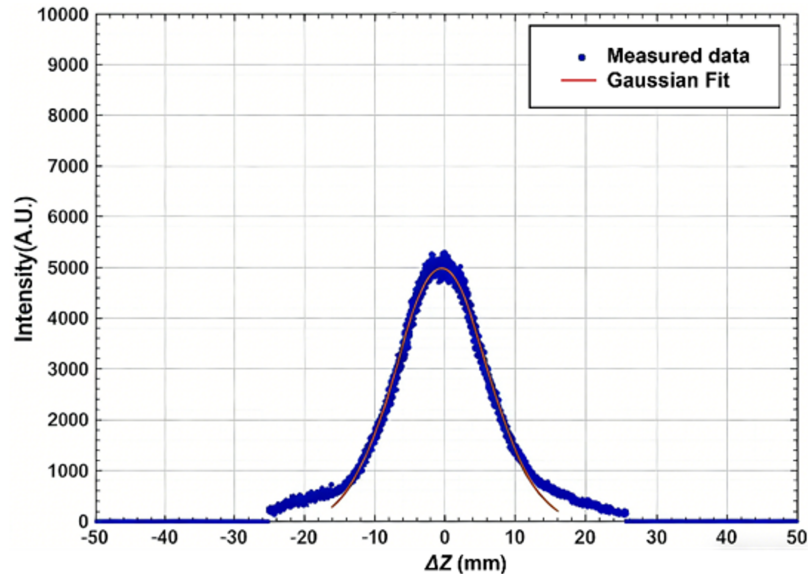


**Figure. 4** The change of particle intensity as it moves out of focus:  $\Delta z = 0$  corresponds to the focal plane

Three-dimensional reconstruction requires accurate mapping between image coordinates and physical space. In the present system, four high-speed cameras observe a liquid-filled transparent vessel. The optical path from a particle to a camera passes through liquid, a quartz-glass wall, and air. Refraction at the liquid–glass and glass–air interfaces invalidates a simple pinhole-camera reconstruction if it is not explicitly modeled. Therefore, a refractive multi-camera calibration framework is developed for transparent flat-walled vessels whose wall geometry and refractive indices are known or can be estimated.

The calibration begins with conventional multi-camera calibration in air to determine camera intrinsics and relative poses. The flat-wall vessel geometry is then introduced. In the present demonstrator, the vessel is made of JGS2 quartz glass with a wall thickness of 3 mm. The external opposite-face distance is 206.3 mm, and the external side length is 85.33 mm. The refractive index of air is taken as 1.0, and the refractive index of JGS2 glass is taken as 1.4585. The refractive index of the oil is treated as an optimization variable because it may differ from nominal values because of temperature, wavelength, or composition.

For each observed calibration-board corner, the corresponding camera pixel is back-projected into a ray in air. This ray is traced through the glass wall and into the oil using Snell's law at each interface, as shown in **Figure 5**. The residual is defined as the distance between the refracted ray in the liquid and the known three-dimensional corner point on the calibration board. The joint optimization minimizes the total point-to-refracted-ray distance over all cameras, all board poses, and all detected corners. The current calibration uses 17 immersed calibration-board poses, a square size of 4.5 mm, and camera C2 as the reference camera. The optimized oil refractive index is  $n = 1.4655$ . The joint calibration achieves a light-corner distance RMS of 0.02 mm and a maximum

reprojection error of 0.19 pixels. Based on the calibrated refractive model, the three-dimensional particle reconstruction RMS is below 0.1 mm.

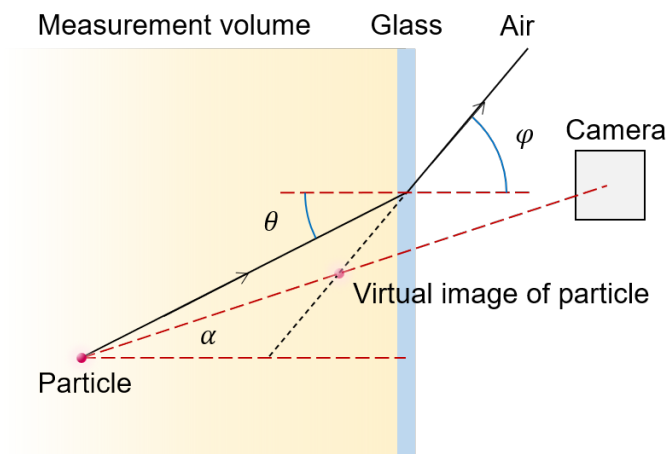


**Figure. 5** Refractive ray-tracing concept for transparent flat-walled vessels.

The full volumetric processing chain starts with multi-view high-speed imaging under pulsed ultraviolet excitation. Each camera records phosphorescent particle images following each excitation pulse. The particle identification step extracts two-dimensional particle position, spot radius, and intensity in each view. Two-dimensional particle tracking is then performed in each camera view by motion prediction, forming planar tracks that carry time sequences of intensity and spot radius. The planar tracks from multiple views are combined through the refractive calibration model. Instead of intersecting straight pinhole rays, the method intersects refracted rays in the liquid domain. Candidate multi-view matches are evaluated using minimum ray distance and temporal consistency. A valid three-dimensional track is associated with intensity and radius sequences from multiple camera views.

For each three-dimensional track, velocity is calculated from the physical position sequence. Temperature retrieval is performed over each phosphorescence-decay lifetime cycle. Raw intensity sequences are corrected using the  $L-d-\sigma-I$  reconstruction model to reduce the effect of imaging geometry. Exponential fitting is then applied to the corrected intensity sequences. When multiple camera views provide valid temperature estimates for the same three-dimensional track, the estimates are averaged after rejecting inconsistent values. The final visualization includes color-coded spatial arrow plots of track velocities, color-coded scatter plots of track temperatures, and voxelized fields generated by moving-window Gaussian averaging.

## 6. Experimental Demonstration

The integrated Phosphorescence-PTV method was evaluated in a central high-temperature injection flow in a large cavity. This configuration was selected because it produces a clear three-

dimensional thermal and velocity structure while remaining experimentally controllable. The working fluid in the cavity was initially at room temperature (20 °C). A high-temperature fluid stream at 100 °C was injected into the cavity through a circular orifice with a diameter of 6 mm. The orifice was located along the axis of the transparent vessel and initially positioned approximately 2 mm below the free liquid surface. The injection speed was adjustable over the range of 10–100 mm/s.

The measurement volume exceeded 60×60×80 mm in the x, z, and y directions, respectively. Four high-speed cameras were synchronized with the pulsed ultraviolet excitation sequence. The reconstructed particles were processed through the complete workflow described above: multi-view image acquisition, neural-assisted particle identification, two-dimensional tracking, refractive three-dimensional reconstruction, intensity–defocus correction, lifetime fitting, and voxelized visualization.

For the current demonstration, the purpose was to verify that the complete processing chain can operate in a macroscopic liquid-flow experiment. The experiment therefore emphasizes three aspects: whether refractive multi-view reconstruction can provide stable three-dimensional tracks, whether corrected phosphorescence intensity sequences can be fitted to retrieve temperature, and whether the resulting particle-level temperature and velocity information can be converted into interpretable volumetric fields. A complete uncertainty budget remains a subject of ongoing work.

## 7. Results and Discussion

The particle-development results provide the physical basis for the measurement. Earlier density-adjustable phosphorescent microspheres had diameters of 57–120 μm and a theoretical density-adjustment range of 0.58–3.2 g/cm<sup>3</sup> (Cai et al., 2025). The present low-density glass microsphere strategy further reduces particle diameter to 30–50 μm. This reduction is important for volumetric PTV because smaller tracers reduce inertial bias and improve particle separation in multi-view images. At the same time, the particles retain sufficient phosphorescence intensity for lifetime-based thermometry under pulsed UV excitation.

The decay-reconstruction results confirm that intensity restoration is a critical part of phosphorescence lifetime thermometry. Maximum-intensity extraction underestimates the true particle intensity and introduces fluctuations caused by the particle's sub-pixel position. Conventional two-dimensional Gaussian fitting reduces this error but becomes unstable for small particle images. The previously developed phosphorescent-decay particle tracking method reduces both trajectory and intensity fluctuations. In the reported injection-flow validation, the method tracked more particles and provided smoother temperature and velocity distributions

than maximum-intensity extraction and conventional Gaussian fitting (Luan et al., 2025). The neural-assisted version preserves the same physical image model but accelerates the parameter extraction process for multi-view datasets.

The refractive calibration results show that physical ray tracing is necessary and effective for liquid measurements through flat transparent walls. The optimized refractive index of the working oil was  $n = 1.4655$ . The joint calibration produced a light-corner distance RMS of 0.02 mm and a maximum reprojection error of 0.19 pixels. The resulting three-dimensional particle reconstruction RMS was below 0.1 mm. These values indicate that the calibrated refractive model is sufficiently accurate for the current measurement volume and provides a quantitative basis for assigning temperature information to reconstructed three-dimensional tracks.

The preliminary volumetric measurement shows a clear central injection structure. The reconstructed temperature voxel field reveals a warm core extending from the injection region into the surrounding cooler liquid. The speed voxel field, expressed in mm/s, shows a high-speed core associated with the injected stream and surrounding entrainment structures. The spatial correspondence between the warm region and the high-speed region indicates that the method captures coupled thermal and velocity features from the same phosphorescent particle trajectories. This is a key distinction from methods that combine temperature and velocity from different tracers or from separate measurements.

The voxel fields are generated from particle-level measurements using moving-window Gaussian averaging, and the temperature and velocity voxel fields are shown in **Figure 6 a)** and **b)** respectively. This produces smoother three-dimensional fields while retaining the underlying Lagrangian information. The approach allows the user to switch between two complementary views: particle-track analysis for local thermo-fluidic events and volumetric field visualization for global flow organization. In the present demonstration, the reconstructed volume exceeds  $60 \times 60 \times 80$  mm, which is substantially larger than typical microscopic phosphorescence lifetime measurements and illustrates the scalability of the method toward macroscopic liquid-flow diagnostics.

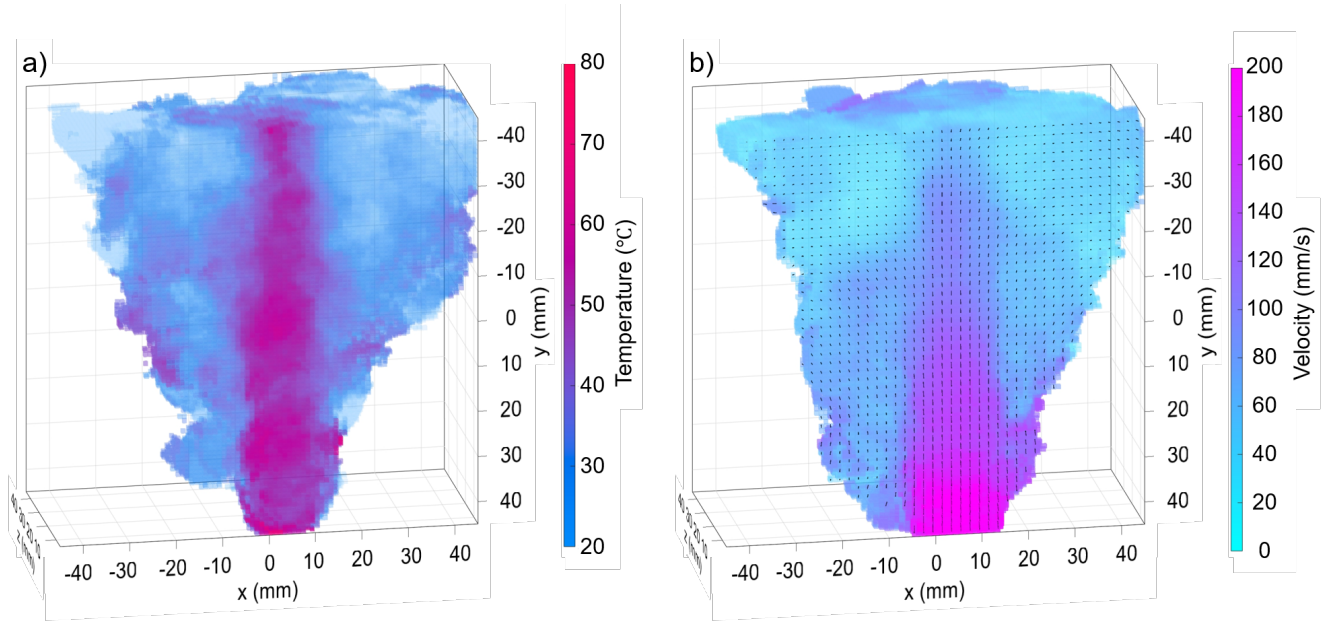


**Figure. 6** Volumetric reconstruction of a central high-temperature injection flow in a large cavity: **a)** temperature voxel field and **b)** speed voxel field.

The proposed framework also clarifies the role of spatial intensity correction. Lifetime thermometry is often described as less sensitive to absolute intensity, but this does not mean that all imaging effects can be ignored. If a particle moves through a large depth range during a decay sequence, defocus-dependent intensity changes can distort the decay shape. The L-d- $\sigma$ -I correction reduces this error by linking the recovered spot radius and three-dimensional position to an experimentally measured optical response. The use of  $\sigma$  as both an image-characterization parameter and a defocus indicator is therefore a key feature of the method.

Several limitations remain. First, the present volumetric results are preliminary, and a full uncertainty analysis is still required. Contributions from calibration error, refractive-index uncertainty, particle localization error, lifetime fitting error, and intensity-correction residuals should be quantified separately. Second, particle overlap and high seeding density remain challenging for particle identification and tracking. Third, the temperature retrieval currently depends on the availability of sufficiently long and reliable decay sequences. Very fast flows or weak phosphorescence signals may reduce the number of usable tracks. Fourth, the temperature dependence of the refractive index may become important in flows with large temperature gradients and should be incorporated in future calibration models.

Despite these limitations, the method provides a coherent path toward three-dimensional simultaneous temperature and velocity measurement in liquids. Density-matched phosphorescent particles improve the physical validity of velocity tracking. Decay-based intensity reconstruction provides robust single-particle lifetime thermometry. Refractive calibration enables quantitative multi-view reconstruction through transparent flat walls. Spatial correction reduces view-

dependent and defocus-dependent intensity bias. The integration of these components makes Phosphorescence-PTV promising for thermal jets, convective plumes, stratified mixing, cooling flows, and other thermo-fluidic systems where three-dimensional coupling is essential.

## 8. Conclusions

A Phosphorescence-PTV method for simultaneous three-dimensional temperature and velocity measurement in liquid flows has been developed and demonstrated. The method integrates density-matched phosphorescent tracer particles, decay-based particle intensity reconstruction, neural-assisted particle characterization, refractive multi-camera calibration, and spatial intensity correction.

First, density-matched phosphorescent tracer particles provide the physical basis for simultaneous thermo-velocimetry. PDMS-based phosphorescent microspheres can be density-tuned for liquid applications, and the current incorporation of low-density glass microsphere fillers enables further particle miniaturization to 30–50  $\mu\text{m}$ .

Second, accurate decay-based intensity reconstruction is essential for lifetime thermometry with moving particles. The phosphorescent-decay particle tracking method and its neural-assisted extension recover particle position, spot radius, and intensity more reliably than maximum-intensity extraction or conventional Gaussian fitting. The current processing strategy uses neural estimation for nonlinear particle parameters and least-squares reconstruction for intensity.

Third, a refractive multi-camera calibration framework was developed for transparent flat-walled vessels with known geometry. By tracing rays through air, quartz glass, and liquid, and by optimizing the oil refractive index, the calibration achieved an oil refractive index of  $n = 1.4655$ , a light-corner distance RMS of 0.02 mm, a maximum reprojection error of 0.19 pixels, and a three-dimensional particle reconstruction RMS below 0.1 mm.

Fourth, spatial intensity correction based on the relationship among focusing distance, defocus distance, spot radius, and intensity enables more reliable lifetime fitting for particles moving in three-dimensional space. The complete workflow reconstructs three-dimensional tracks, corrects intensity sequences, fits phosphorescence lifetimes, and assigns temperature and velocity to the same particles.

Finally, preliminary measurements of a central high-temperature injection flow in a large cavity demonstrate simultaneous volumetric reconstruction of temperature and velocity over a region exceeding 60×60×80 mm. These results indicate that Phosphorescence-PTV is a promising experimental tool for studying three-dimensional thermo-fluidic coupling in liquid flows.

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