

Optical measurements inside a 3D model packed bed with gas flow

K. Hülz^{1,*}, C. Velten¹, K. Zähringer¹

1: Laboratory of Fluid Dynamics and Technical Flows, Otto-von-Guericke University, Germany

* Correspondent author: kerstin.huelz@ovgu.de

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ABSTRACT

Packed bed reactors with gaseous flow are used in a wide variety of industrial applications and are associated with high energy and resource consumption. To optimize these reactors, a better understanding of the internal processes, including flow behaviour, is required. Therefore, a novel model reactor concept, designed to enable optical measurements inside the packed bed, was adapted in this study for LIF measurements. The model reactor consists of different layers of parallel bars rotated against each other, thus modelling a packed bed of polyhedral particles. In this study, laser induced fluorescence (LIF) was used to investigate the dispersion of an anisole doped side jet. The jet was introduced at two third of the reactor height into the main flow that enters the reactor from the bottom. The main volume flow rate was $Q_p = 9.14 \frac{1}{\text{min}}$ corresponding to a particle Reynolds number of $Re_p = 99$, while the side jet volume flow rates were $Q_{jet} = 2 \frac{1}{\text{min}}$ and $10 \frac{1}{\text{min}}$. The LIF measurements are compared to particle image velocimetry (PIV) data from a previous work (Velten & Zähringer, 2026b) to correlate the dispersion behaviour with the underlying flow structures. It was found that the anisole doped side jet dispersed both, downstream and upstream of the main flow, corresponding to PIV results showing that the jet injection increased fluctuations and disrupted the regular flow structure of the main flow. Therefore, at the measurement positions (one layer below and two layers above the jet injection point) different structures of the anisole dispersion can be recognized; a homogeneous dispersion in the reactor cross-section does not exist. Increasing the side jet flow rate enhanced the fluctuations and the upstream flow, resulting in stronger mixing and a more homogeneous anisole distribution.

1. Introduction

Packed beds with gaseous flow play an important role in many industrial processes that come with high energy demand and resource consumption (Brunke, 2017). To optimize these processes, a better understanding of the flow behaviour inside such packed beds with gaseous flow is necessary.

For the purpose of characterizing the gas flow through packed beds, optical measurement methods would be ideal, as they enable the simultaneous measurement of two-dimensional (and in special cases also three-dimensional) fields and do not disturb the flow. In order to apply such measurement techniques, optical access to the areas of interest is necessary, realized by using

transparent packing material, but comes along with the difficulty to deal with optical distortions. Significant distortions occur particularly in packed beds with non-flat surfaces of the packing particles, which is mostly the case. Several techniques exist to address this problem, ranging from special calibration techniques (Kováts et al., 2015) to ray tracing corrections of the acquired distorted images (Velten et al., 2024; Martins et al., 2018). Other authors only measure at the bed surface (Linsong et al., 2025; Patil et al., 2024) or in optically easily accessible regions as near walls (Shaffer et al., 2013) or, in regular packings, in directly visible pores (Velten & Zähringer, 2023). Another technique, often used in liquids, is refractive index matching (Khayamyan et al., 2017; Nguyen et al., 2019; Patil & Liburdy, 2013). Unfortunately, this technique is not possible for direct measurements in the gas phase.

Therefore, in this study we present a model reactor concept that allows for direct optical measurements in the gas flow through the bed. First, the velocity fields in the voids of different configurations of the polyhedral model packed bed were investigated with particle image velocimetry (PIV). Then, the dispersion of an anisole doped gas jet is studied with laser-induced fluorescence (LIF).

2. Model packed bed

To overcome the aforementioned challenges, a novel structured model reactor concept was developed that allows for direct optical measurements within the voids of a packed bed by avoiding curved surfaces (Velten et al., 2026a). Therefore, a polyhedral particle structure of the bed is used that can be assembled as regular or irregular structure. The packed bed of this model reactor is built from 18 individual modules that are stacked on top of each other. One individual module is shown in Figure 1, left. It consists of five parallel bars with a height and width of 10 mm and a spacing of 5 mm between each bar. The cross-sectional area exposed to the flow is $A = 3031 \text{ mm}^2$. This leads to a porosity of $\varphi = 0.332$ that is similar to that of industrially relevant packed beds. By rotating the modules against each other, different inner pore structures are obtained. Rotating every module with a defined angle in the same direction results in a regular structured configuration with a spiral like inner shape, while rotating without a defined pattern leads to an irregular packing.

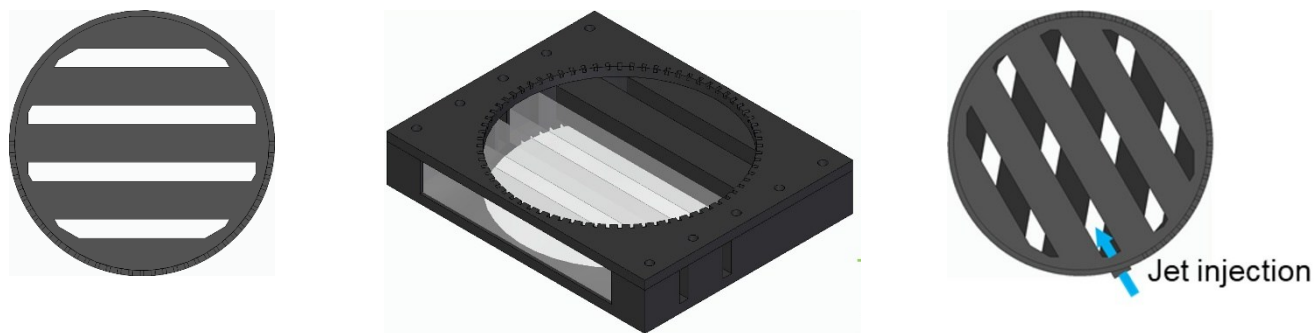


Figure. 1 Standard model packing module consisting of five parallel bars (left); special module with three transparent, exchangeable bars allowing for optical access (centre); special module for the integration of a side jet to the packed bed (right) From: Velten et al., 2026a.

Optical access to the packed bed is enabled by a special module with three removable bars, which can be replaced by transparent ones (see Figure 1, centre). By positioning the camera perpendicular to these transparent bars, the flow throughout the void space can be examined avoiding optical distortion. The laser light enters the packing through small windows perpendicular to the transparent bars on the side of the optical module. This module can be placed at any position throughout the reactor, except at the topmost layer or in place of the jet module, and thus allows for optical measurements throughout the complete reactor volume. By rotating the optical module by 180° , measurements in all four void spaces are possible. Further special modules can be conceived, as e.g. for the integration of a side jet anywhere in the packing by using the module shown in Figure 1, right.

In this reactor we measured the velocity fields by PIV in a regular assembly, where each module is rotated by 40° with and without a side jet introduced in the 12th layer (Velten & Zähringer, 2026b). The configuration with the side jet was now used for determining the dispersion inside the reactor. For this, LIF of anisole was used to determine its distribution in the reactor when introduced through the side jet.

3. Measurement positions

The centre of each void space was selected as horizontal measurement positions. Consequently, each module contains four horizontal measurement positions, labelled Pos. 1, 3, 5, and 7, counted from the nearest to the camera towards the back side of the module. The vertical location is defined by the layer number, with each layer corresponding to one module. For example, L10 refers to measurements taken in the 10th module counted from the bottom of the reactor. PIV measurements were conducted in layers L11 and L14–L17, while LIF measurements

were performed in layers L11 and L14, below and above the jet injection in layer L12, at all horizontal positions.

4. Experimental setup for PIV

The air flow seeded with small Di-ethyl-hexyl-sebacat droplets ($d \approx 10 \mu\text{m}$) by a nebulizer (Type AGF 10.0 from Palas GmbH) was introduced into the packed bed from below. The volume flow rate is controlled by a Bronkhorst Mass-Stream Controller (MASS-STREAM D-6400 100L/min air) and set to a flow rate of $Q_P = 9.14 \frac{1}{\text{min}}$, resulting in a particle Reynolds number of $Re_P = 100$, according to the following definition:

$$Re_P = \frac{v_s \cdot \rho \cdot l_{ch}}{\varphi \cdot \mu} \quad (1)$$

The superficial velocity v_s is calculated from the volume flow rate Q_P .

$$Q_P = v_s \cdot A \quad (2)$$

with the cross-sectional area $A = 3031 \text{ mm}^2$. The bar width is selected as the characteristic length $l_{ch} = 10 \text{ mm}$. All measurements are conducted under ambient conditions ($T = 20 \text{ }^\circ\text{C}$ and $p = 1 \text{ atm}$), corresponding to an air density of $\rho = 1.204 \frac{\text{kg}}{\text{m}^3}$ and viscosity of $\eta = 1.822 \cdot 10^{-5} \frac{\text{kg}}{\text{m}\cdot\text{s}}$. The optional side jet is injected in layer L12 by placing the corresponding module (see Figure 1, right). The jet inlet has a diameter of $d = 2 \text{ mm}$, corresponding to a cross-sectional area of $A_{jet} = 3.14 \text{ mm}^2$. The volume flow rate of the side jet is $Q_{jet} = 2 \frac{1}{\text{min}}$ for all PIV measurements presented here.

A double pulse Nd:YAG PIV-laser (Quantel Q-Smart Twins 850) operated at 532 nm and 10 Hz with $10 \frac{\text{mJ}}{\text{pulse}}$ illuminated the flow and an Imager CX 12MP camera from LaVision GmbH with a Nikon 35 mm f/2D lens captured the scattered light. A traversing system enabled the laser and camera to remain in a fixed position while the reactor was moved and rotated in the illuminated area perpendicularly to the camera. After geometrical calibration, 500 double-frame images were recorded with a recording rate of 10 Hz. The processing procedure of the recorded particle fields was conducted in Davis 10.2 and included the following steps: applying the calibration, using a time filter operation, using an intensity normalization, applying masks, PIV calculation, vector post-processing, taking the average of the 500 images, scaling and cutting the images. A detailed description of the PIV setup and processing procedure can be found in Velten et al., 2026a.

5. Experimental setup for LIF

The experimental setup for the dispersion measurements of the anisole doped gas jet by LIF can be seen in Figure 2. The packed bed reactor (R) with an inlet and outlet zone is shown on the left side of Figure 2. In that figure, the special module allowing for optical access (O) is integrated in layer L11. The main flow enters the packing from the bottom, while an additional side jet is introduced in layer L12 (J) (see Figure 2, right). Nitrogen is used as the working fluid, and the volume flow rate $Q_p = 9.14 \frac{1}{\text{min}}$ is set to the same value as in the PIV experiments, where air was used. Due to the slightly different properties of nitrogen, with a density of $\rho = 1.1496 \frac{\text{kg}}{\text{m}^3}$ and a viscosity of $\eta = 1.757 \cdot 10^{-5} \frac{\text{kg}}{\text{m} \cdot \text{s}}$ ($T = 20 \text{ }^\circ\text{C}$ and $p = 1 \text{ bar}$), the resulting particle Reynolds number ($Re_p = 99$) differs slightly from the PIV case ($Re_p = 100$). Side jet flow rates of $Q_{\text{Jet}} = 2 \frac{1}{\text{min}}$ and $10 \frac{1}{\text{min}}$ are investigated for LIF. The side jet is seeded with anisole as a fluorescent tracer by passing nitrogen through a gas scrubber containing liquid anisole (G) (see Figure 2, left). Before entering the reactor, the seeded side jet passes through a flow cell (F) positioned adjacent to the measurement location (see Figure 2, right), enabling simultaneous measurement of both, the anisole distribution inside the reactor and the original anisole concentration in the jet.

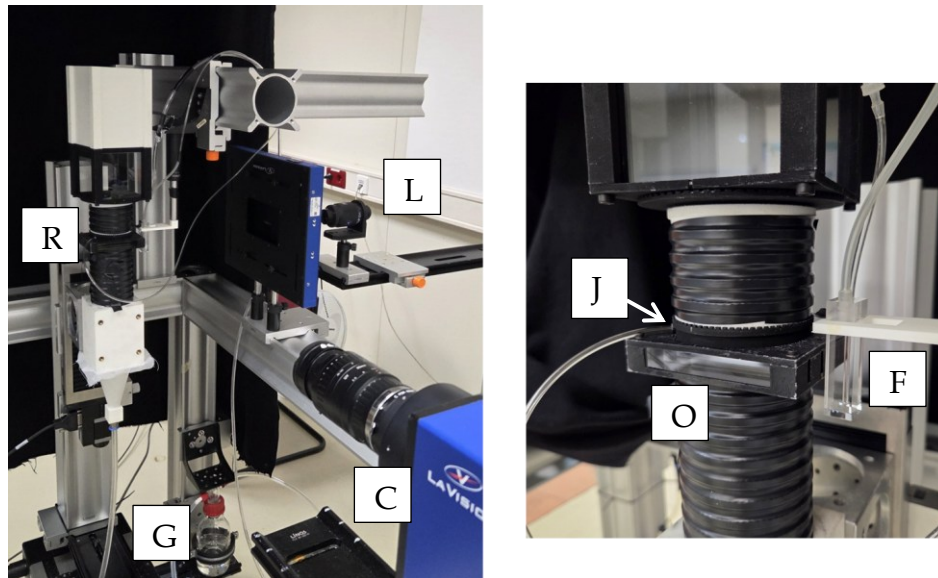


Figure. 2 Experimental setup used for LIF measurements. Overview of the whole setup (left) and enlarged view of the reactor packing with side jet injection module (J), optical module (O) and adjacent flow cell (F) (right).

This arrangement allows monitoring the stability of seeding and laser illumination while also providing a reference signal for subsequent normalization of the results. The laser (Quantel Q-Smart Twins 850), operated with a wavelength of 266 nm and 10 Hz with an energy of $23 \frac{\text{mJ}}{\text{pulse}}$, is

used to excite the anisole molecules. A light sheet optic (L) shapes the laser beam into a light sheet. An intensified camera (Nanostar from LaVision GmbH) (C) with an UV 85mm f/2.8 objective (LaVision GmbH) captures the fluorescence signal with a recording rate of 5 Hz. Since anisole shows the highest fluorescence signal at a wavelength of 290 nm ($T = 296\text{ K}$) (Faust et al. 2013), an optical filter was used (BG4 from LaVision GmbH) to capture the fluorescence signal. 500 images were recorded for each measurement position and flow condition. Figure 3 shows a raw image of the anisole distribution in the optical module (left, blue rectangle) and in the flow cell (right, green rectangle).



Figure. 3 Raw LIF image in the second void (Pos. 3) of layer L14 for $Re_p = 99$ and $Q_{jet} = 2 \frac{1}{\text{min}}$. The anisole distribution in the optical module is shown on the left hand side (blue rectangle) and the anisole in the flow cell on the right hand side (green rectangle).

These raw images are processed in DaVis 10.2 from LaVision GmbH. For evaluation, the images were separated into two regions: the reactor interior and the flow cell, as these frames were processed individually.

The flow cell images are cropped in a way, that a homogeneous intensity field was obtained (red rectangle). Subsequently, 50 counts are subtracted from each frame, as this value was identified as the background signal of the empty flow cell. Finally, all 500 images were averaged to obtain the reference intensity value for the inlet concentration.

For the frames showing the anisole distribution inside the reactor (blue rectangle in Figure 3), a polynomial geometric calibration is applied and the images are scaled accordingly. Afterwards, a background image was subtracted from each of the 500 frames. The images were then normalized using the previously determined reference value. Finally, the individual normalized snapshot images were also averaged.

6. Results

6.1 Velocity fields

Figure 4 shows the averaged velocity fields obtained by the PIV measurements between the first and second transparent bar (Pos.1) of the optical module inside the packed bed for a configuration, where every module is rotated by 40° for $Re_p=100$ without (left) and with a side

jet of $Q_{Jet} = 2 \frac{1}{\min}$ (right). The measurements were conducted in layer L11 and in layers L14 to L17. For the case without the side jet, it can be seen that the structure of the flow fields in the different layers is very similar to each other as expected due to the regular geometric arrangement. The flow is characterized by two vertical jets with higher velocity magnitudes than the area in between them and on the left side of the void. Furthermore, the jets exhibit internal flow structures, meaning that the highest velocity is not always located at the centre of the jet. This can be explained by geometric effects from the layers below: in some pores, the jet flow is partially obstructed before reaching the measurement position, while in other cases, flows arriving from different directions merge and contribute to a single jet.

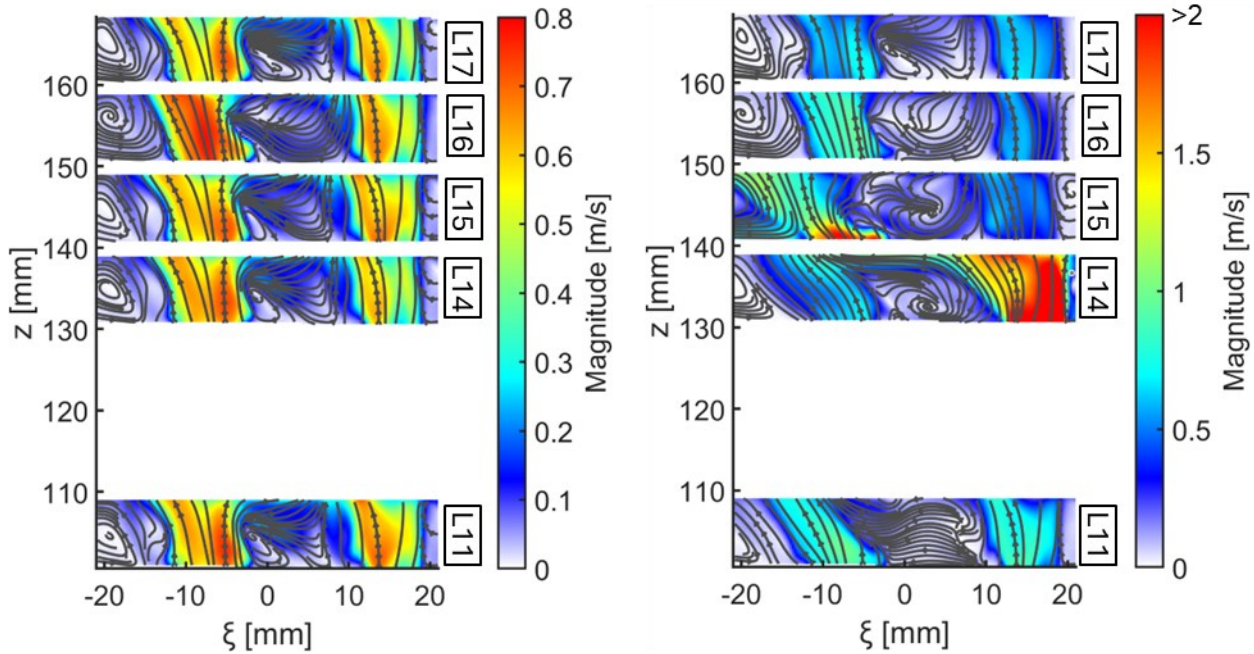


Figure. 4 Averaged velocity fields in the first void (Pos. 1) of layers L11 and L14 to L17 inside the packed bed for a 40° -packing configuration for $Re_p = 100$ without (left, Figure adapted from Velten & Zähringer, 2026b) and with a side jet injection of $Q_{Jet} = 2 \frac{1}{\min}$ in the third void (Pos. 5) of layer L12 (right, based on data from (Velten & Zähringer, 2026c)). The colour scale indicates the velocity magnitude and the streamlines indicate the flow path.

Introducing a side jet in layer L12 significantly changes the flow fields (Figure 4, right). This influence is less pronounced in layers L16 and L17, where the flow structures are similar to the case without jet. Different flow structures appear in layers L11, L14 and L15 and the injected jet leads to much higher velocity magnitudes. A detailed analysis of the flow fields with and without jet can be found in (Velten & Zähringer, 2026b).

Figure 5 presents individual snapshot data of the flow field in layer L14, illustrating that the flow with the side jet is characterized by increased fluctuations.

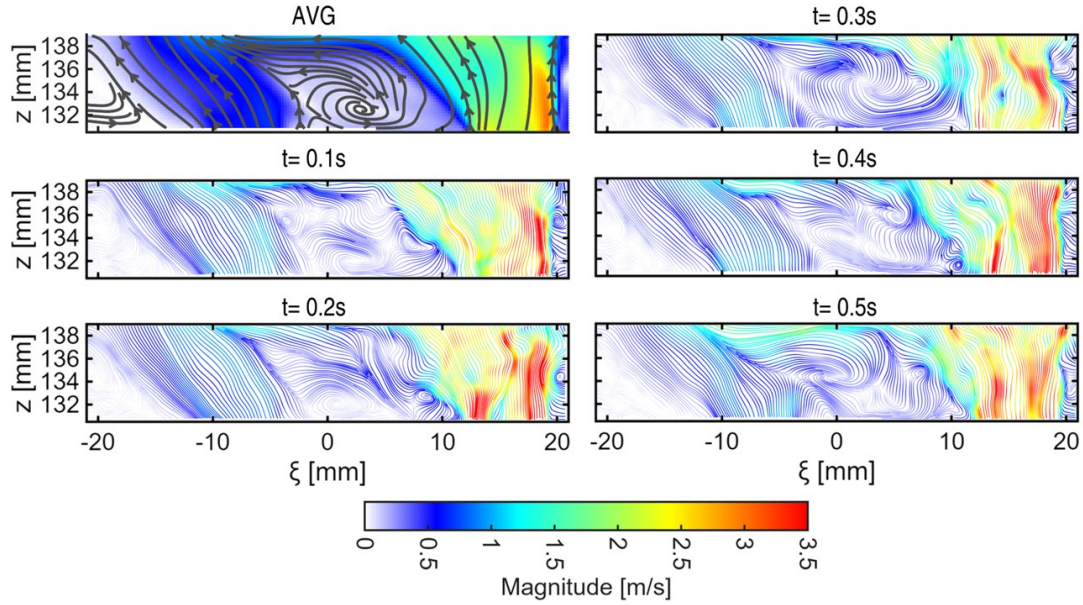


Figure. 5 Averaged velocity field (top left) and snapshots of the flow fields in the first void (Pos. 1) in layer L14 inside the packed bed for a 40° -packing configuration for $Re_p = 100$ with a side jet injection of $Q_{jet} = 2 \frac{1}{\text{min}}$ in the third void (Pos. 5) of layer 12. The colour scale indicates the velocity magnitude and the streamlines indicate the flow path.

6.2 Dispersion

The dispersion of the anisole doped side jet in the main flow for a configuration, where the modules are rotated by an angle of 40° is discussed in the following. So far, LIF measurements have been conducted in layers L11 and L14 for a main flow with $Re_p = 99$ and side jets with $Q_{jet} = 2 \frac{1}{\text{min}}$ and $10 \frac{1}{\text{min}}$. Figure 6 shows the normalized fluorescence intensity in layers L11 and L14 alongside the corresponding PIV results.

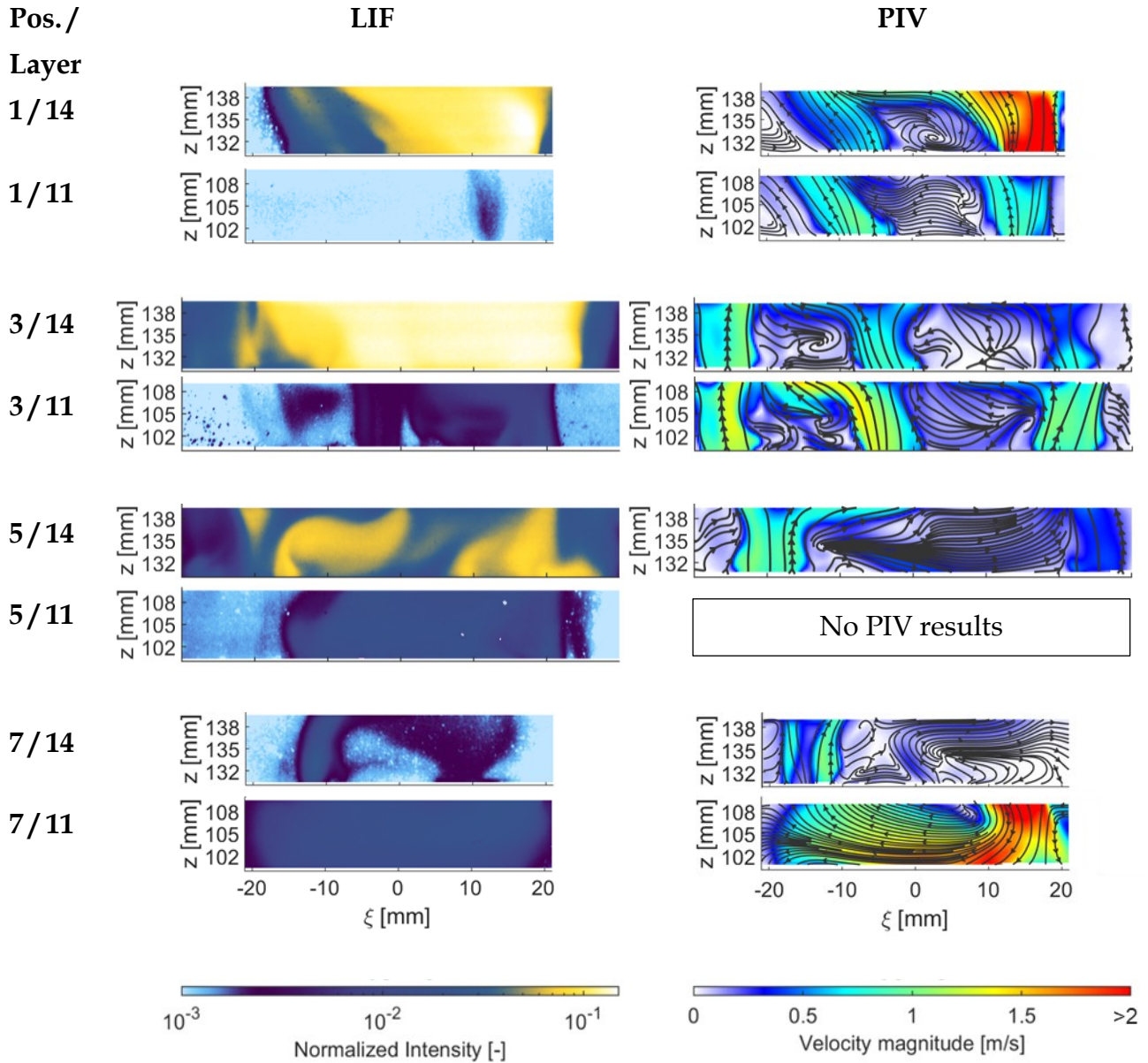


Figure. 6 Averaged normalized fluorescence intensity fields (left) at the positions 1,3,5 and 7 in layers L11 and L14 inside the packed bed for a regular 40°-packing configuration for $Re_p = 99$ and $Q_{jet} = 2 \frac{1}{min}$, with the corresponding averaged velocity fields (right) for $Re_p = 100$ and $Q_{jet} = 2 \frac{1}{min}$. The logarithmic colour scale on the left indicates the normalized intensity of the fluorescence signal and the linear colour scale on the right the velocity magnitude.

The anisole doped side jet is observed to spread not only downstream but also slightly upstream into layer L11, where a clear fluorescence signal can be observed at all positions. These observations correspond well with the velocity field, in which a strong downward flow can be seen at Pos. 7 in layer L11, transporting the side jet upstream into the packing. This behaviour results from the side jet flow impinging on the side wall of the third void (Pos. 5) in layer L12, where it splits into upstream and downstream branches. Interestingly, positions with relatively

high anisole concentrations in layer L11 exhibit relatively low anisole concentrations in layer L14, and vice versa. This can be attributed to the spiral inner structure of the geometry, which induces a spiral-shaped main flow inside the reactor and distributes the two anisole-seeded jet branches in different directions. Nevertheless, the anisole concentration in layer L11 is low compared to layer L14, indicating that the majority of the seeded jet is transported into the upper layers. Overall, the averaged anisole concentration at the measurement positions in layer L14 is seven times higher than in layer L11.

In layer L11, two distinct phenomena are responsible for the appearance of the fluorescence signal. At Pos. 7, the observed fluorescence signal primarily results from the anisole doped jet flowing against the direction of the main flow. At Pos. 5, no reliable flow fields could be obtained from the PIV measurements, due to the high level of 3D fluctuations at this position, in particular in the centre of the void. We therefore assume that the observed fluorescence signals originate from the seeded side jet being pushed downward through the central pore. In addition, part of the seeded side jet that flows downward at Pos. 7 appears to recirculate upward at the right side at Pos. 5, leading to the fluorescence signal there.

Although the flow fields at Pos. 1 and 3 in layer L11 are only weakly affected by the anisole doped jet, small amounts of anisole are still detected. This suggests that anisole is transported upward from deeper layers by the main flow, indicating that the recirculation extends across multiple layers. Surprisingly, however, only limited mixing appears to occur in the lower layers. Some of the main flow jets, visible in the velocity field in layer L11, show no detectable fluorescence signals, while in jets carrying anisole, the tracer is not distributed across the entire jet area. Instead, clearly defined structures remain visible within the jets.

In layer L14 the seeded side jet is neither evenly distributed across the reactor cross-section nor within individual void spaces, indicating that the main flow and side jet are not yet well mixed. At Pos. 7 only a small trace of anisole can be observed, which might be delivered by the recirculating anisole instead of the direct jet contribution, whereas at the other positions anisole starts to disperse throughout the entire void space, exhibiting different distribution patterns. At Pos.1 the majority of anisole seems to enter the void space from the right side, which is consistent to the PIV results, where the right jet shows very high velocity magnitudes as a result of the jet injection in layer L12. The downstream-directed branch of the anisole-doped jet, formed upon impingement at the side wall at Pos. 5 in layer L12, directly reaches this region. From there, anisole is transported leftward within the void following the flow direction. The jet on the left side at Pos.1 carries less anisole, leading to lower concentrations in that region. No accumulation of anisole is observed in the regions of low flow velocity at the left edge of the void space. Pos. 3 in layer L14 exhibits the highest anisole concentration of all measured positions. At this location,

the right and central jets transport high amounts of anisole into the measurement region, while the left jet contains comparatively lower anisole concentrations. At Pos. 5, the flow field reveals that the magnitude of the left jet is the strongest but its structure is less influenced from the jet. The central jet, existing when no side jet is introduced to the reactor, is missing and the flow turns to the right leaving together with the side jet on the left of the pore. This leads to a distribution of anisole over the entire measurement plane with different intensities. The left jet appears to be formed by the convergence of two streams coming from different directions, with only one of them having previously mixed with the anisole-doped jet. The strong rightward flow motion observed in the PIV measurements is also evident in the LIF images. Regions with high anisole concentrations form streak-like structures aligned with the direction of the flow.

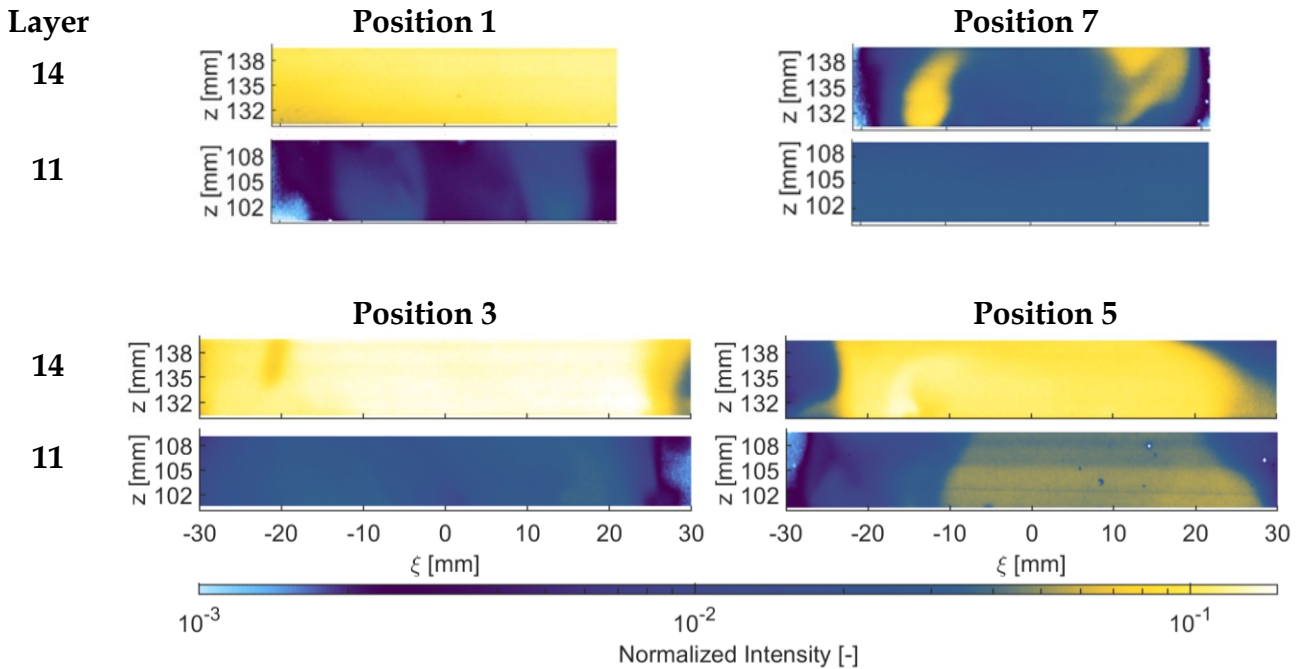


Figure. 7 Averaged normalized intensity fields at positions 1,3,5 and 7 in layers L11 and L14 inside the packed bed for a regular 40°-packing configuration for $Re_p = 99$ and $Q_{Jet} = 10 \frac{l}{min}$. The logarithmic colour scale indicates the normalized intensity of the fluorescence signal.

Increasing the jet volume flow rate leads to stronger upstream flow and fluctuations are increased (Velten & Zähringer, 2026b). Correspondingly, higher fluorescence signals can be observed in layer L11 compared to the case with $Q_{Jet} = 2 \frac{l}{min}$ (see Figure 7). Moreover, it can be observed that some jets in layer L11, which do not show any fluorescence signal for $Q_{Jet} = 2 \frac{l}{min}$, fluoresce at higher jet volume flow rates. From this observation, it can be concluded, that not only more from the anisole-doped jet moves upstream, but also the recirculation zone extends even lower into the layers of the reactor. With the exception of Pos. 7, the images in layer L14

show a significantly more homogeneous concentration field. This could indicate that higher side jet volume flow rates lead to faster mixing of the main flow with the side jet, in the sense that fewer layers are required to achieve complete mixing.

7. Conclusion

In this study we adapted a modular innovative packed bed reactor for direct optical measurements in a model packed bed to perform LIF measurements to compare them with flow field data from Velten & Zähringer, 2026b. A regular configuration of the reactor with 40° rotation angle has been investigated by PIV with the outcome that the velocity fields in every layer are nearly the same, due to the regular geometry. This pattern is broken, when a side jet is added.

The present results show that an anisole doped side jet distributes not only in the direction of the main flow, but also partly upstream to deeper layers. Anisole follows the velocity jets through the reactor in a spiral shape, leading to an uneven distribution over different positions of the reactor cross section. Two layers after injection (layer L14), anisole from the jet is not yet evenly distributed across the entire reactor cross-section and many structures are still visible. Increasing the side jet velocity leads to stronger upstream flow and an enhanced mixing process.

The results show, that this reactor allows for direct acquisition of flow, concentration and in the future also temperature data by optical measurement techniques, e.g. for the validation of theoretical models and numerical simulations. Therefore, the data of the velocity fields can be accessed in a data base through the internet (Velten & Zähringer, 2026c) and will be completed by the dispersion measurements in the future. Further steps of this study include completion of the dispersion measurements by measuring in higher as well as lower layers and for different flow conditions varying the main flow rate as well as the side jet flow rate.

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