Experimentelle Untersuchung von Strömungsfeldern in den Zwischenräumen grober Schüttungen

Experimental investigation of flow fields within cavities of coarse packed bed

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Abstract

Die Strömungsverhältnisse und daraus entstehenden Konzentrationsverteilungen in durchströmten Schüttungen stellen einen wichtigen Parameter zur Prozessoptimierung in solchen Systemen dar. Da der Zugang zu den Partikelzwischenräumen sowohl für Sondenmessungen, als auch für optische Messverfahren äußerst schwierig ist, gibt es bisher nur wenige zuverlässige Messdaten hierzu. Diese wurden meist in brechungsindex-angepassten Medien, d.h. ausschließlich Flüssigkeiten, gewonnen. Zur Übertragung auf Gasströmungen müssen dann komplizierte Ähnlichkeitsbetrachtungen durchgeführt werden.
Ziel unserer Untersuchungen war daher eine Machbarkeitsstudie zur Erfassung von Strömungsfeldern in Modellschüttungen ohne brechungsindex-angepasstes Zwischen-medium. Hierzu wurde die Particle-Image-Velocimetry (PIV) verwendet. Die geometrische Kalibrierung stellt hierbei eine besondere Herausforderung dar, die im Rahmen der Untersuchung zunächst mittels messtechnischer Methoden angegangen wurde.

Introduction

Many industrial processes, drying or incineration rely on gaseous flow in porous media. In these systems porous media can be fixed or randomly packed. Because of the complex geometry and experimental difficulties, most of the studies concerning the determination of flow fields in such media, deal with liquid flows in porous media. Besides numerical simulations [e.g., 1], many articles have been published about flow characterization using Particle Image Velocimetry (PIV) in packed beds [e.g., 2-4] or in the free flow above the porous media [5]. For these PIV experiments it is necessary to have an optical accessibility to the flow. Furthermore, most publications deal with refractive index matching in transparent packed beds [e.g., 6], but very few can be found concerning gaseous flows in packed beds.
This study presents a proof of concept for investigating the flow field in a coarse packed bed using PIV, with air as flow media. The objective was to achieve direct PIV measurements in a transparent packed bed, and to find a solution for geometrical calibration in such an environment, without refractive index matching. The study shows, that measurements are possible not only in the cavities between spheres, but also behind them, by adapting the calibration and postprocessing procedure.

Experimental setup

The experimental setup used for the PIV measurements in this study in shown in Fig. 1. The 200 x 236 mm ground size square tank was made from acrylic glass (number 1 in Fig. 1), with a wall thickness of 10mm. The box was filled with hollow acrylic spheres with a diameter of 100mm and wall thickness of 1.2 mm. An air flow was generated in the box through a hole in the center of the bottom wall.

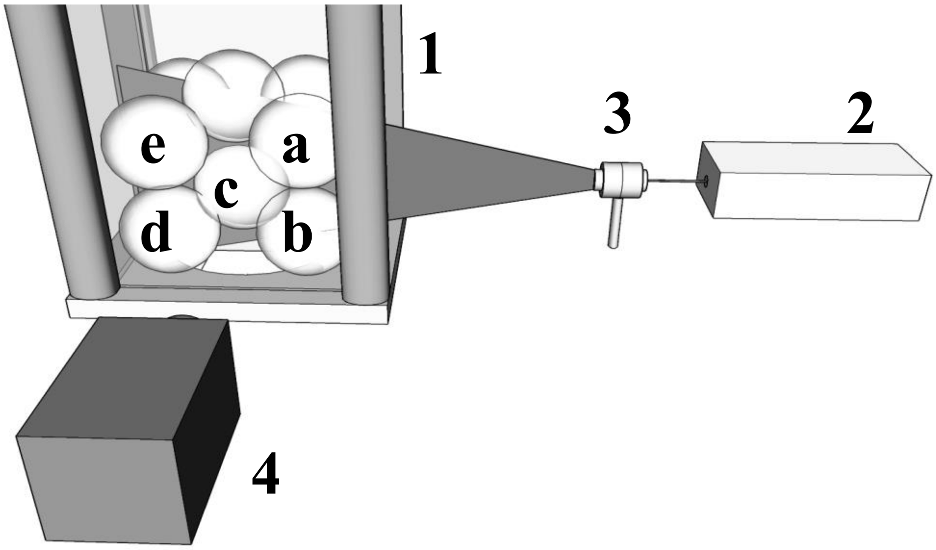

Figure 1. Experimental setup

This flow carried droplets as tracers for the PIV measurements. These droplets were generated with a nebulizer (Pari LL Nebuliser), which was supplied with pressurized air to generate the droplets. It produces droplets with a diameter between typically 10 and 100 µm in a log-normal distribution. Two types of droplets were used, which are described in more detail later. To illuminate these droplets, a double-pulsed Nd:YAG laser (Spectra Physics) with 532nm laser light (number 2 in Fig. 1) was applied. The produced laser beam was expanded by a light sheet optics (number 3 in Fig. 1). During the measurements the laser power was selected in a way, to get the highest droplet illumination and the lowest reflections on the sphere surfaces.
The images were recorded with a CCD - PIV camera (number 4 in Fig. 1) with a 1376x1040 pixel^2 resolution and 10Hz maximal frame rate. The camera was equipped with a Nikon AF Micro Nikkor 60mm f/2.8D lens. All the measurements were made at atmospheric pressure and room temperature.

Calibration

Because spheres were filled up into the tank very tight, as in reality, the usage of a conventional calibration target was impossible. Therefore, a self-made calibration target was used during the calibration process. This laminated printed paper sheet could be slid between the spheres. Preliminary experiments have proved that the spheres should be filled with air, to minimize optical distortions. If the sphere was filled, e.g., with water, it functioned as a magnifier lens (Figure 2).

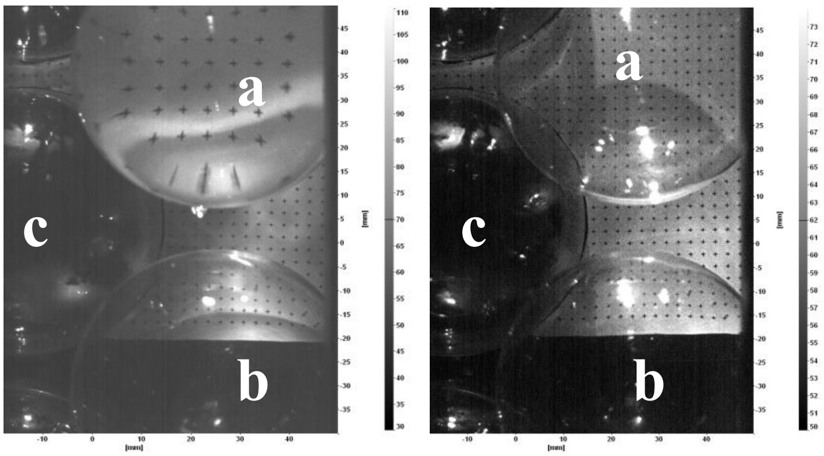

Figure 2. Sphere “a” filled with water (left image), spheres “a” and “b” filled with air (right image)

None the less, even with a slim calibration target and air in the spheres, optical distortion is noticeable behind the spheres. Therefore, the free spaces and the spaces behind the spheres were calibrated separately in the experiments (Figure 3). With this method, the effect of optical distortion was reduced to small areas along the sphere walls.

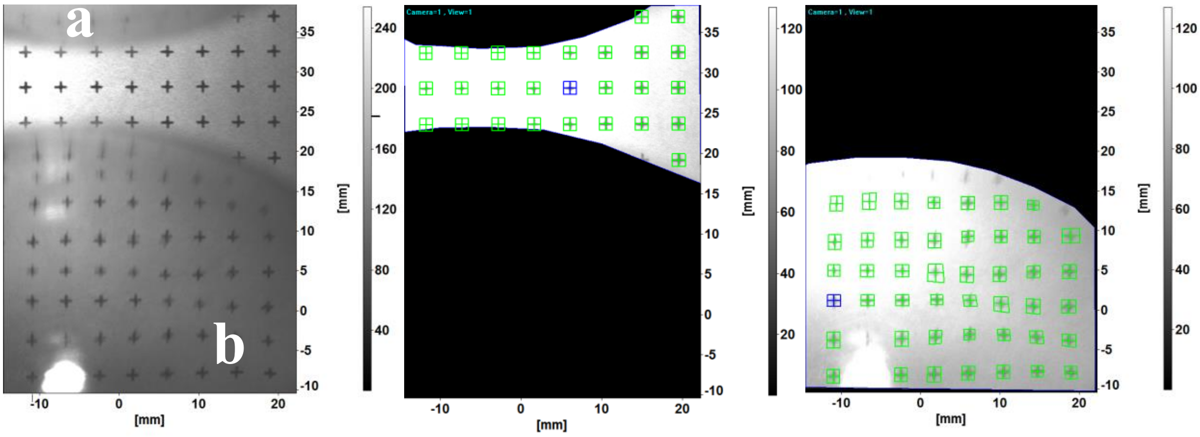

Figure 3. Calibration target and calibration sign identification

Tracer liquids:

1. Riboflavin

Riboflavin – common name Vitamin B2 – is used as a fluorescent tracer in this experiment, since it is not harmful [7]. It is ideal for PIV measurements if reflections have to be excluded. The 100mg/l mass percent riboflavin solution was filled into the above mentioned vaporizer's canister and with the help of pressurized air, fluorescent droplets were generated. The generated fluorescent fog was led into the tank, through the bottom opening. To excite the fluorescent droplets, a laser light sheet was directed into the tank, behind the front spheres (Figure 1. a, b, d, e) exactly in the previously calibrated plane. The fluorescence light of the droplets was recorded with a CCD camera with 5Hz frame rate. To suppress the laser light and reflections on the spheres' surfaces a 550nm bandpass filter was applied on the camera.

2. DEHS

The other liquid used in the experiment was Di-Ethyl-Hexyl-Sebacat (DEHS). The aerosol was generated and applied in the same way as riboflavin. As DEHS is not fluorescent, the camera had no filter. To avoid damage of the camera because of strong reflections on the sphere surfaces, a lower laser power was used. The frame rate was still 5Hz.

Results

During the experiment, different spaces in the tank were investigated to get information about the flow within the cavities and behind the spheres, too. For the riboflavin measurements two places were defined as shown in Figure 4 between the spheres a and b and behind sphere b (left), furthermore between the spheres a and b and behind sphere a (right). The light sheet was introduced behind the front spheres in all cases. Preliminary tests had shown that the light sheet could not illuminate the droplets on the left side of the tank, because of scattering and refraction on the surface of sphere c. If measurements have to be done on this side of the tank, the laser light sheet has to be introduced from the left side.

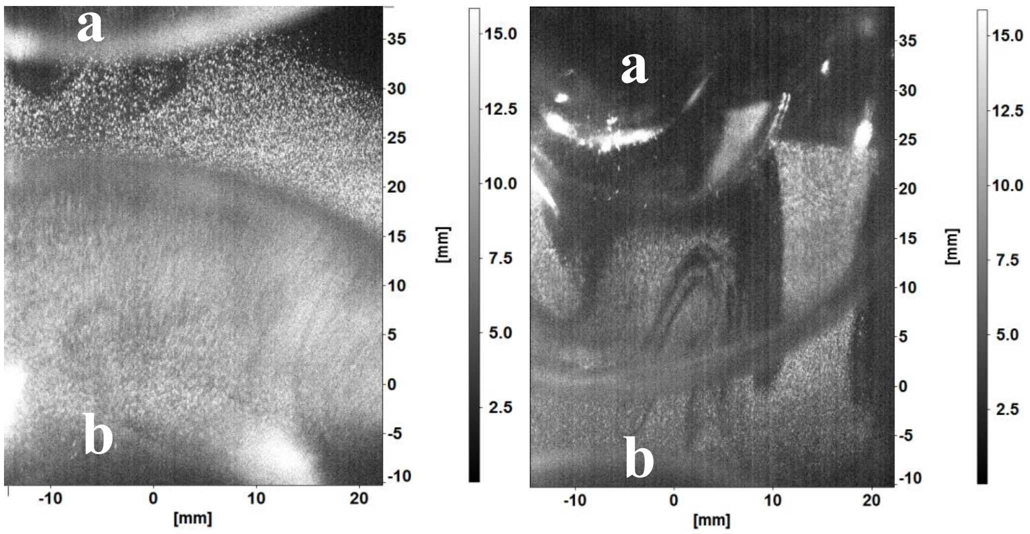

Figure 4. Measurement positions for the measurement with riboflavin

For the DEHS measurements two places were defined for the investigation (Figure 5), first between the spheres b-c*-d, where sphere c was moved to the front (thus now written c*), and second behind sphere c* (left); furthermore between the spheres a and b and behind spheres a and b (right). In both cases the laser light sheet was introduced behind the front layer of spheres.

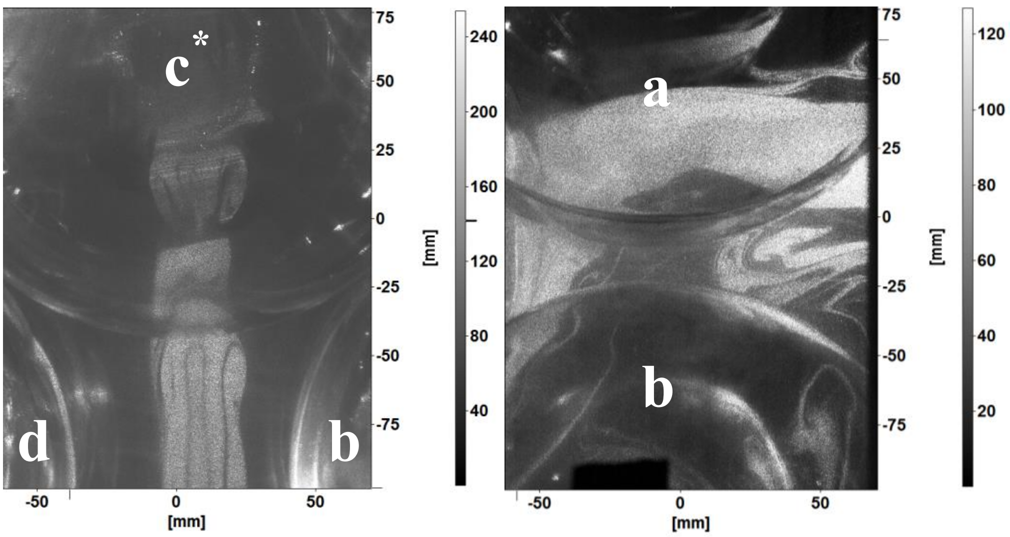

Figure 5. Measurement positions for the measurement with DEHS (c* corresponds to the sphere c moved in the front layer)

For postprocessing of the raw images DaVis 8.2 (LaVision) has been used. For the vector calculation a cross-correlation (multi-pass, decreasing size) PIV algorithm was used with an interrogation window size from 64x64 pixel^2 to 32x32 pixel^2.

To remove false vectors and refine the vector field, especially near the spheres surfaces, vector post-processing was applied. During postprocessing, first an allowable vector range filter was employed according to the generated *Vx/Vy* scatter plot. Then, with the help of a median filter and taking into account the 8 neighbouring interrogation areas, the highest (here, wrong) correlation peak, was replaced by the second, third or fourth highest correlation peak, until the given filter criteria was fulfilled. The vector position was disabled if none of the peaks fulfilled the criteria. These few disabled areas were then replaced with an interpolated value from the 8 neighbours. The resolving flow fields are shown for one exemplary snapshot in figures 6-9.

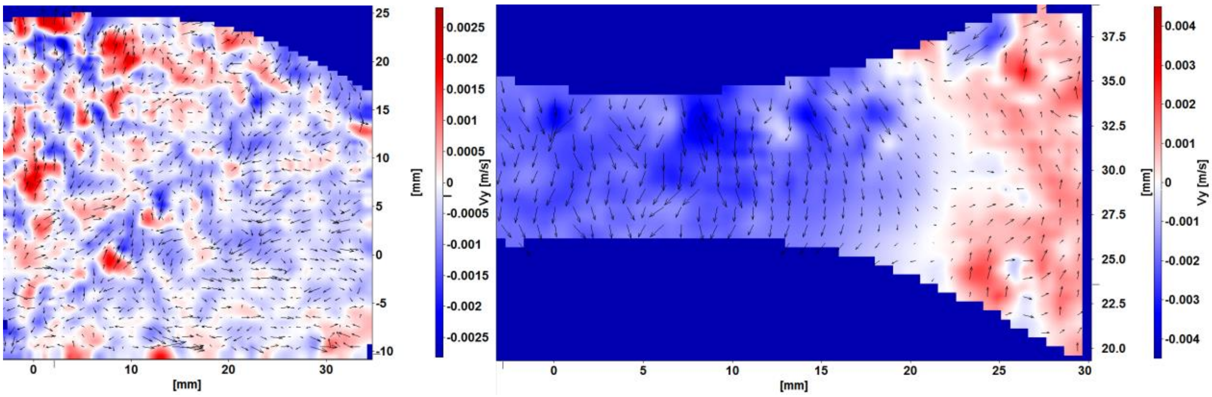

Figure 6. Vertical velocity component (colors) and velocity vectors for one snapshot from riboflavin images (left side - behind sphere b, right side – cavity between a and b)

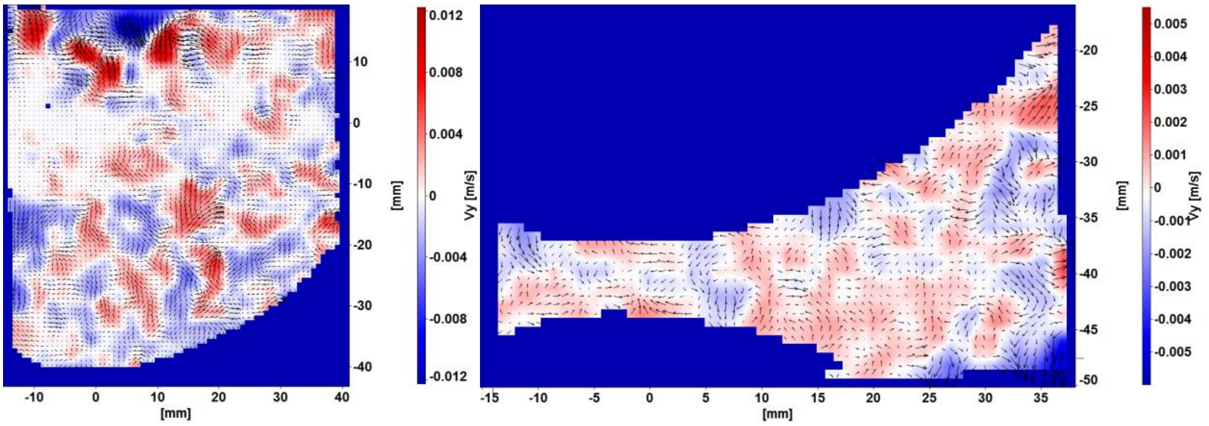

Figure 7. Vertical velocity component (colors) and velocity vectors for one snapshot from riboflavin images (left side - behind sphere a, right side – cavity between a and b)

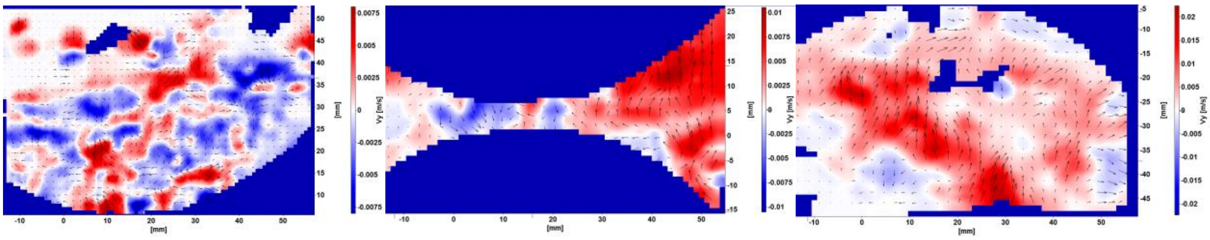

Figure 8. Vertical velocity component (colors) and velocity vectors for one snapshot from DEHS images (left side - behind sphere a, middle – cavity between a and b, right side – behind sphere b)

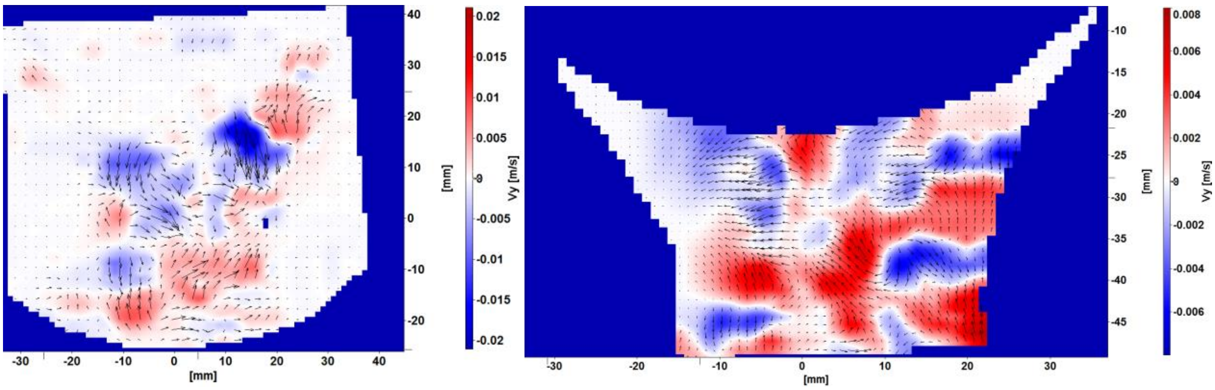

Figure 9. Vertical velocity component (colors) and velocity vectors for one snapshot from DEHS images (left side - behind sphere c*, right side – cavity between b, c* and d)

Small-scale turbulent structures can be recognized in these images, especially in the space behind the spheres. Between the spheres a flow acceleration in the free spaces is measured, whereas the velocity is nearly zero in the thin space between the spheres. As mentioned before, optical distortion near the sphere walls is rather strong. In these areas droplet detection mostly fails, thus leading to a zone of about 1-2 mm thickness near the sphere wall, where no reliable velocities could be measured.

On the averaged vertical velocity images (e.g., Figures 10-13) it is noticeable, that the flow in the middle of the cavities shows larger coherent structures, while behind the spheres, where the size of the cavities decreases, only small turbulent structures exist, with higher fluctuations.

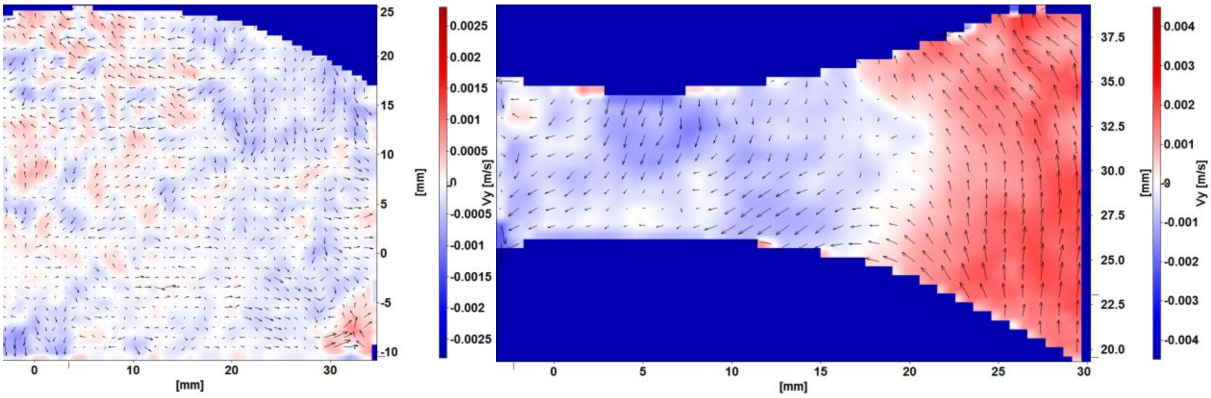

Figure 10. Averaged vertical velocity component from riboflavin images (left side - behind sphere b, right side – cavity between a and b)

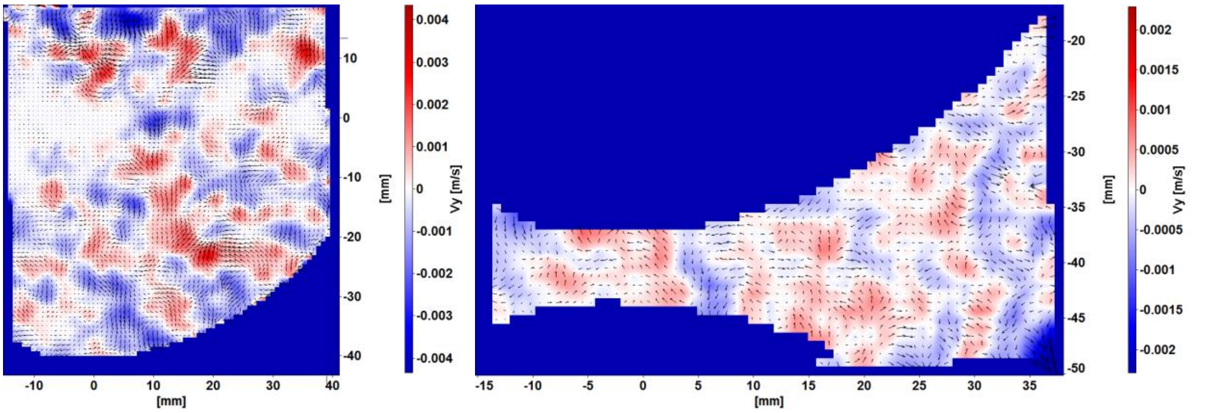

Figure 11. Averaged vertical velocity component from riboflavin images (left side - behind sphere a, right side – cavity between a and b)

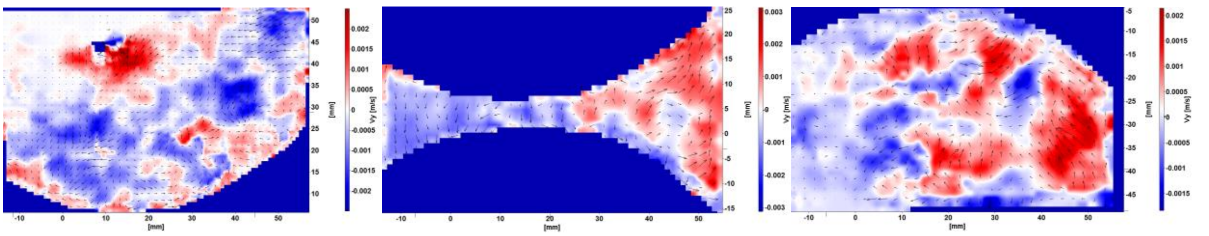

Figure 12. Averaged vertical velocity component from DEHS images (left side - behind sphere a, middle – cavity between a and b, right side – behind sphere b)

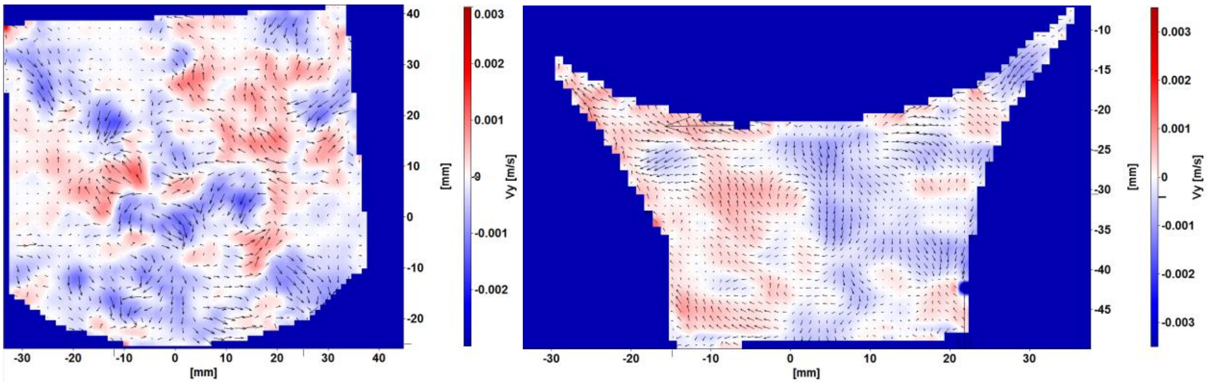

Figure 13. Averaged vertical velocity component from DEHS images (left side - behind sphere c*, right side – cavity between b, c* and d)

Conclusions

In this study, a proof of concept was carried out concerning PIV measurements in coarse packed beds. It was proved, that it is possible to implement PIV measurements with transparent spheres in air, without refractive index matching. In the experiment two types of tracer droplets were applied and the results are presented. Both of them are found suitable for these measurements. The riboflavin droplets are fluorescent. Thus, the reflections and scattering on the spheres surfaces can be reduced with the use of an appropriate filter. The images obtained with DEHS droplets can be post-processed as well, but it was observed that the DEHS liquid is quite aggressive. After the measurement campaign, damages on the spheres surfaces and along the tank sealing were noticeable.
With the help of the separated geometrical calibration, more accurate PIV measurements are possible, so that the flow fields can be determined by PIV both within cavities and behind the spheres.

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