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Experimental investigation of flow fields in the interstices of bulk particles with ray tracing based reconstruction

Motivation and Goals

Analysis of highly resolved gas flow fields in interstices

- Measurement of highly resolved (ms, 100µm) gas velocity and turbulence data for validation in numerical and experimental partner projects
- Direct optical measurement of flow fields in the gas phase of packed beds:
  - Avoid limitations of similarity theory used for results of refractive index matching for liquids
    → But optical distortion for transparent bulk particles
- Solution: reconstruction with ray tracing simulation
  - Adaptation of ray tracing to PIV
  - Introduction of specific physics to existing numerical models

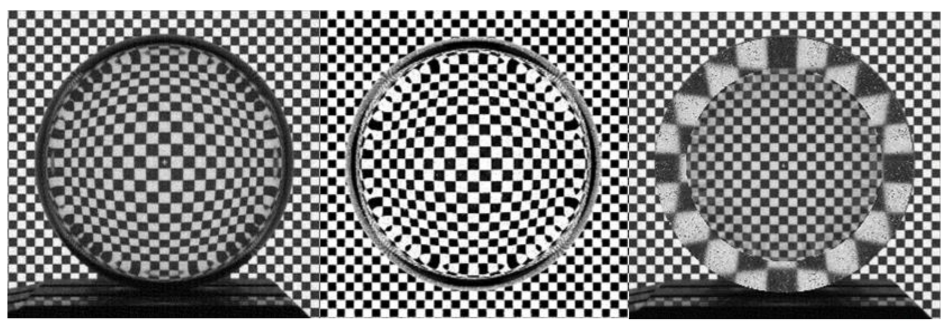

Fig. 1: Image correction of optical distortions caused by two 40-mm-diameter spheres with a distance of 6mm in front of a 2D chessboard target. Acquired image (left) after dewarping and cropping, computer-generated image (centre), based on the estimated setup parameters, and corrected image (right)

Challenges

- Adaptation of ray tracing for PIV
- Reproduction of exact experimental set-up in simulations
- Optimization of PIV lighting in interstices and calibration procedures
- Numerical optimization for best results
- Effective Monte-Carlo sampling strategies for ray tracing

Method

- Particle Image Velocimetry (PIV) in transparent packed bed based on reference configuration
  - 40mm N-BK7 spheres in body centred cubic packing
  - 3x3 spheres in the first layer
  - Up to21 layers Design of inlet conditions by honeycombs and packing material to reach symmetrical flow conditions
- Image acquisition adapted to the requirements of the ray tracing based correction
  - Calibration
  - Reference images based on a of a purpose-made target
  - Particle field images

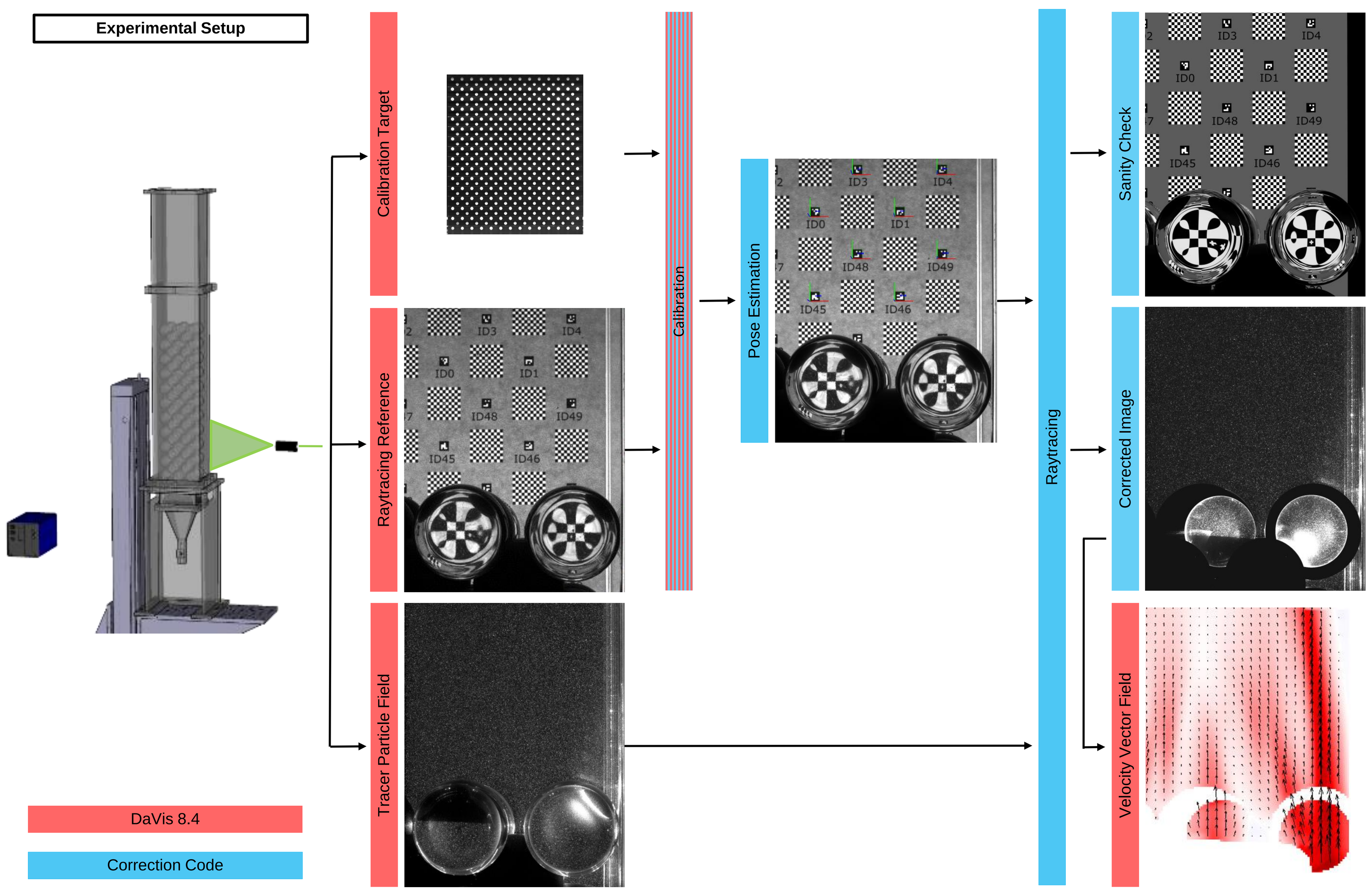

Fig. 2: Workflow for ray tracing PIV evaluation

- Ray Tracing simulation of light propagation for reconstruction (Fig. 4)
  - Reference images for pose estimation and exact reproduction of test rig in the simulation
  - Combined calibration based on a pinhole model
  - Image correction based on a two step light field simulation
- Vector field calculation
  - Standard PIV evaluation with a cross correlation method

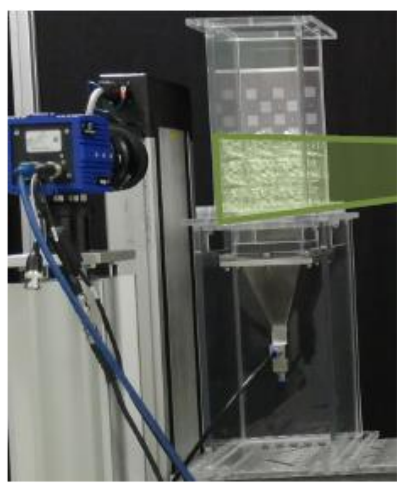

Fig. 3: Experimental set up

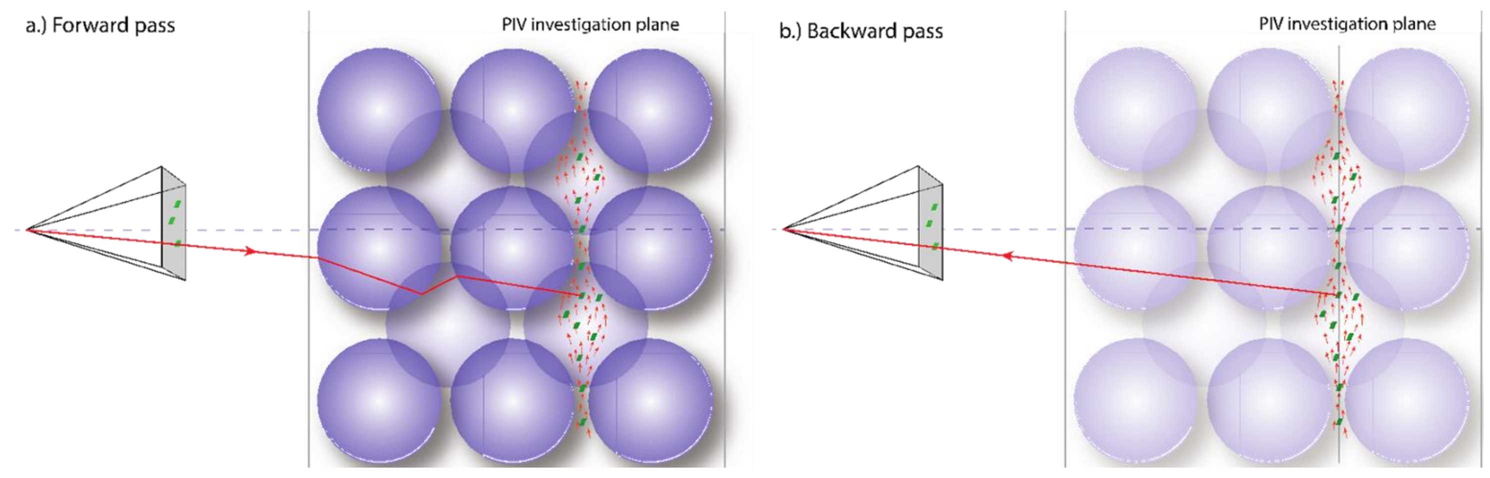

Fig. 4: Principle of the ray tracing based reconstruction

Results

Inlet conditions and bed height independent flow

- PIV Measurements of the empty bulk reactor
  - Particle Reynolds number range from 200 to 500
  - Symmetric inlet flow (Fig. 5)
- PIV Measurements in different bed heights
  - Symmetric flow above the bed
  - Bed height independent flow field can be assumed from 17 layers (Fig. 6)
  - Flow fields above odd layers of spheres as validation data will be provided for C6

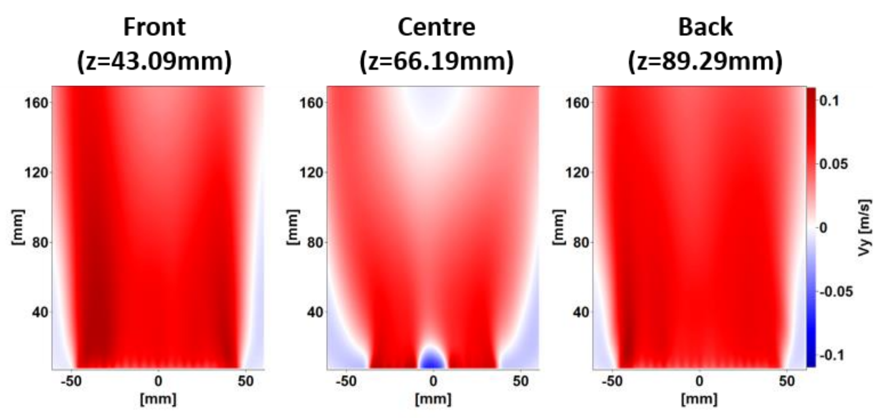

Fig. 5: Averaged flow field of the main vertical velocity component for Re_p=200 in different positions in the bulk reactor

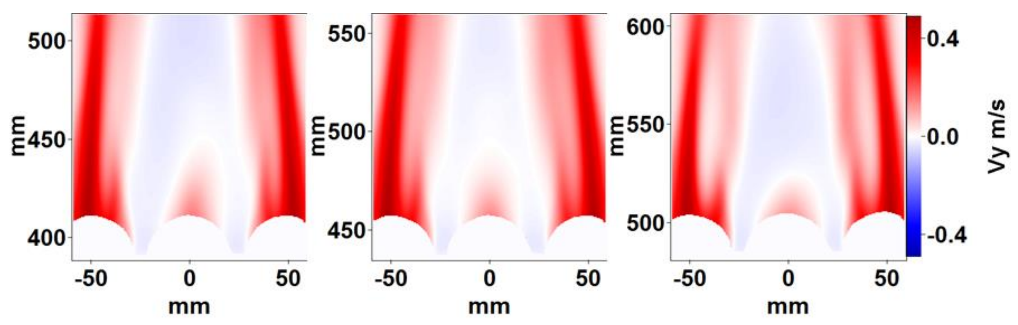

Fig. 6: Averaged flow field of the vertical velocity for Re_p=400 above layer 17 to 21 where the inlet independent bed height is reached

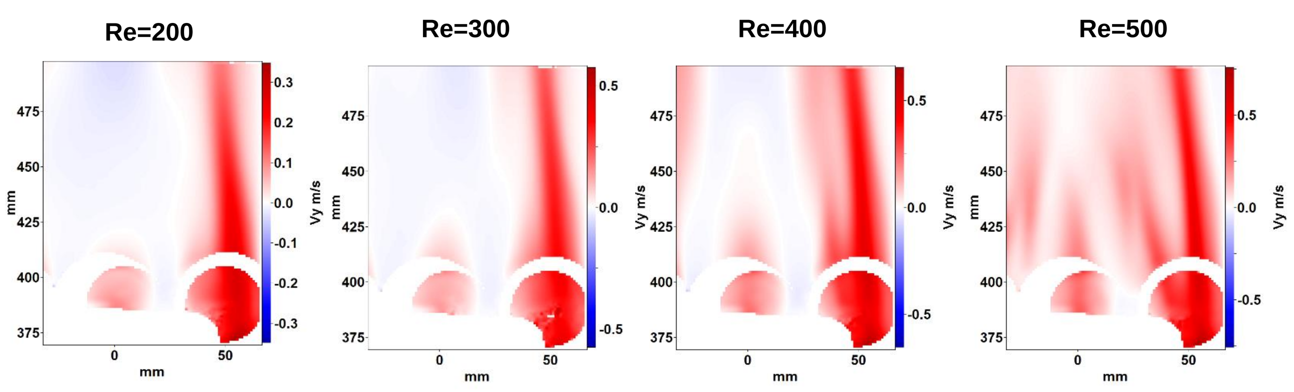

Fig. 7: Averaged flow field of the main vertical velocity component for different particle Reynolds numbers above 17 layers of spheres with ray tracing based reconstructions

Simulation

- Robust and automatic reconstruction reconstruction
  - Removal of artifact by using ray differentials as weighting of ray samples
- End-to-end simulation of PIV setup allows for rapid testing of experimental setups and reconstruction methodologies
  - Example: stereoscopic setup to reduce or remove regions where optical distortion is too high for reconstruction (Fig. 8)
- Ray tracing applied to radiative heat transfer in cooperation with B3
  - More details on dedicated poster

Ray tracing based correction

- PIV surface measurements
  - Correction of particle fields behind two spheres in different bed heights for particle Reynolds numbers from 200 to 500 (Fig. 7)
  - Corrected flow field matches the freeboard flow
  - No significant change applied to regions without distortion due to correction method
  - Perspective allows also to correct highly distorted regions (rim region)

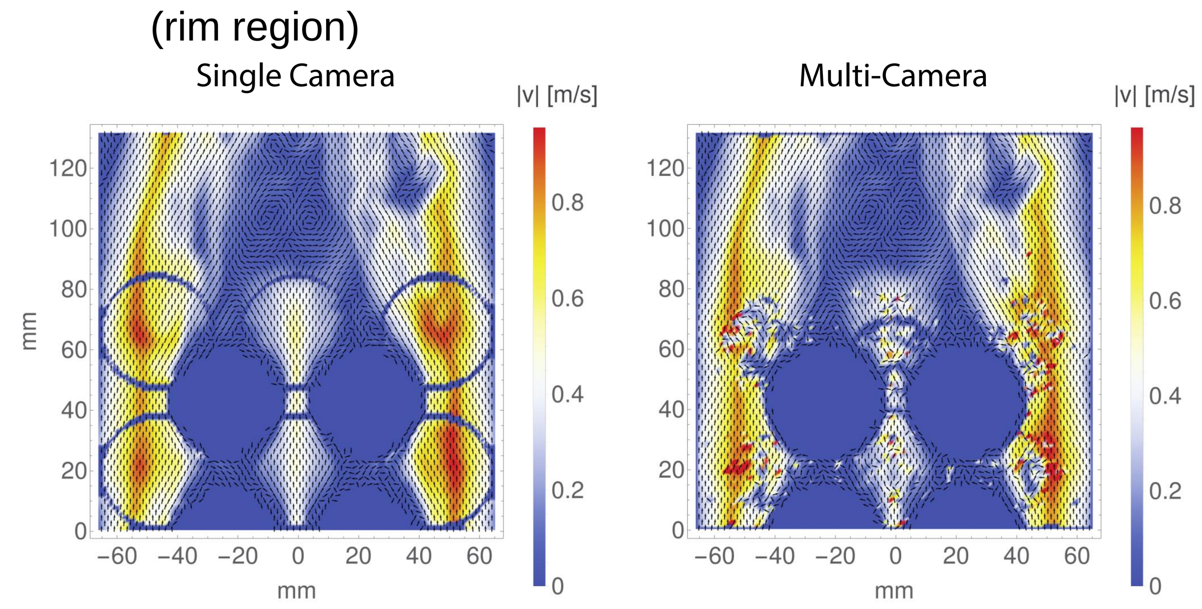

Fig. 8: Stereo reconstruction of artificial particle field, presence of strong artifacts need to be treated in future work

Future Work

- Flow velocity fields in the interstices accessible without ray tracing with high spatial resolution
- Influence of the perspective to increase the reconstructed area
- Tomographic PIV with ray-tracing correction as additional concept for access inside the packed bed
- 10x10 bcc packing of 10mm spheres as second reference configuration
- Investigating still persisting artefacts in the light field reconstruction
- Extension of reconstruction method to anisotropic light field
- Investigation of different camera models and setups using the end-to-end simulation
- Automatic correction of minor displacement errors between real world geometry and simulated ones using a numerical optimization

Current Collaborations

A4	Exchange of geometry and inlet conditions of the test rig for numerical simulations. First simulations were carried out.
B3	Heat Simulations based on Monte-Carlo-Raytracing
C6	Exchange of geometry and inlet conditions of the test rig for numerical simulations. Cooperation on configuration related errors.
A2	MRI in similar reference configuration for liquid flow
M1	Heat simulation in a packed bed