

Figure 1. Schematic of the experimental set up.

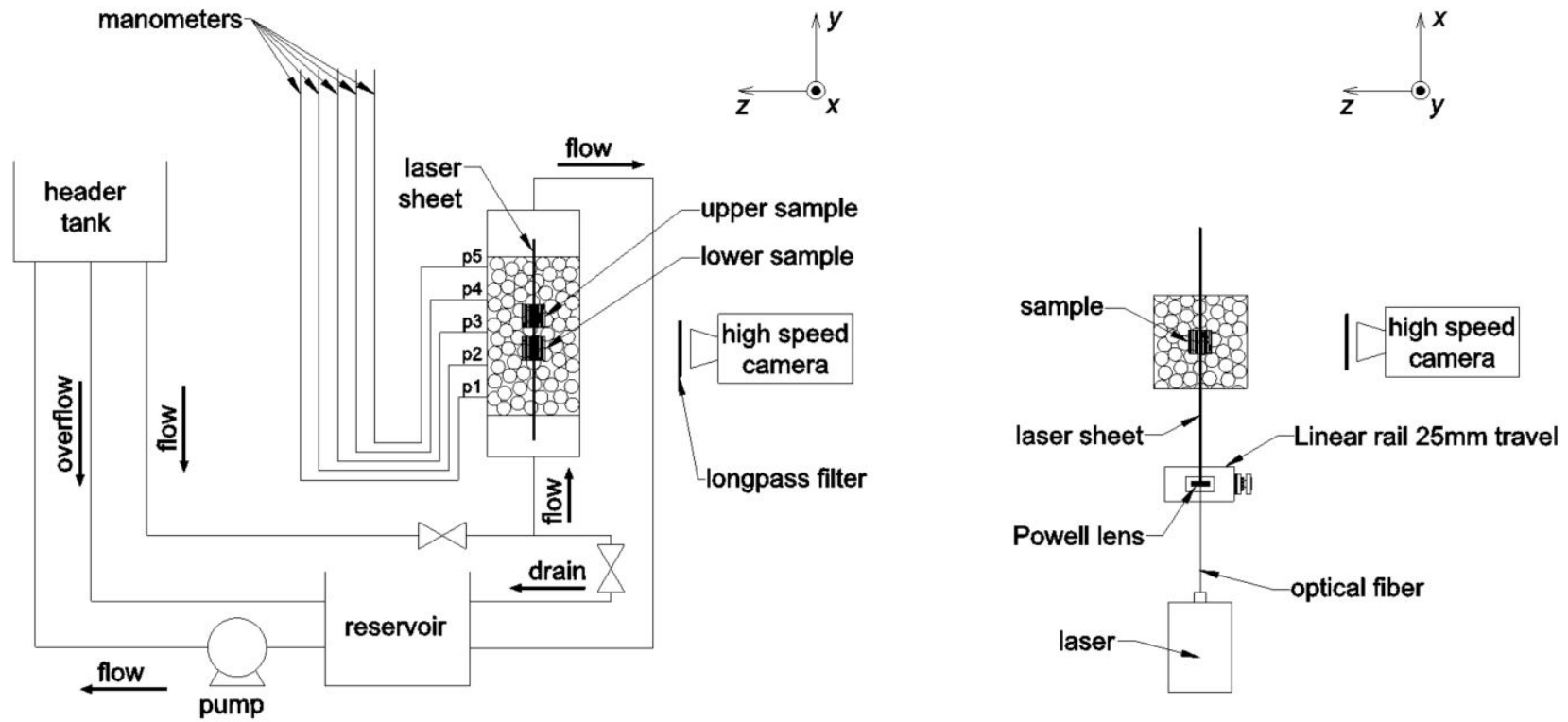


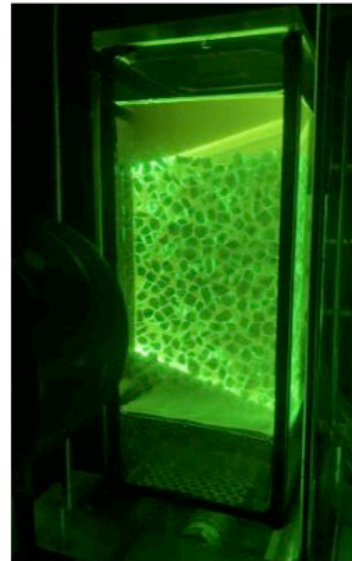
Figure 2. Images of experimental setup: (a) Permeameter cell partially filled with oil; (b) Beads sample illuminated by laser sheet; (c) Angular particles sample illuminated by laser sheet; (d) top view of the laser sheet.



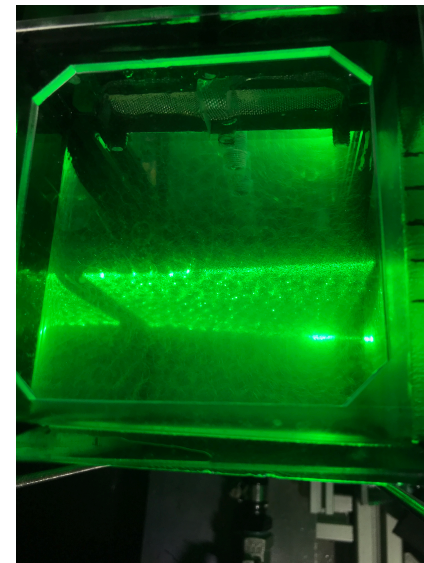
(a)



(b)



(c)



(d)

Figure 3. Flow fields in the (a) left, (b) middle and (c) right for the permeameter with beads.

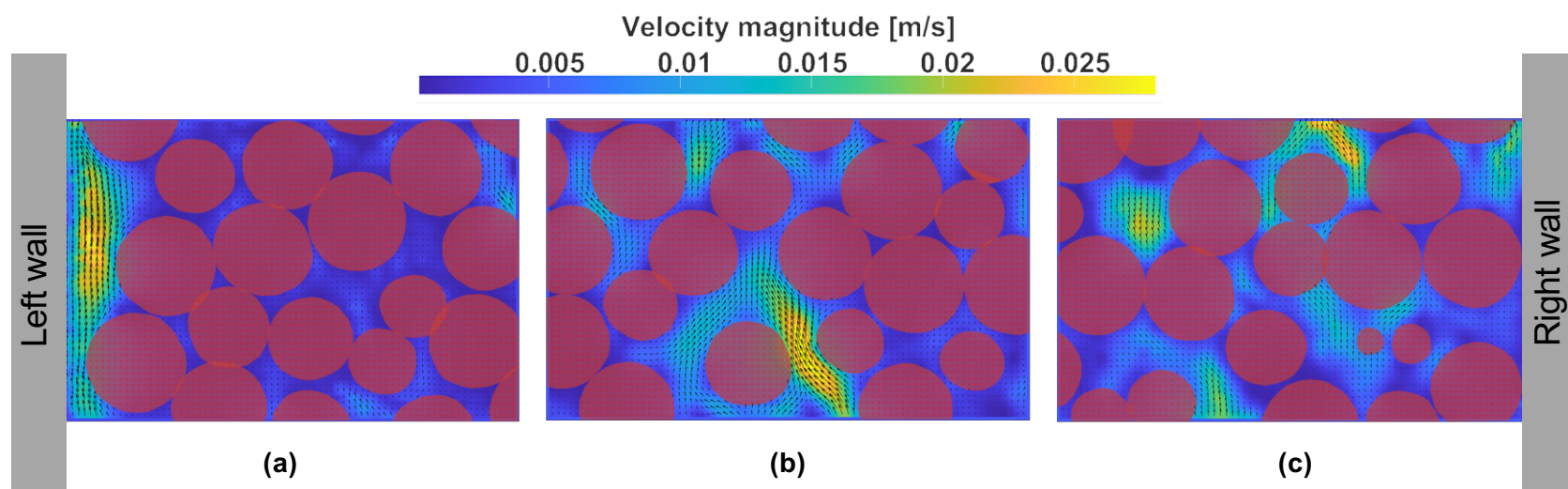


Figure 4. (a) Typical grey-scale image in Beads-U sub-volume, $z = 0$ mm. (b) Histogram of grey values. Inset in (a) shows that the non-uniform intensity is a consequence of the finite laser width.

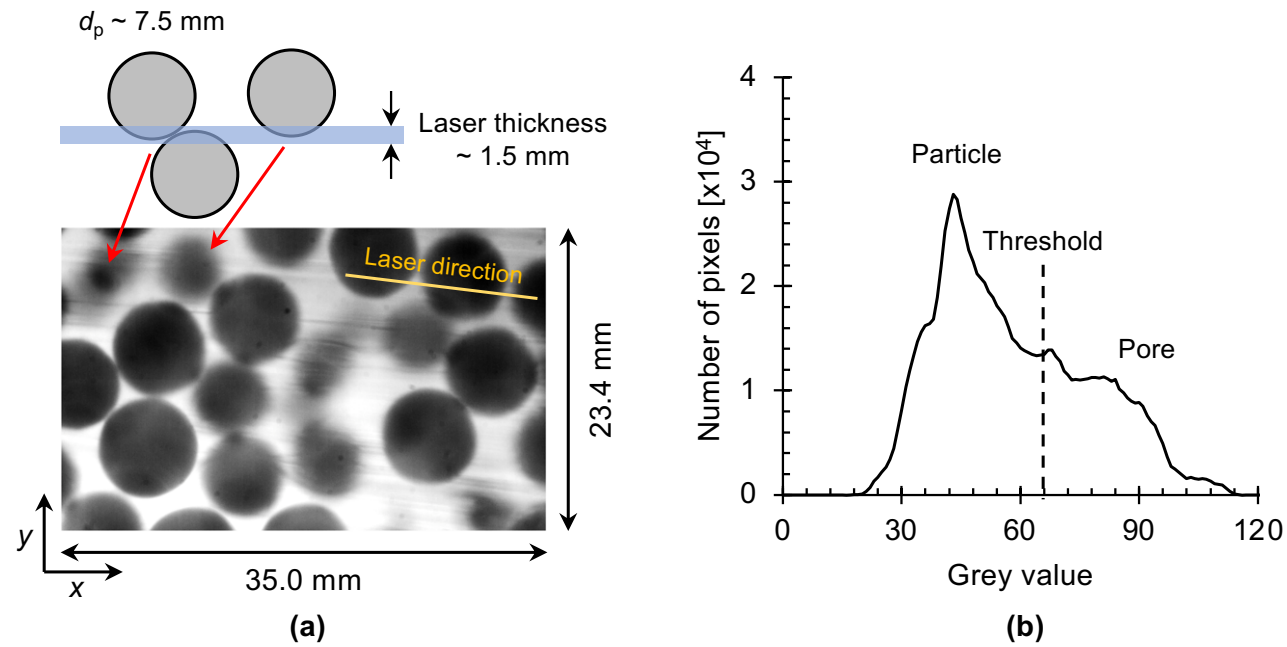


Figure 5. Segmentation results for three typical slices in Beads-U sub-volume using three different segmentation methods: threshold segmentation with Otsu's threshold, trainable Weka segmentation, and U-Net segmentation. Note: dashed circles indicate the artifacts produced by inaccurate segmentation.

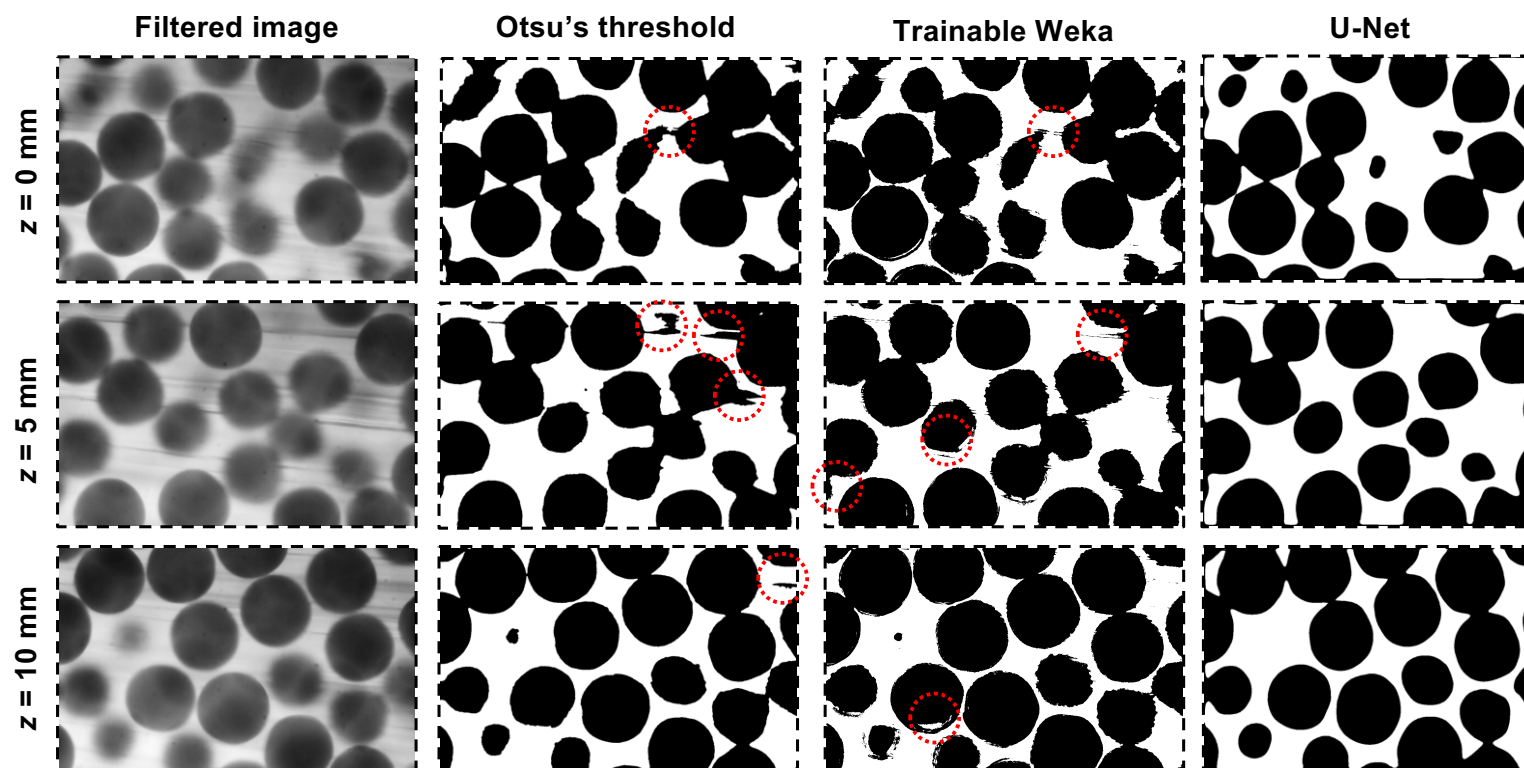


Figure 6. U-Net segmentation procedure for Beads-U sub-volume: (a) Step-1: prepare training and validating data sets; (b) Step-2: train U-Net algorithm; (c) Step-3: apply trained U-Net as a classifier for segmenting new images.

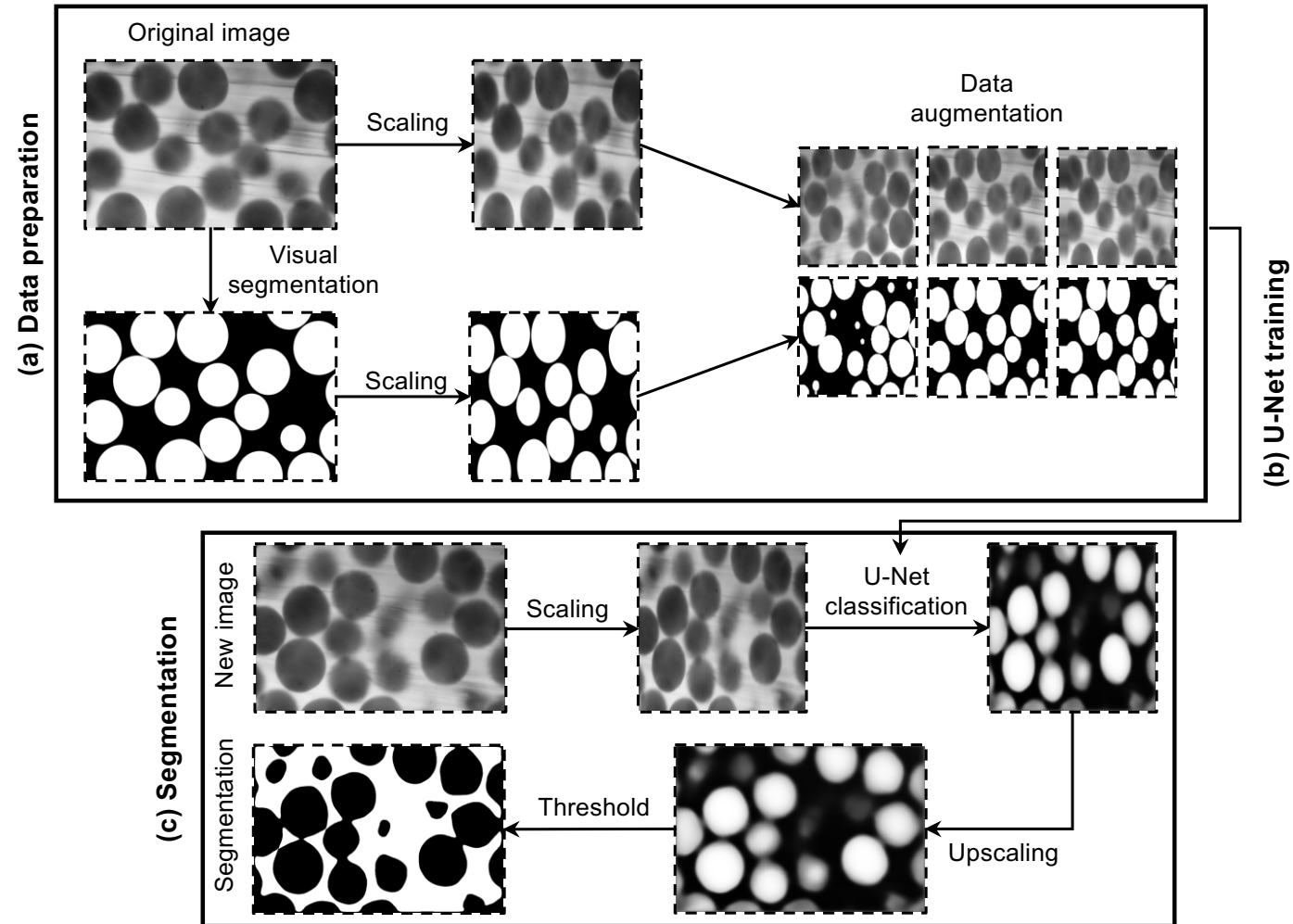


Figure 7. Upscaling along z-direction on the U-Net classified image for Beads-U sub-volume: (a) Unscaled image data; (b) Image obtained by scaling without interpolation; (c) Image obtained by scaling with bilinear interpolation; (d) Image obtained by scaling with bicubic interpolation.

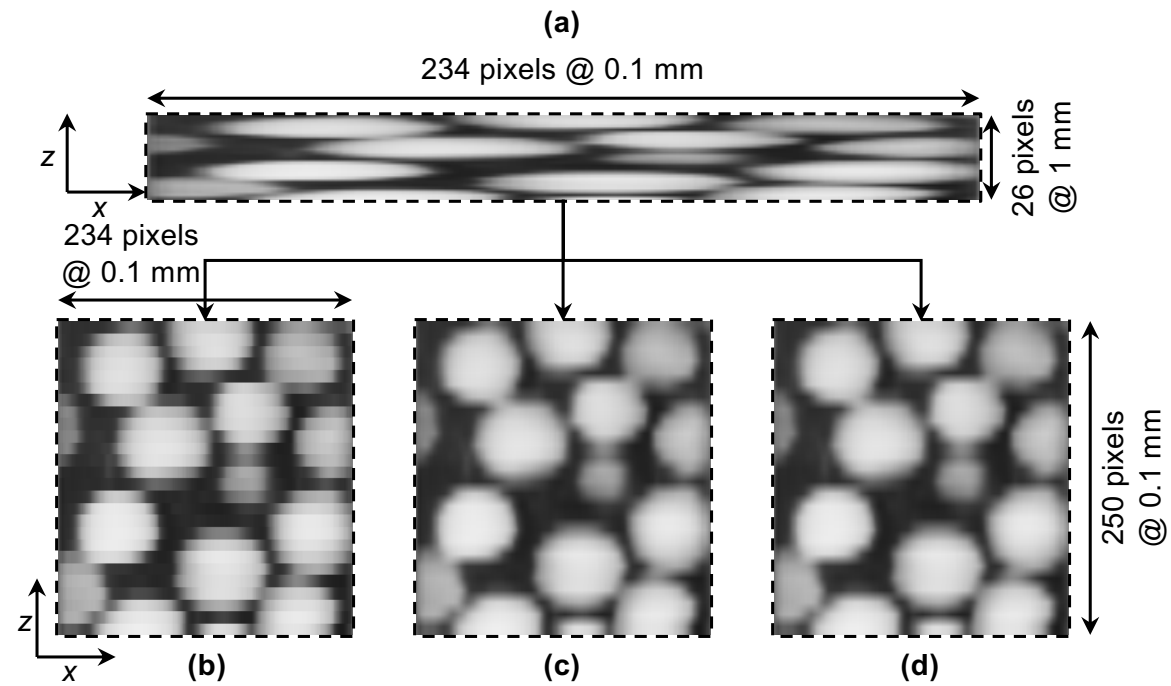


Figure 8. Labelled images with particles represented by different colours for Beads-U sub-volume on (a) x-y plane and (b) x-z plane and Ang-U sub-volume on (c) x-y plane and (d) x-z plane.

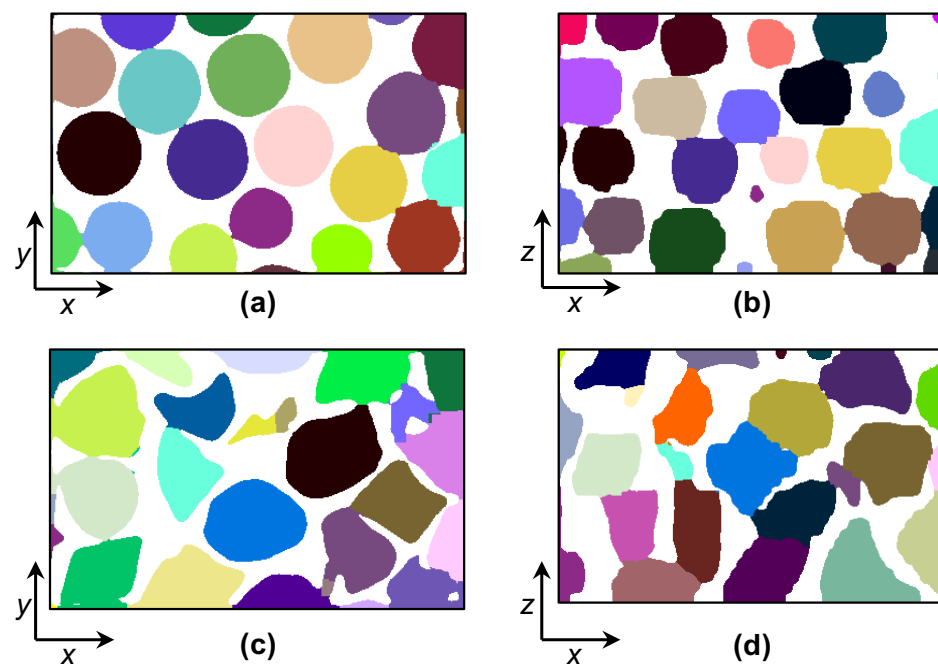


Figure 9. Three-dimensional views of the combined surface meshes for (a) Beads-U sub-volume and (b) Ang-U sub-volume. Note: colour is used to distinguish the surfaces of individual particles. Hexahedron meshes which discretize pore structure for CFD simulation for (c) Beads-U sub-volume and (d) Ang-U sub-volume.

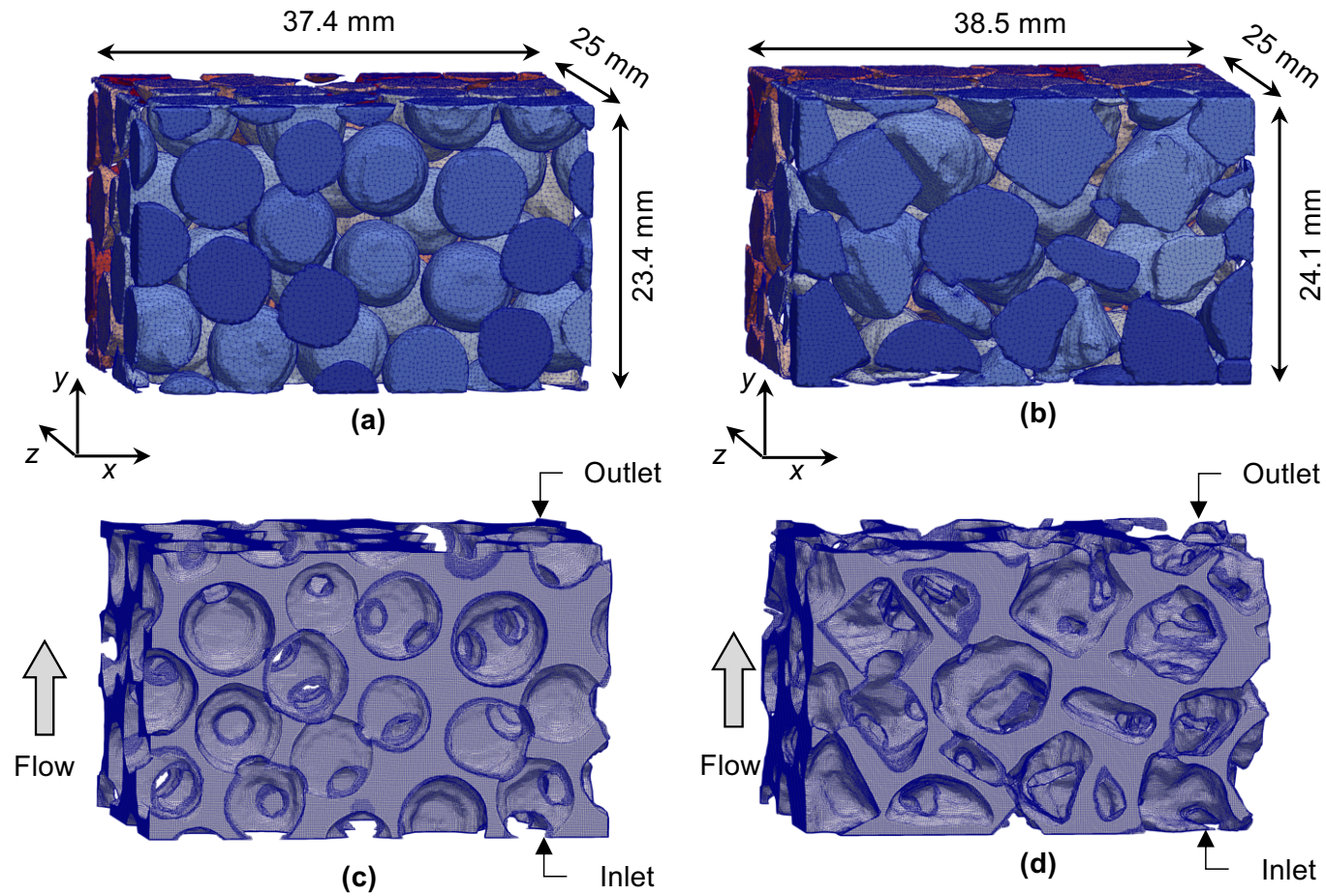


Figure 10. Verification of CFD modelling approach: (a) Confirmation of ability to capture the influence of porosity on the fluid-particle interaction coefficient $\bar{F}_{f \rightarrow s}$, dashed lines indicate a curve fit to the Zick & Homsy (1982) data; (b) Mesh dependence of $\bar{F}_{f \rightarrow s}$ for SC packings; (c) Mesh dependence of $\bar{F}_{f \rightarrow s}$ for FCC packings. The results predicted by the Immersed Boundary Method (IBM) with a regular grid and from fully resolved CFD using an unstructured meshes from Knight et al. (2020) are included in (a) and (c), respectively.

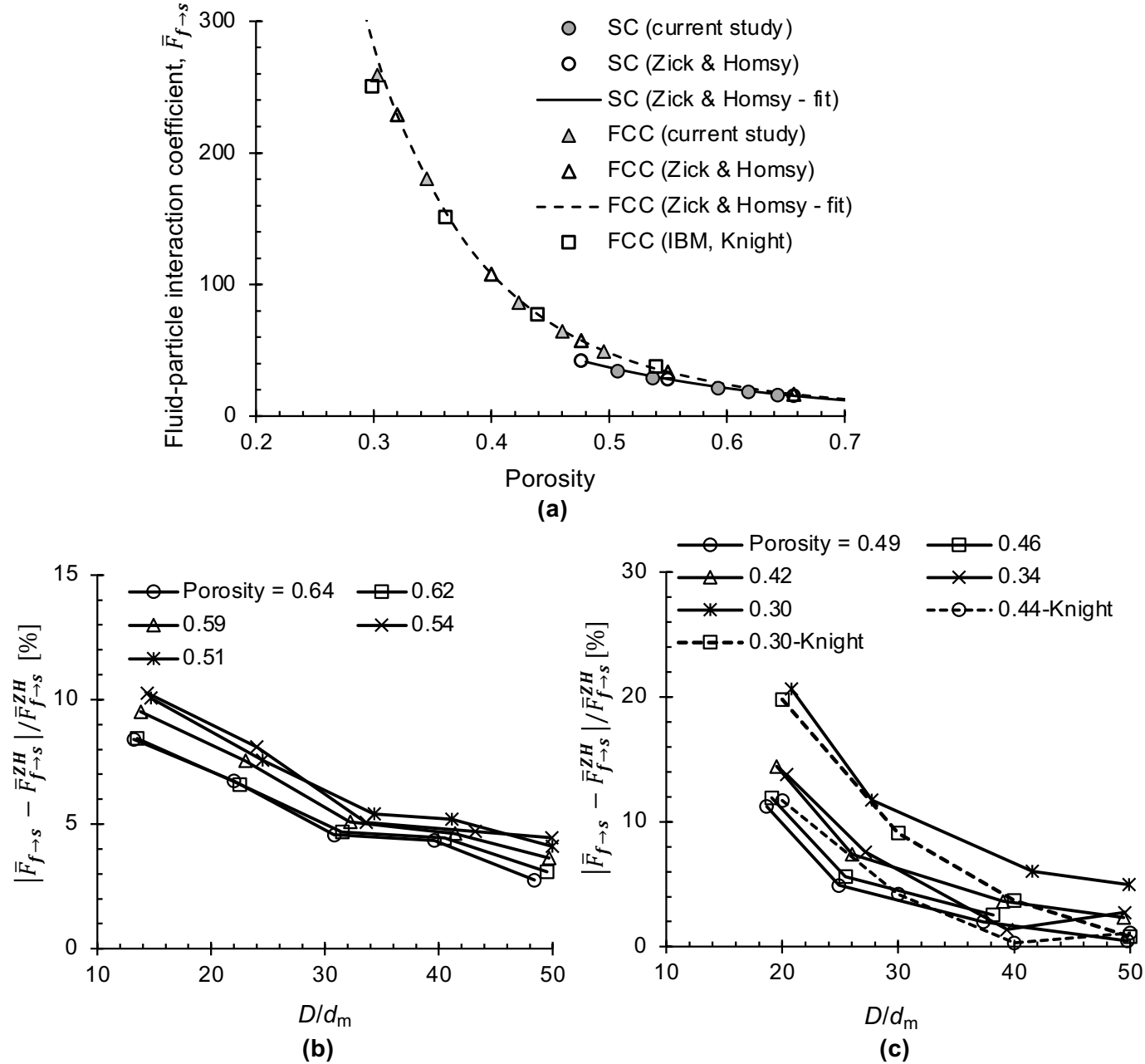


Figure 11. (a) Hydraulic permeability values predicted by experiments, PIV and CFD measurements. (b) Influence of porosity on hydraulic permeability as estimated by CFD modelling for Beads-U and Ang-U sub-volumes. The prediction results from Kozeny-Carman Equation (KC Eq.) is included in (b).

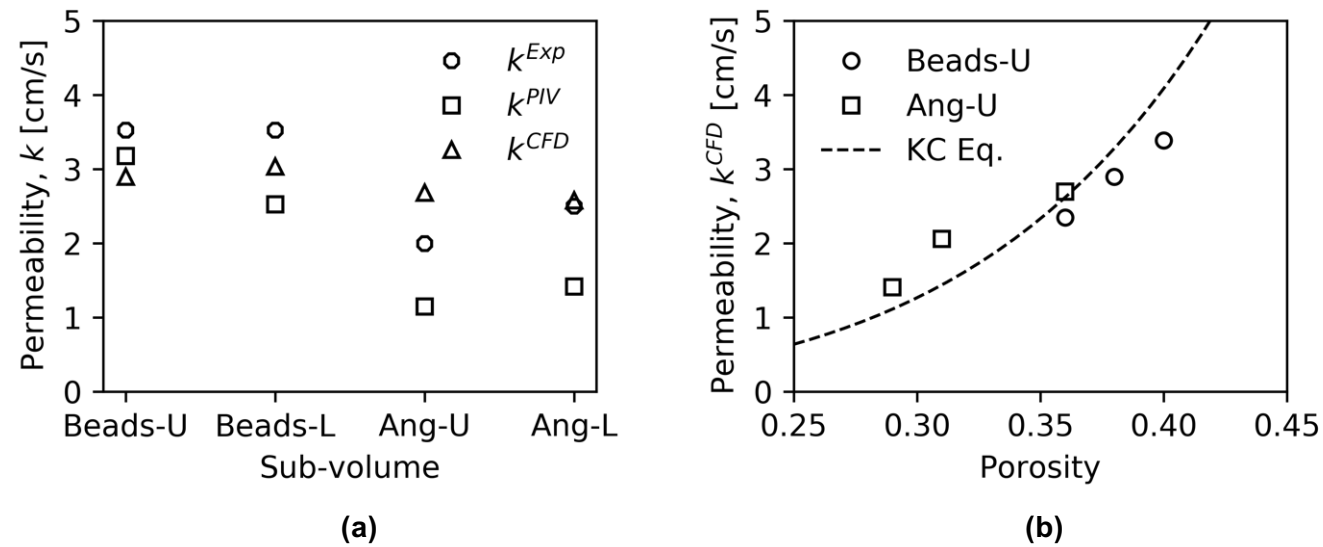


Figure 12. Comparison of the PIV and CFD flow fields in Beads-U sub-volume on the vertical slice with $z = 16$ mm.

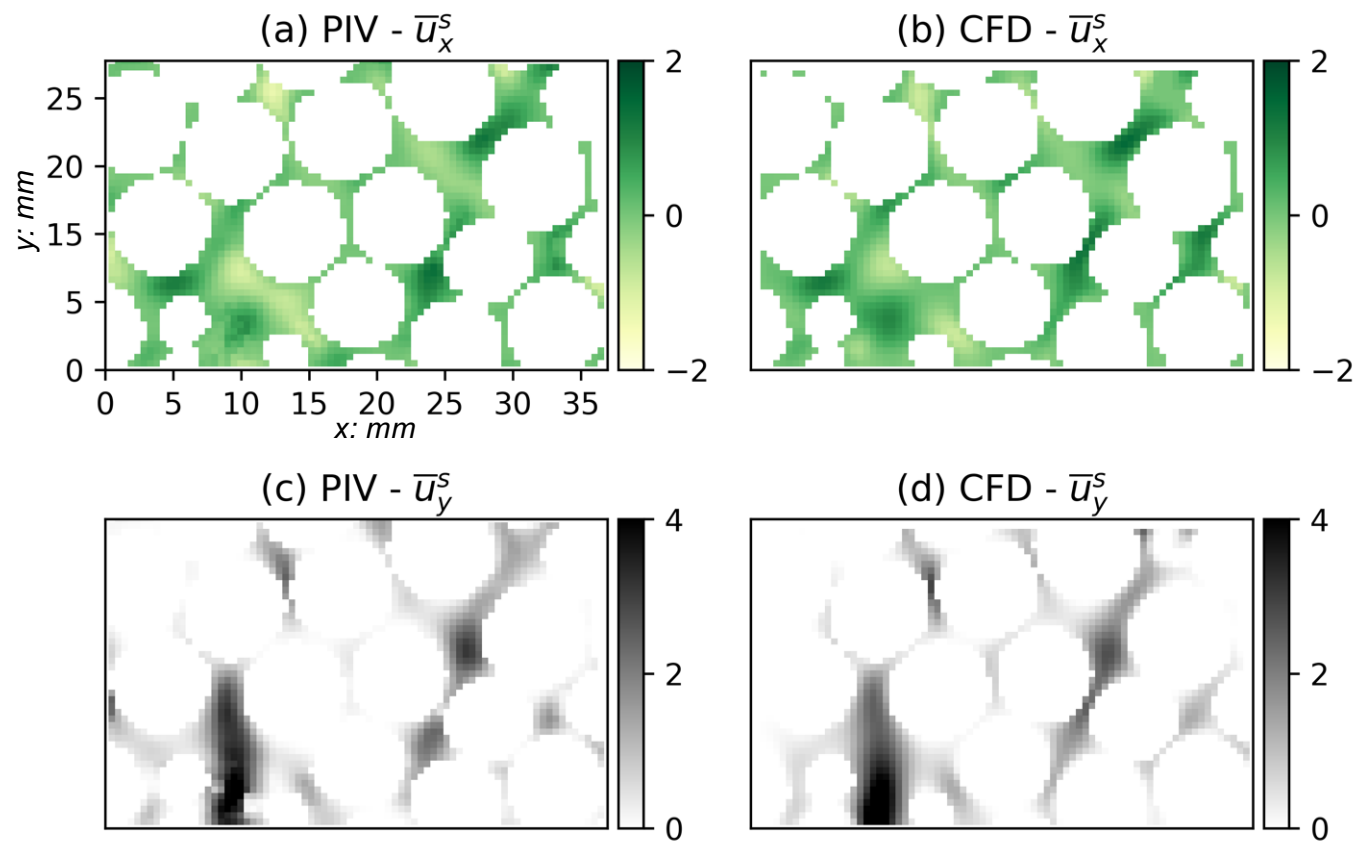


Figure 13. Comparison of the PIV and CFD flow fields in Beads-U sub-volume on three slices with $z = 1, 8$ and 16 mm. Velocity vector length is normalized by seepage velocity.

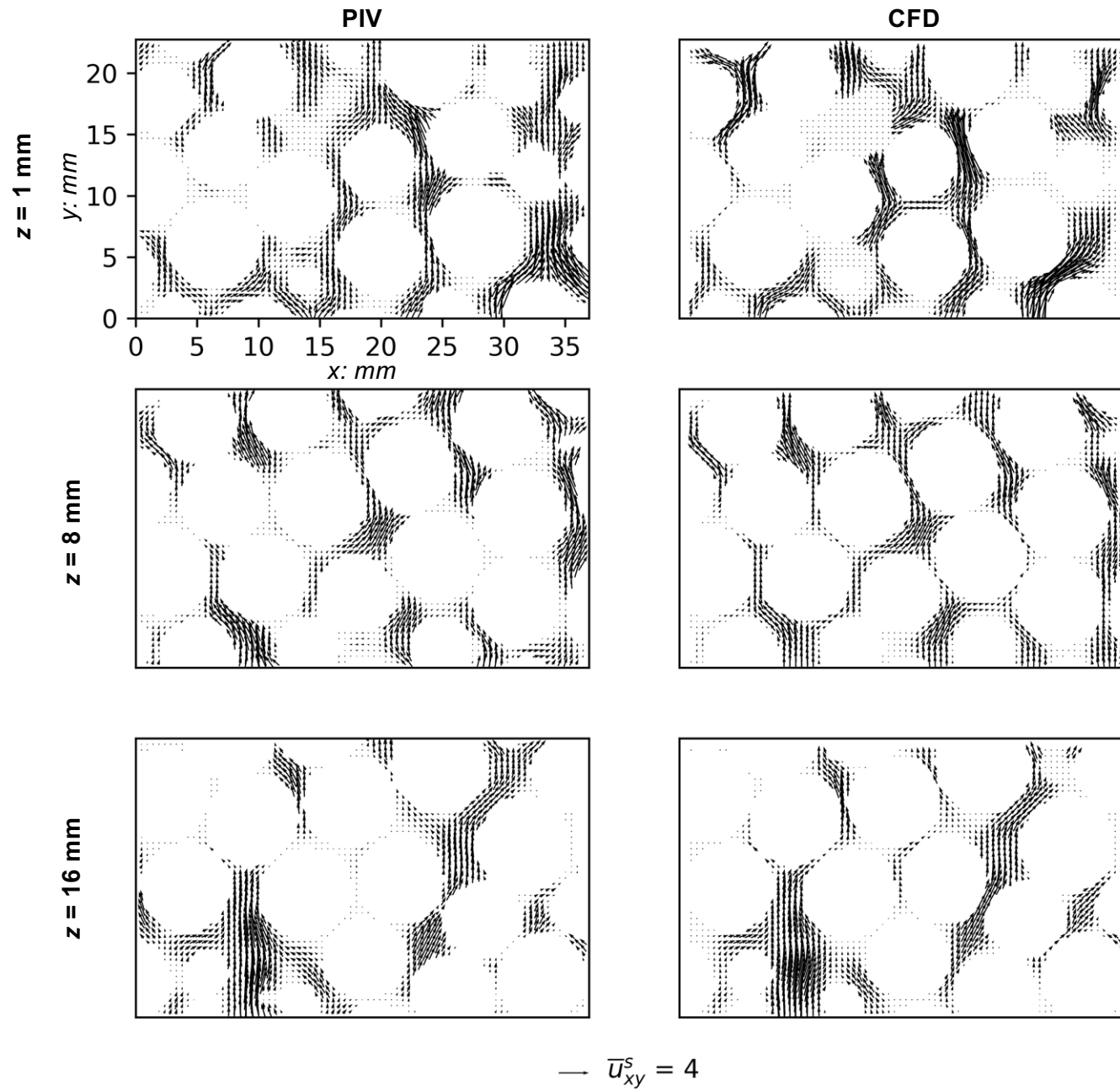


Figure 14. Cumulative distributions of flow velocity at four vertical planes in Beads-U sub-volume obtained from PIV and CFD results.

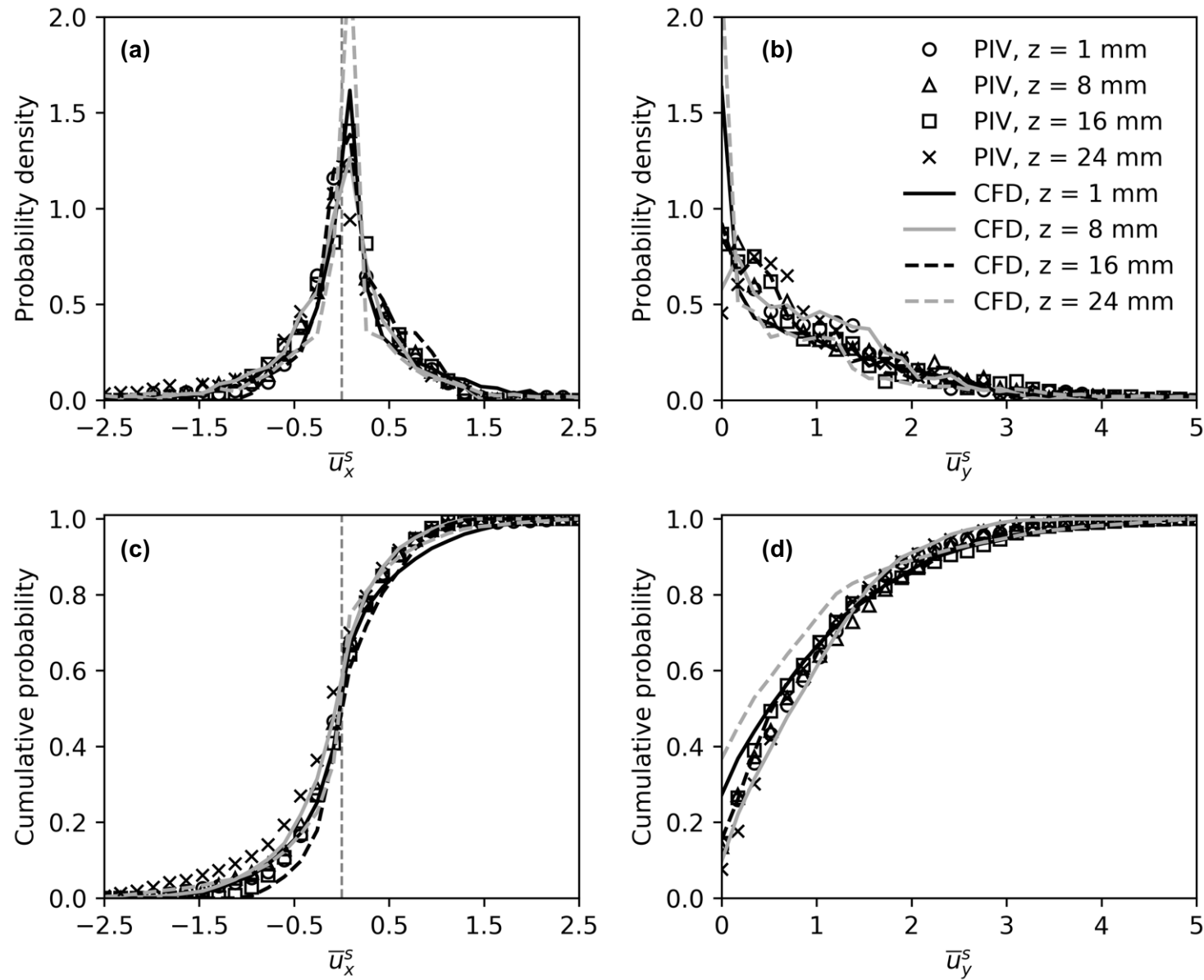


Figure 15. Comparison of the PIV and CFD flow fields in Ang-L sub-volume on three slices with $z = 1, 8$ and 16 mm. Velocity vector length is normalized by seepage velocity. Arrows indicate narrow flow paths.

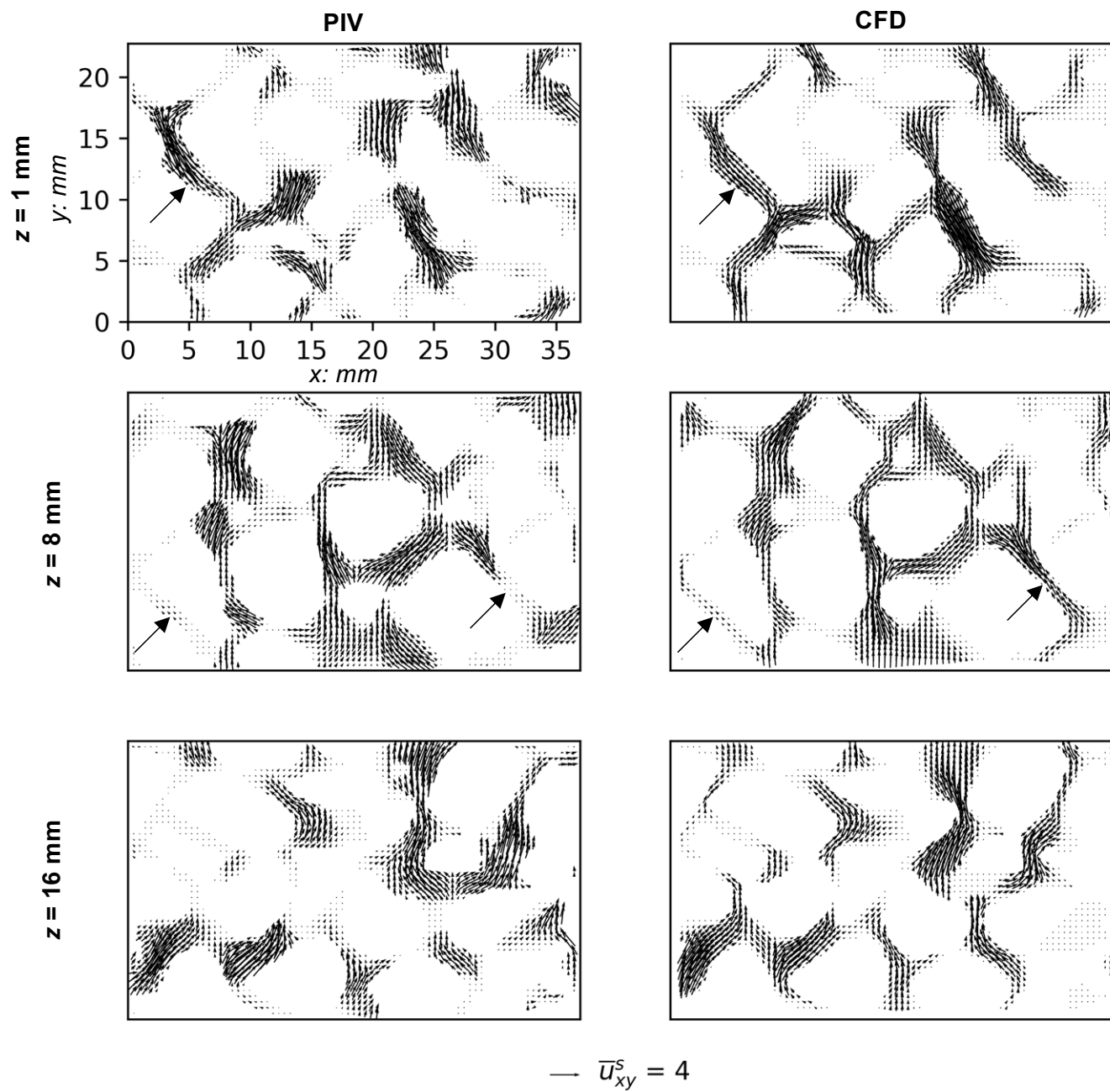


Figure 16. Cumulative distributions of flow velocity at four vertical planes in Ang-L sub-volume obtained from PIV and CFD results.

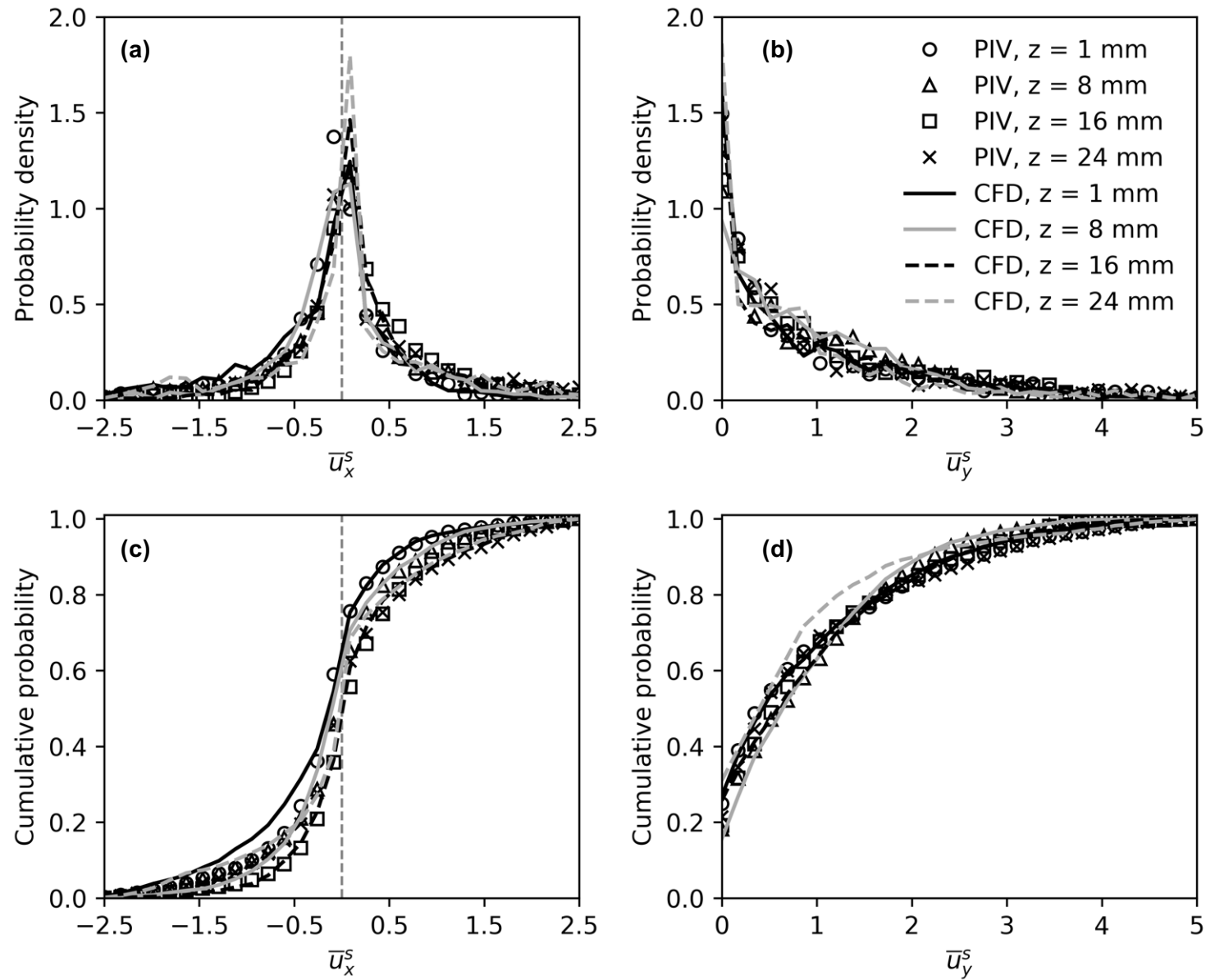


Figure 17. Difference between PIV and CFD flow fields for the vertical slice with $z = 16$ mm in Beads-U sub-volume: (a) horizontal velocity; (b) vertical velocity. The cumulative distributions of PIV and CFD difference for (c) horizontal velocity and (d) vertical velocity on five typical slices in Beads-U sub-volume.

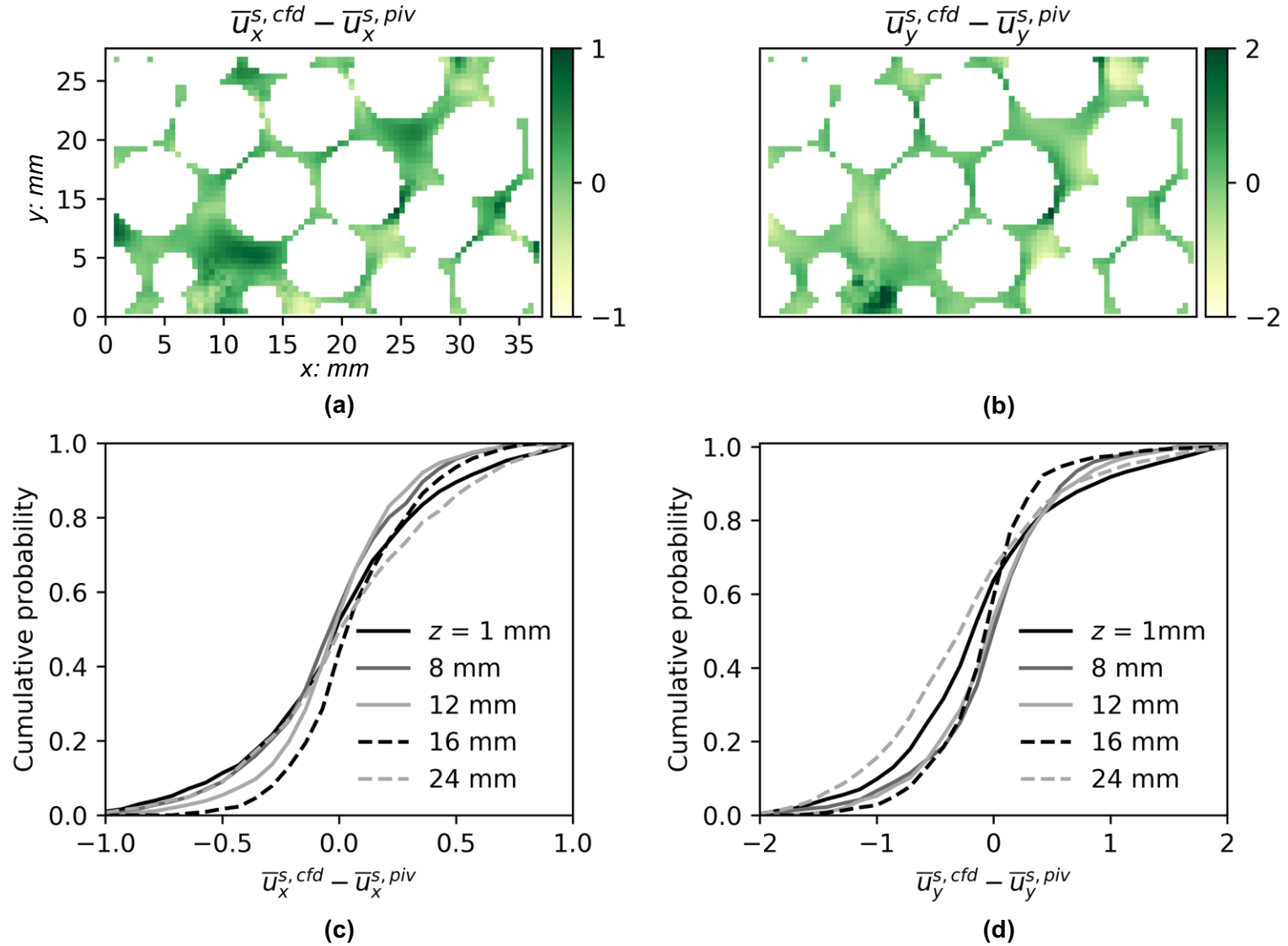


Figure 18. Variation of the mean velocity values obtained from PIV and CFD results and the slice porosity on x-y planes parallel to flow direction.

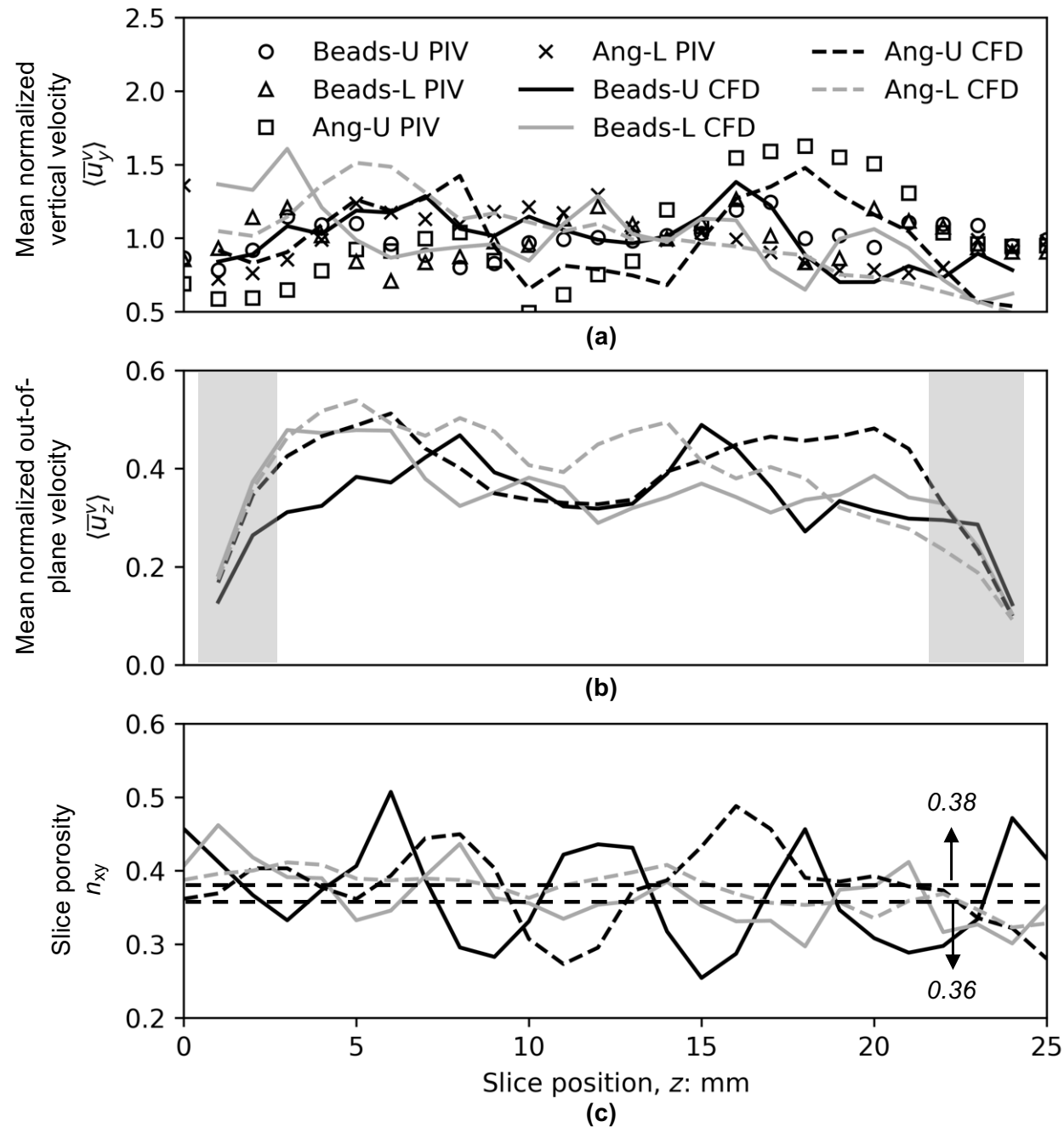


Figure 19. Variation of mean vertical velocity, porosity and hydraulic gradient on x-z planes perpendicular to flow direction predicted by CFD simulations.

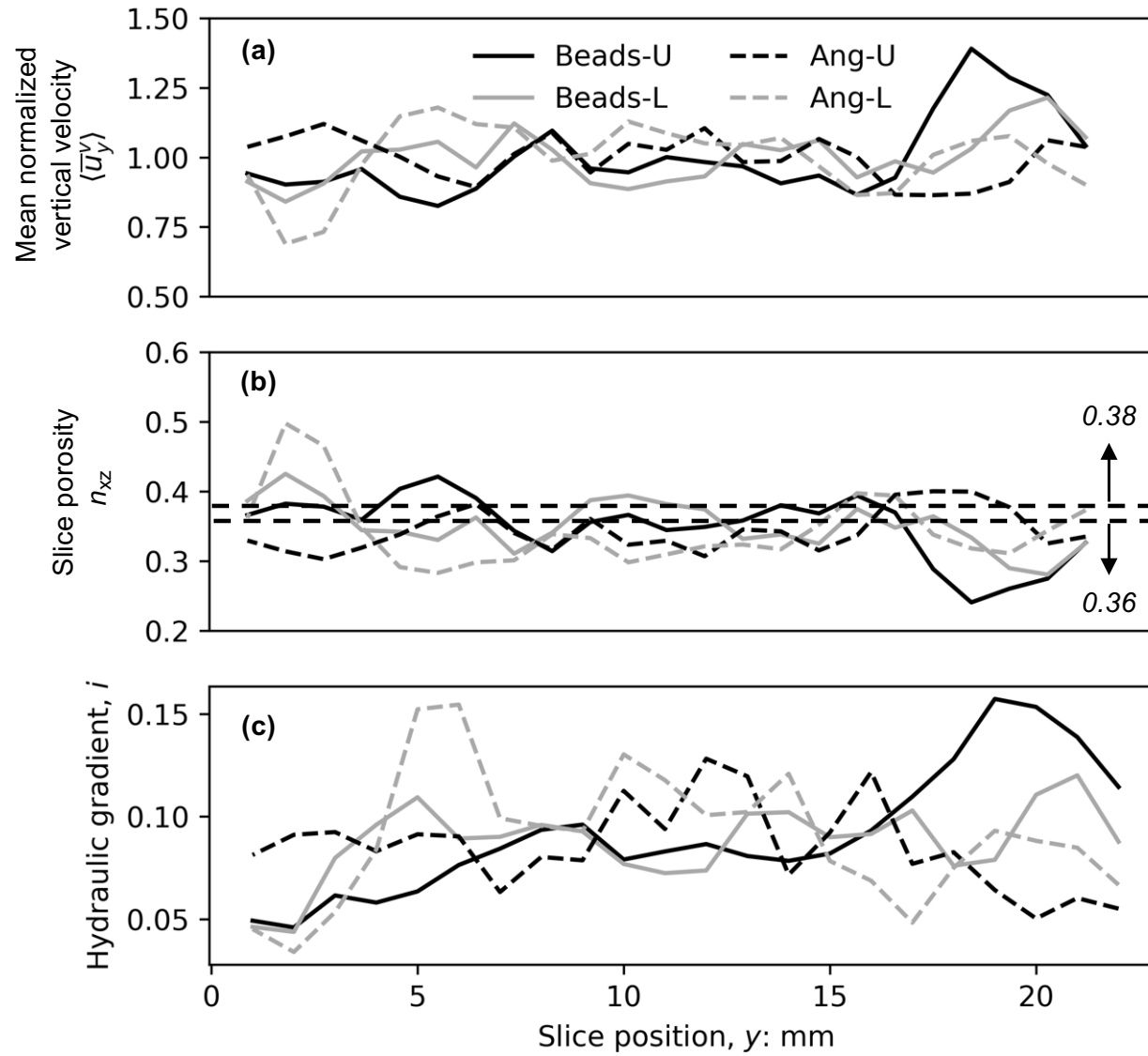


Figure 20. Projection views of drag force vectors for the particles that are not intersecting with boundary walls.

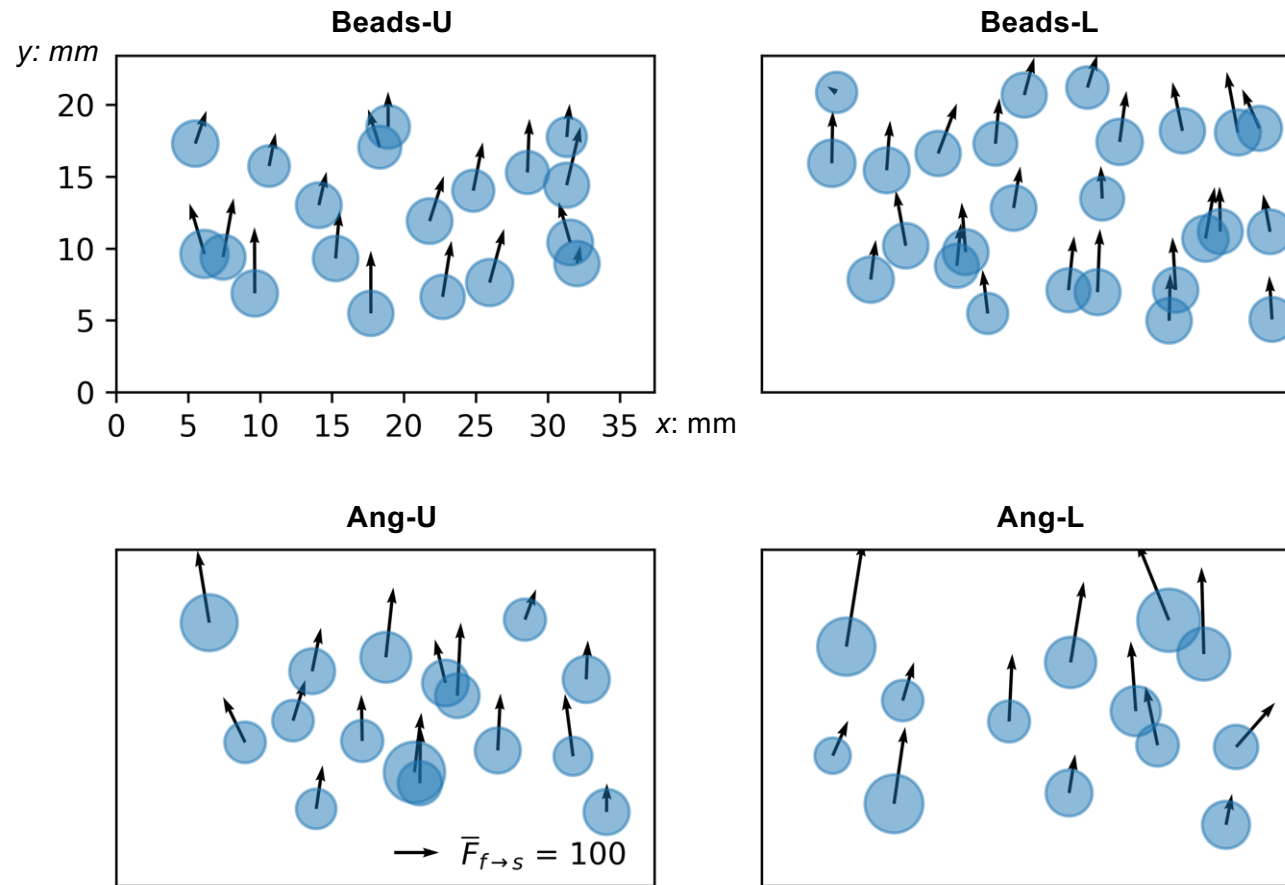


Figure 21. Cumulative distributions of (a) fluid-particle interaction coefficients for beads and angular particles and (b) the normalized fluid-particle interaction coefficients.

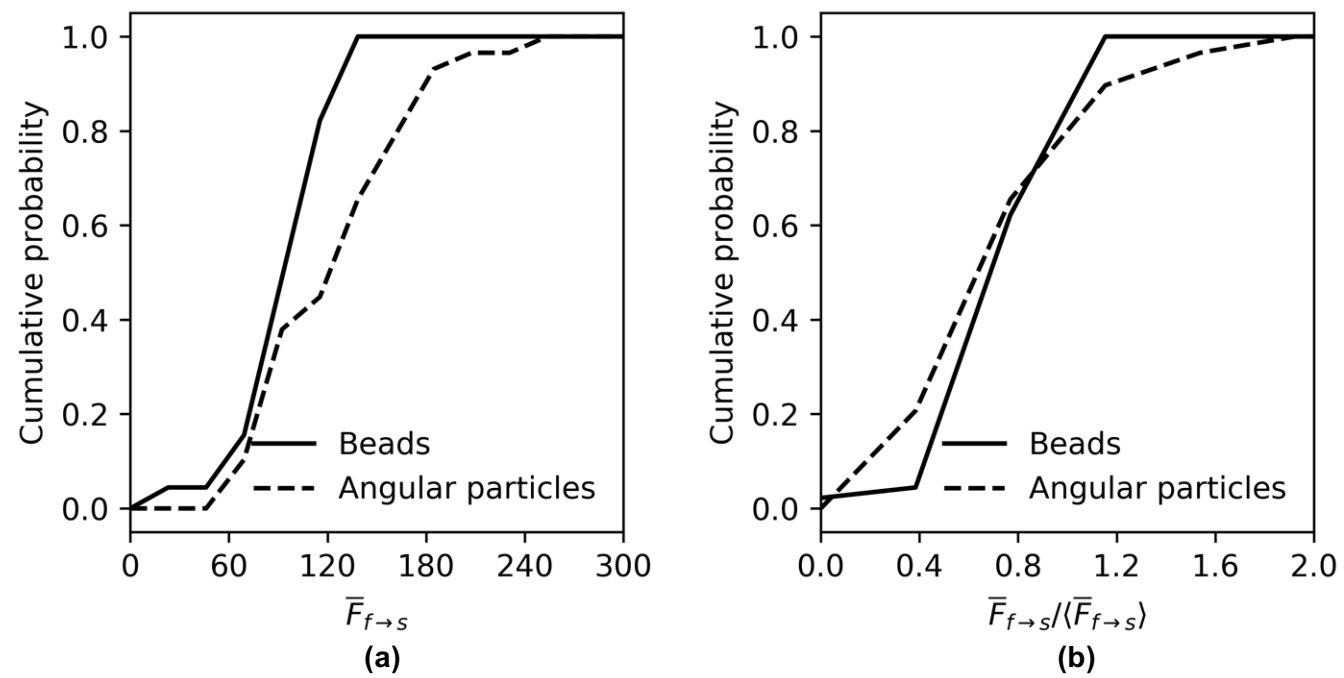


Figure 22. Distributions of (a) the ratio between pressure and viscous drag components, and (b) the angle between fluid-particle interaction and flow direction.

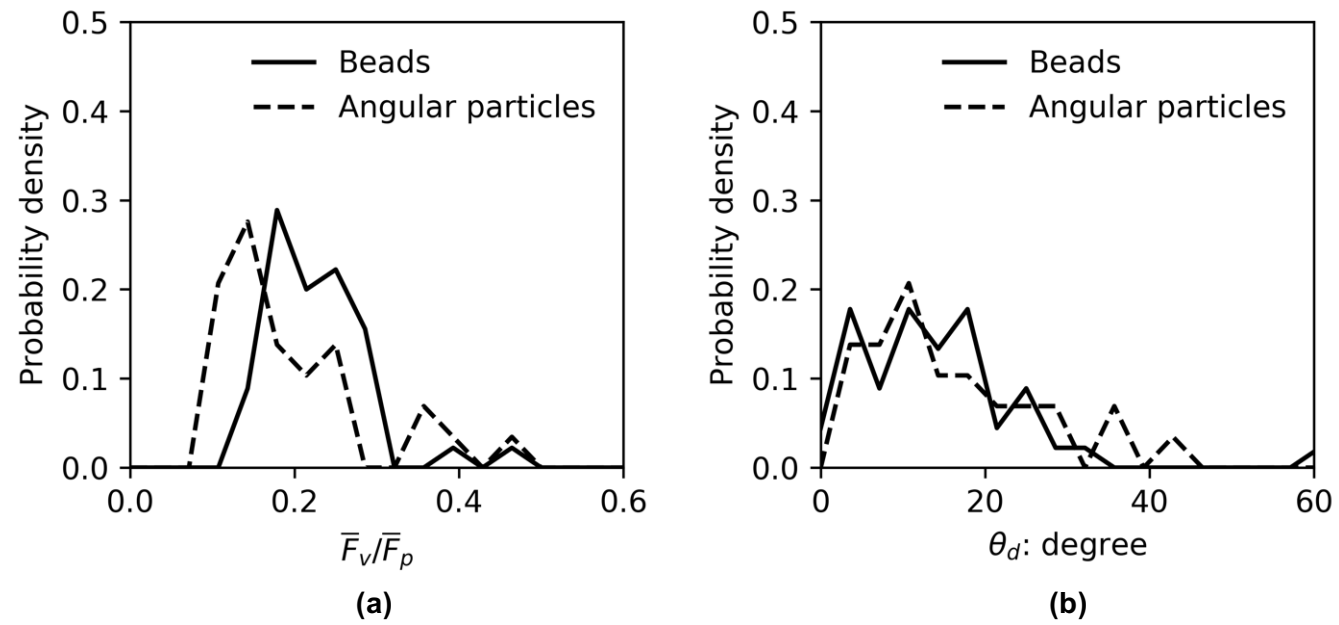


Figure S1. Example of the effect of time resolution of PIV analysis on the estimate of the time averaged component (a) u_x and (b) u_y . The velocities are estimated along the yellow dashed lined shown in the inset of (a).

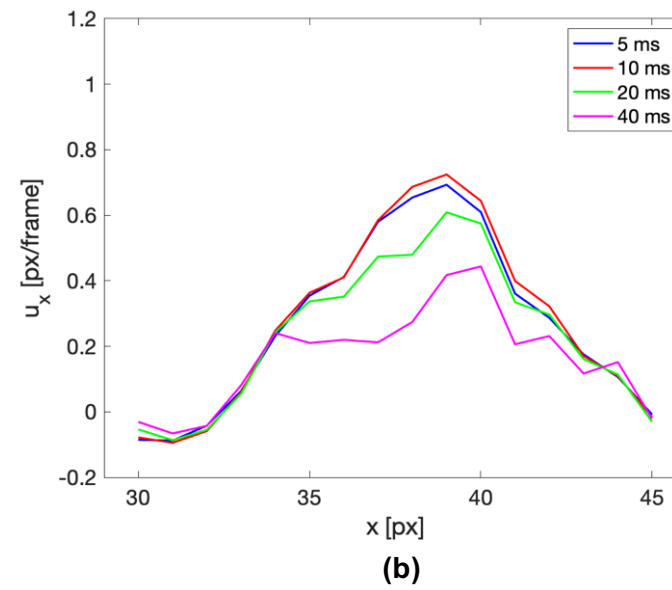
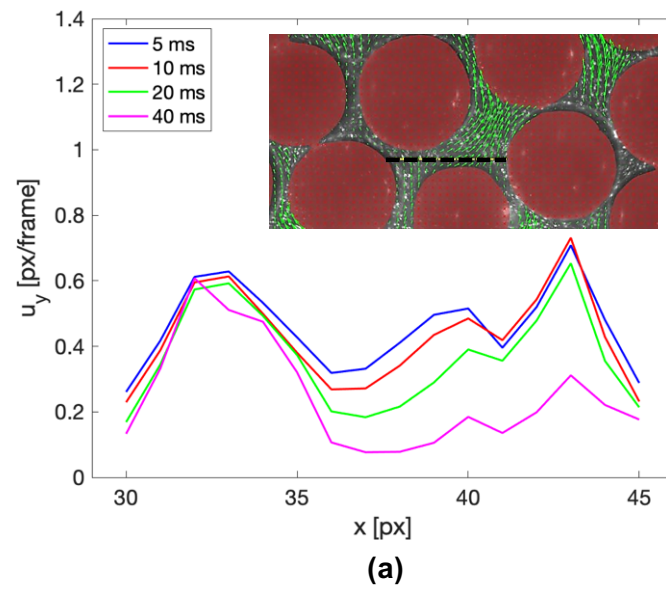
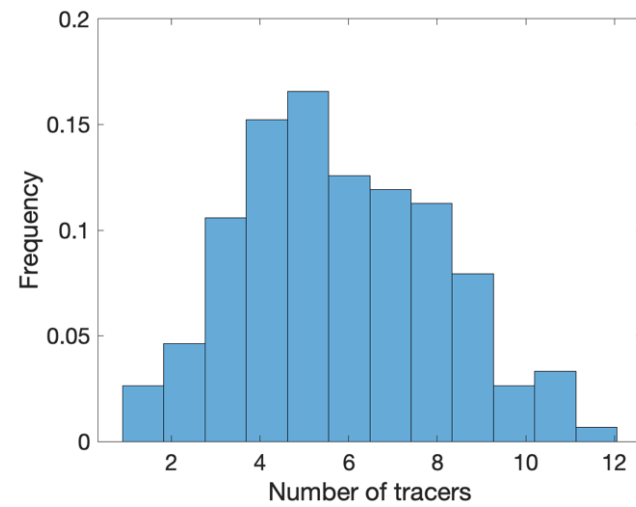
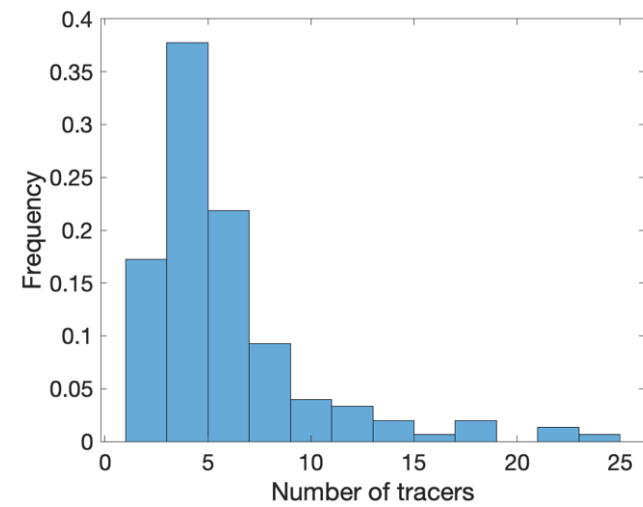


Figure S2. Distribution of the number of tracers for a subsets of interrogation windows (32 x 32 pixels) for (a) beads and (b) angular particles.

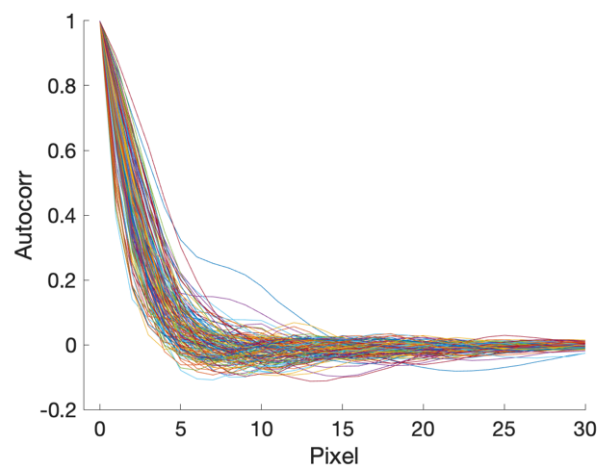


(a)

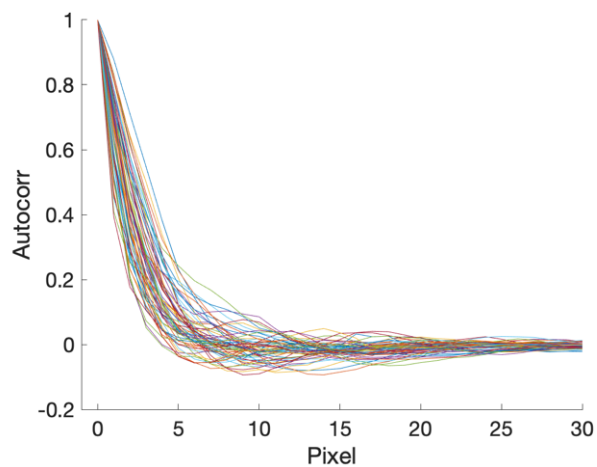


(b)

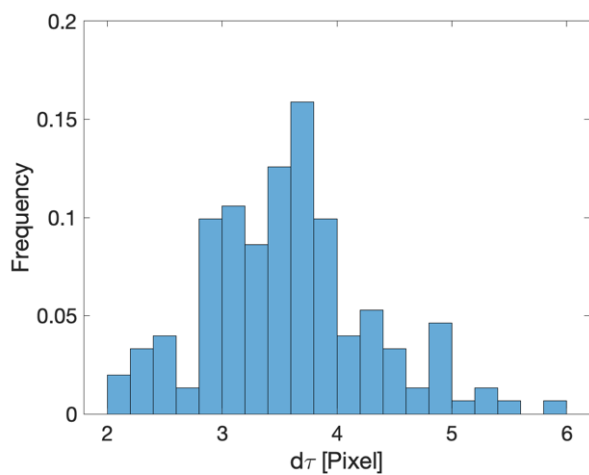
Figure S3. Autocorrelation function for a subsets of interrogation windows (32 x 32 pixels) for (a) beads and (b) angular particles. Histogram of autocorrelation peak width for (c) beads and (d) angular particles.



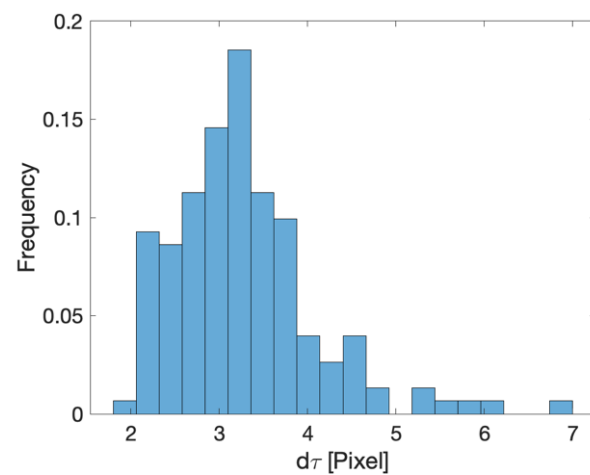
(a)



(b)



(c)



(d)

Figure S4. (a) Typical slice of Ang-U processed by U-Net, and the binarization results at different porosity values (b) 0.31, (c) 0.29, and (d) 0.27.

