

Online Resource 2

Domain-size and microstructure analysis

To test whether two-dimensional flow simulations can reproduce three-dimensional permeability, we generated synthetic porous media with three different geometries (Overlapping Spheres, Fibrous, and Gaussian Random Fields), each created at three porosity levels (0.4, 0.6, and 0.8). We then computed the permeability on both 2D slices (100×100 voxels) and 3D volumes (100×100×100 voxels).

B1. Domain size and microstructure

To assess how domain size affects results, we performed calculations at six different domain lengths (window sizes) ranging from 40 to 100 voxels, representing the full domain and five nested subdomains centered at the midpoint (Fig. B1). This allowed testing whether permeability converges to a representative value with increasing subdomain size, or whether systematic scale-dependent variations persist indicating failure to achieve a representative elementary volume (REV) within the tested domain.

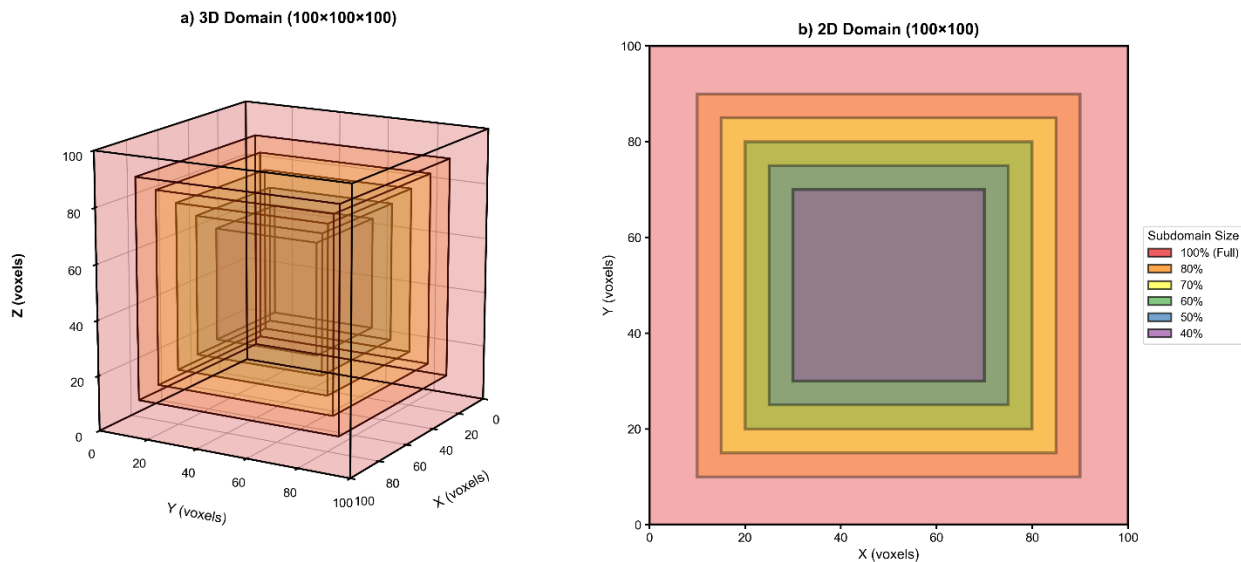


Fig. B1 Simulation domains. Three-dimensional (a) and two-dimensional (b) domains with side lengths of 100, 80, 70, 60, 50 and 40 voxels

To test the impact of microstructural complexity on the permeability difference between 2D and 3D simulation results and the required domain size we systematically increased feature density while maintaining constant porosity. Five variations were generated for each porosity, with Variation 0 corresponding to the base structure and Variations 1–4 introducing progressively finer features.

For the Overlapping Spheres medium, variations were created by increasing the number of spheres while proportionally decreasing their individual radii. This approach ensured that the total solid volume remained constant while the characteristic grain size decreased across variations 0 through 4. For instance, at 0.4 porosity, variation 4 contained approximately 6000 spheres with proportionally smaller radii compared to the base structure's 300 spheres, resulting in identical porosity but distinctly different pore size distributions and connectivity characteristics.

For the Fibrous medium, variations were created by systematically decreasing fiber thickness (0, 20, 35, 50 and 60% reduction for variations 1-4, respectively). In order to maintain the target porosity with thinner fibers, fibers were added to the domain until the desired solid volume fraction was achieved. This resulted in structures with identical porosity but higher fiber densities, as thinner fibers require greater numbers to fill the same total solid volume.

For the Gaussian medium, we created five variations for each porosity by decreasing the Gaussian filter standard deviation ($\sigma = 2, 1.6, 1.3, 1.0$, and 0.8). Smaller σ values produce finer features by reducing the smoothing of the random field. For each variation, the threshold T was adjusted to match the base structure's porosity exactly. With this method we created structures with identical porosity but progressively smaller pore features, with variation 4 having features covering approximately 2 voxels compared to the base structure's 5 voxels.

REV Analysis: Permeability vs Window Size
 3D (solid) | 2D (dashed, slice-avg) | Var 0→4: Base→Fine features (same porosity)

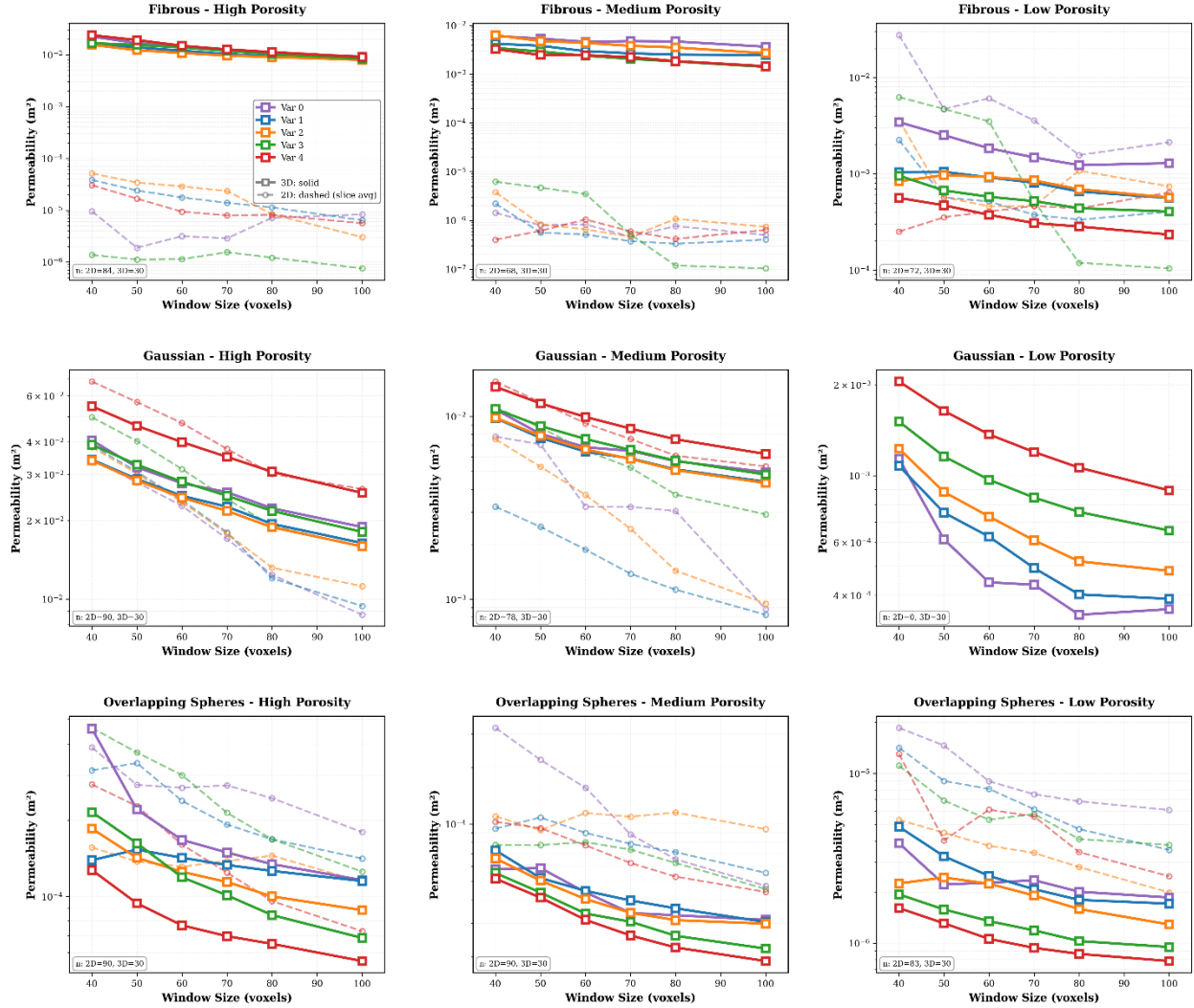


Fig. B2 Two-dimensional (2D) and three-dimensional (3D) permeability across multiple porous media geometries, porosities, and microstructural variations. Permeability was computed at six window sizes (40–100 voxels) for three geometry types (Fibrous, Gaussian Random Field, Overlapping Spheres) across three porosities (High = 0.8, Medium = 0.6, Low = 0.4). 5 variations (Var 0–4) with increasing feature density at constant porosity test whether finer microstructural resolution can enable 2D to reproduce 3D behavior, with Var 0 having the coarsest features and Var 4 the finest. Solid lines with square markers indicate 3D simulations, while dashed lines with circular markers represent 2D simulations (averaged across multiple slices)

Across all geometries, the 3D permeability curves consistently stabilize and become nearly constant between 80–100 voxels, indicating REV convergence. In contrast, 2D values show variable behavior even at the largest window size.