Micro-CT-Based Permeability Characterization of Virgin and Pyrolyzed Wood Using Deep Learning Segmentation and Image-Based CFD Simulations

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Abstract: We present an image-based workflow to quantify how pyrolysis modifies the intrinsic anisotropic permeability of *Pinus pinaster* (maritime pine) earlywood by coupling synchrotron X-ray micro-computed tomography, deep-learning segmentation, and voxel-resolved CFD. Matched submicron microtomography volumes were acquired before and after in-situ pyrolysis under nitrogen (up to 525 °C). Orientation-robust 3D pore/solid segmentation was obtained using three 2D U-Net models trained on longitudinal, radial, and tangential slice sets and fused by majority vote. The segmented pore space was converted into voxel–hexahedral meshes and steady incompressible creeping-flow simulations ($Re \ll 1$) were performed with `OpenFOAM` (`simpleFoam`) to compute the full permeability tensor from volume-averaged velocities and macroscopic pressure gradients. Mesh and padding sensitivity analyses, together with a permeability-based representative elementary volume (REV) study, supported a representative cube size of 390 μm (1300^3 voxels). Pyrolysis caused a slight increase in porosity while shifting the pore local-thickness distribution toward smaller characteristic sizes. Transport was markedly restructured: longitudinal and radial permeabilities decreased substantially, whereas tangential permeability increased by nearly one order of magnitude, yielding a strong reduction of permeability anisotropy. These results suggest that pyrolysis alters flow primarily through changes in constrictions and transverse connectivity, rather than by a uniform opening of conduits.

Keywords: micro-computed tomography; image-based modeling; voxel-resolved CFD; U-Net segmentation; wood permeability; REV; permeability anisotropy.

(a) Segmented 3D volume of the virgin wood.

(b) Segmented 3D volume of the corresponding pyrolyzed wood.

Figure 1: Comparison of segmented microstructures from an anatomically matched earlywood region before and after pyrolysis.