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Effect of roughness in the fluid flow in porous media: based on random fields theory and 3D printing technology

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The morphology of pores is an important factor influencing the permeability of porous materials[1,2,3]. In recent decades, the influence of the morphology of pores on fluid flow in geomaterials has attracted extensive attention in the engineering fields of petrochemistry, hydrogeology, civil and geotechnical structures, with applications in radioactive hazardous waste storage[4], oil and gas storage[5,6,7], carbon dioxide sequestration[8], and geothermal energy extraction[9].

To model porous media whose morphology is precisely controlled, excursion sets of random fields have been used recently[10]. The models generated by this method have the advantages of isotropy, ergodicity, generalizability, stability, and controllability. In previous studies, researchers have focused on generating correlated random fields using the Gaussian covariance function. However, the actual pores are not smooth.

To explore the effect of roughness on fluid flow within porous media, in our research, the Matérn covariance function has been chosen to describe the random field. The Matérn covariance function allows controlling the level of smoothness, which can be adjusted by a parameter ν greater than 0[11]. Using this function, a three-dimensional continuous field can be generated. Afterwards, to transform this continuous field into a binary field with only matrix and pores, the excursion set method is used. This method transforms the continuous field into a binary field with varying volume fractions by selecting different threshold values. Therefore, by controlling the threshold value, the porosity of the generated porous medium can be precisely controlled.

By the above methods, models of porous media whose roughness is precisely controlled are generated. In order to relate the parameter ν to common roughness parameters, we analyze the fractal dimension and the specific surface area of the generated field and compare the relationship between them. Afterwards, to analyze the effect of roughness on fluid flow, experimental and numerical investigations have been performed.

In terms of testing, a number of samples with different roughnesses were generated using SLA 3D printing, which printing accuracy can reach 50 microns. To verify the accuracy and the quality of the 3D printed samples, the samples were characterized by micro-CT technique. By comparing the scanned images with the numerical model, the parameters such as porosity, pore connectivity, fractal dimension, tortuosity, and specific surface area were analyzed. Subsequently, the permeability of each sample was measured through Darcy tests, and the correlation between permeability and roughness was analyzed.

In order to compare with the experimental data, numerical simulations were performed using the lattice Boltzmann method[12], using the Palabos library[13]. This method has advantages in dealing with complex boundaries and parallel operations, which is very suitable for porous media models. Considering factors such as stability and applicability, the D3Q19 lattice model was selected. The numerical model of all the samples used in the test was considered, the fluid flow in the porous medium was simulated under the same conditions in the test, and the flow rate and permeability were calculated.

Finally, the results of the test and simulation were compared and analyzed, and a law describing the evolution of permeability with roughness was proposed.

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