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Laminar to Turbulent Convection in Porous Media: The Role of Solid-Fluid Conductivity Ratios and Porosity Variations

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Transition from laminar to turbulent flow within the framework of conjugate heat transfer in porous media occurs in various applications across different scales, including geothermal energy extraction, thermal energy storage systems, high-temperature gas-cooled reactors, and microchip cooling. Understanding this transition is critical for optimizing systems designed to maximize surface area for efficient heat and mass transfer.

To tackle the regime transition, we developed an advanced lattice-Boltzmann Method (LBM) solver optimized for simulating conjugate heat transfer in porous media. Built on the STLBM open-source platform, the solver integrates thermo-physical heterogeneity and supports multi-threaded, parallelized computations on both CPUs and GPUs. It accurately captures the Navier-Stokes–Fourier dynamics under the Boussinesq approximation, providing a robust framework for analyzing heat and fluid flow in porous structures, including inertial effects and thermophysical heterogeneity.

Using staggered isotropic porous media composed of cylindrical structures, we investigate the effects of porosity, solid-to-fluid conductivity ratio, and Rayleigh number on overall dynamics, including Nusselt number, Reynolds number, and boundary layer thickness. In pure hydrodynamics, increasingly confined pore space strongly influences the transition from Darcy to non-Darcy flow as porosity decreases from 45% to 30%. Extending this analysis, we explore natural convection behavior during the transition from Darcy to non-Darcy (Forchheimer) flow, focusing on Darcy numbers around 10^{-6}. Our simulations further assess the impact of conductivity ratios (0.1 to 10) on convective dynamics across Rayleigh numbers spanning four orders of magnitude (10^{7}–10^{10}).

Our results reveal that inertial forces drive regime transitions from steady-state to oscillatory convection, as evidenced by spatial Reynolds number analysis. Nusselt–Rayleigh scaling in steady-state convection aligns with the classic Nu ~ Ra at low porosities but deviates significantly at higher porosities. For low porosities, the transition to oscillatory convection is strongly influenced by the solid-to-fluid conductivity ratio. At high Rayleigh numbers, higher kinetic energy does not necessarily enhance heat transfer, as boundary layer thickness is influenced by both velocity and the thermal conductivity of the solid and fluid phases. Furthermore, within the examined Darcy numbers, the pore-scale Prandtl number fails to reliably predict the transition to the Forchheimer regime.

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References

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