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Self-organized colloidal streamers in porous media: Emergence, development and clogging consequence

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Colloidal particles from industrial and natural sources can alter the environment they flow through. Colloidal retention and accumulation in porous media may cause catastrophic consequences, such as fouling of filtration membranes, formation damage in geological systems and thrombosis in human bodies. It can also be utilized in many aspects, including enhanced hydrocarbon recovery and targeted drug delivery. Therefore, prediction of retention and accumulation mode is crucial for understanding colloidal transport in porous media.

Conventional description of colloidal transport in porous media is based on filtration theory and core-scale measurements, where the collector efficiency serves as a comprehensive parameter reflecting all particle interactions with the medium. Recent advances in microfluidics have provided tremendous insight into pore-scale particle behaviors. Geometrical confinement in porous media is the most common origin of clogging, such as size exclusion and bridging effects. Physicochemical interactions also drive particle accumulation by promoting surface deposition and aggregation under favorable conditions. Previous studies mainly focus on the direct interaction between intercepted particles and surrounding medium, leading to increased flow resistance at narrow throats. However, the self-organization of colloids under constrained porous flow condition is overlooked.

In this work, we report unexpected formation of colloidal streamers in porous media. Microfluidic experiments with high-speed imaging system combining bright field and fluorescence observations enable us to visualize the emergence and development of self-organized particle structures. Streamer formation is initiated by particle retention in the stagnant zone between solid grains, where the interparticle adhesion contributes to the connection and thickening of streamer structures. Colloidal streamers are found to be ubiquitous by constructing regular arrays with various packing arrangements and densities. Balance between fluid shear force and particle-wall adhesion determines the extension state of these streamers, which is confirmed under oscillate boundary conditions. Numerical simulation with developed model based on computational fluid dynamics and discrete element method reproduces our experimental observations. The triggering mechanism and criterion for streamers are further clarified via theoretical analysis. When introduced into disordered porous medium, streamer development is further strengthened due to the complex geometry. Clogging consequences are observed and quantified for upscaling of streamer impact. Our results reveal the existence and importance of self-organized colloidal streamers, deepening understanding of microscopic colloidal behaviors with macroscopic flow consequences during transport in porous media.

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