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Trapping criteria for three-dimensional periodic liquid particles in micropillar scaffolds

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Liquid particles within three-dimensional periodic scaffolds play a crucial role in various natural and engineering applications, for example, cellular arrays composing living tissue, 3-D materials that mimic tissue with an unprecedented level of control, and innovative liquid-infused materials designed for carbon capture. Although it has been known that fluid interfacial energy during multiphase displacement can drive the emergence of 3-D periodic liquid particles in micropillar scaffolds, the underlying microscale physics and the macroscopic formations of liquid particles in scaffolds remain unclear. Here we establish trapping criteria for the formation of liquid particles in micropillar scaffolds based on the evolution of fluid-fluid interfacial curvature during multiphase displacement, considering four key parameters (pillar size α, contact angle θ, capillary number Ca, and viscosity ratio M). The fundamental trapping criteria are theoretically derived in α-θ space under a viscous stable state and main meniscus-dominated flow, where critical α distinguishes trapping mode and complete displacement, and critical θ further distinguishes between diamond-like and spherical particles in the trapping mode. However, the critical pillar size α for trapping mode or completed displacement can be further affected by viscous instability under lower viscosity ratio M and inter-pillar interface-dominated flow under lower capillary number Ca. These criteria are validated through numerical CFD simulations and confirmed by microfluidic experiments. These results indicate the conditions for trapping 3-D periodic liquid particles in micropillar scaffolds, offering insights that extend and clarify prior literature. The derived criteria provide valuable guidelines for the design of micropillar scaffolds and for the emergence of 3-D periodic liquid particles in micropillar scaffolds under various conditions by controlling multiphase displacement processes.

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