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The pinning dynamics of a non-wetting droplet penetrating a permeable substrate

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Problem statement
The droplet penetration plays an essential role in various fields such as inkjet printing, fuel cells, oil and gas development, new material preparation, and enhanced heat transfer. The functions of non-wetting droplets are used to be limited due to the capillary resistance to its penetration into micropores, but the application of magnetic, electric, acoustic and optical forces, has overcome the limitation. However, the dynamics of the penetration and contact line pinning of non-wetting droplets remain unclear.
Methods
The contact line pinning mechanisms of a non-wetting droplet penetrating a permeable substrate are theoretically explained by considering the force balance of volumetric force, capillary force, and pinning and depinning forces. We propose two dimensionless numbers, Bo_* - the ratio of the volumetric force to the capillary force, and Ct - the ratio of the depinning force to the pinning force, to establish a phase diagram that quickly determines the droplet penetration patterns. We further perform a series of lattice Boltzmann (LB) simulations, and the results match well with our theoretical analysis.
Results
The time evolutions of the contact area diameter Dc, the droplet height h, the penetrated droplet volume percentage Sp, and the apparent contact angle θ are derived as illustrated in Figure 1, in which the contact angle dynamics during contact line pinning and shrinking are further clarified. For Bo_* ⊠ 1, the droplet will not penetrate the substrate; for $Bo_* > 1$ and Ct ⊠ 1, the droplet will penetrate with a pinned contact line; for $Bo_* > 1$ and $Ct > 1$, the droplet will penetrate with contact line shrinking. The phase diagram that quickly determines the droplet penetration patterns is exhibited in Figure 2.
Discussions and Conclusions
The penetration dynamics of a non-wetting droplet into a permeable substrate are studied both theoretically and numerically, with a special focus on the contact line pinning mechanisms. The lattice Boltzmann simulations are performed and show excellent agreements with our theoretical derivations and intuitively illustrate the dynamic penetration processes.
We propose two dimensionless numbers: a modified Bond number Bo_* and a new dimensionless number Ct. These two numbers are applied to establish a phase diagram using that determines the penetration patterns and pinning conditions of the droplet: if Bo_*⊠1, the droplet will not penetrate the substrate; if $Bo_*>1$ and Ct⊠1, the droplet will penetrate with a pinned contact line; if $Bo_*>1$ and $Ct>1$, the droplet will penetrate with contact line shrinking. For the droplet penetration mode with contact line shrinking, we also find the contact angle change can be divided into three patterns: the constant contact angle, the contact angle rebound, and the contact angle decrease.
This work successfully explains the pinning mechanisms of the penetrating non-wetting droplet found in experiments, moreover, the phase diagram offers a quick evaluation of the droplet penetration patterns, and provides new guidelines to achieve better performance for many applications.

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References

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