Capillarity

Vol. 12, No. 1, p. 1-5, 2024

Perspective

Microfluidic experiments and numerical simulation methods of pore-scale multiphase flow

Jianchao Cai[1]*, Jianlin Zhao[2], Junjie Zhong[3,4], Bate Bate[5]

[1]*National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, P. R. China*

[2]*College of Petroleum Engineering, China University of Petroleum, Beijing 102249, P. R. China*

[3]*National Key Laboratory of Deep Oil and Gas, China University of Petroleum (East China), Qingdao 266580, P. R. China*

[4]*School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, P. R. China*

[5]*MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Institute of Geotechnical Engineering, Zhejiang University, Hangzhou 310058, P. R. China*

Keywords:
Microfluidics
pore network model
numerical simulation
multiphase flow
pore-scale modeling

Cited as:
Cai, J., Zhao, J., Zhong, J., Bate, B. Microfluidic experiments and numerical simulation methods of pore-scale multiphase flow. Capillarity, 2024, 12(1): 1-5.
https://doi.org/10.46690/capi.2024.07.01

Abstract:
Multiphase flow is a common scenario in industrial and environmental applications. Especially at microscopic scale, accurately describing flow processes is challenging due to fluid-fluid, fluid-solid, and solid-solid interactions. Pore-scale microfluidics and numerical simulation methods considering complex topology are increasingly being applied to study multiphase flow phenomena. This work focuses the recent applications of microfluidic experiments and new numerical simulations in complex flows for enhanced oil recovery. Two types of coupling algorithms are provided to integrate the advantages of pore network model and direct numerical simulation methods. For fines migration, the computational fluid dynamics-discrete element method is proposed to describe the coupling process between fluid and solid particles. Pore-scale microfluidic experiments and simulation methods deals with complex flow processes at micro/nano scales, providing effective solutions for complex industrial processes.

1. Introduction

Flow and transport in porous media is a common phenomenon in a lot of engineering and scientific problems, such as oil and gas field development, hydrate extraction (Jung et al., 2012), geological CO_2 storage (Othman et al., 2018), groundwater remediation (Liu et al., 2019b). The microscopic multiphase flow patterns are complex due to the influences of capillary force, viscosity force, gravity, etc., making it difficult to predict by conventional means. In recent years, with the rapid development of imaging techniques and computing power, pore-scale experimental and numerical simulation methods are becoming increasingly important in revealing the underlying physics of fluids flow or fines transport in porous media (Cai et al., 2022; Chen et al., 2022a).

Microfluidics, known for its precise manipulation of minute fluid volumes, is a popular pore-scale experimental method. By downsizing the experimental scale to the micro level, researchers can directly observe and manipulate fluid dynamics within porous structures. It stands as a transformative force within the oil and gas industry, impacting operations from upstream exploration to downstream processes. In exploration, microfluidic devices enable unprecedented reservoir characterization, providing high-resolution analyses of rock and fluid properties. The role of microfluidics extends to real-time monitoring, where portable devices allow on-site analysis of oil and gas samples. Beyond operational efficiency

Yandy Scientific Press

*Corresponding author.
E-mail address: caijc@cup.edu.cn (J. Cai); zhaojianlin@cup.edu.cn (J. Zhao); zhongjunjie@upc.edu.cn (J. Zhong); batebate@zju.edu.cn (B. Bate).

Received February 21, 2024; revised March 2, 2024; accepted March 19, 2024; available online March 22, 2024.

gains, this precision and portability hold promise for reducing environmental impact through targeted and sustainable hydrocarbon extraction practices. In addition, it also helps to reveal phenological behaviors of fines transport in porous media directly (Liu et al., 2019a; Bate et al., 2022). The ability to mimic realistic conditions at a microscopic scale advances our fundamental understanding of fluid and particle behaviors in porous media.

Although the microfluidics enables direct observation of fluid flow and fines transport in porous media, the interacting mechanisms between fluids, fine particles and porous matrix cannot be elucidated. Numerical simulation methods hold the promise of quantifying fluid-fluid, fluid-solid and solid-solid interactions, yielding deep understanding of the governing factors for multiphase flow in porous media. At the pore-scale, fluid flow in porous media can be modeled by the direct numerical simulation (DNS) method or pore-network model (PNM). The DNS method simulates fluid flow through solving the Navier-Stokes equation directly in the reconstructed digital porous structures, which is accurate in describing fluid flow process with high computational costs. While the PNM uses the Darcy-type equation to characterize fluid flow in the simplified pore network of a porous medium, which is much more computationally efficient at the expense of accuracy. To further consider the influence of particle fines, the discrete element method should be incorporated, which represents individual particles as discrete entities. In addition, a coupling algorithm between fluid flow solver and particle transport solver is required to introduce the fluid-solid interactions.

This work presents the recent main advances in modeling of pore-scale multiphase flow in porous media by means of microfluidic experiments and numerical simulation methods. The development in microfluidics for pore-scale fluid phase behavior and transport phenomena are summarized, and the effects of hypergravity on two-phase displacement are analyzed. Then the pore-scale fluid flow simulation methods coupling DNS and PNM are analyzed, which aim to combine the advantages of both methods. Finally, the computational fluid dynamics-discrete element method (CFD-DEM) simulations for fines migration are presented.

2. Microfluidics for pore-scale fluid

Zooming into the pore scale, microfluidics has emerged as an indispensable tool in unraveling fluid phase behavior and transport phenomena(Sun et al., 2021). Studies showcase microfluidic devices that replicate complex porous structures encountered in reservoir rocks (Gaol et al., 2020). These scaled-down representations empower researchers to observe and analyze fluid behaviors in unprecedented detail, exploring critical aspects such as phase change, miscibility, and multiphase flow (Bao et al., 2017). This utility also extends to comprehending capillary trapping mechanisms during carbon sequestration, providing insights into factors influencing storage efficiency (Abolhasani et al., 2014). Microfluidics not only elucidates fluid flow physics at the pore scale but also contributes to informing larger-scale reservoir management strategies within the oil and gas industry.

In unconventional reservoirs, microfluidics has recently assumed a pivotal role in studying fluid properties at the nanoscale. Studies showcase microfluidic platforms simulating conditions within nanoscale pores in shale formations (Zhong et al., 2018). These investigations delve into phenomena such as condensation, vaporization and diffusion of hydrocarbons within the tight porous matrix (Zhong et al., 2020). Additionally, using microfluidic devices elucidates transport behaviors of complex fluid mixtures in unconventional reservoirs (Liu et al., 2022). This evolving research not only contributes to a fundamental understanding of fluid dynamics at the nanoscale but also holds immense promise for optimizing extraction techniques and maximizing shale gas and oil recovery.

Beyond understanding fundamental reservoir fluid properties, microfluidics plays a pivotal role in EOR. Employing microfluidic platforms, investigations scrutinize the pore scale interaction between surfactants and reservoir rock surfaces during surfactant flooding for enhanced oil recovery (EOR) (Lifton, 2016). Exploration into nanoparticle-stabilized CO_2 foam for EOR provides insights into foam stability and sweep efficiency at the pore scale (Nguyen et al., 2014). Microfluidics focus on understanding the rheological behavior of polymer solutions in porous media—a crucial aspect for optimizing injection strategies (Del Giudice, 2020). Furthermore, employing microfluidics to study microbial-enhanced oil recovery (MEOR) reveals insights into the impact of microbial activity on oil viscosity and wettability alteration, paving the way for innovative biological EOR methods (Gaol et al., 2019).

The displacement efficiency and flow pattern of the invading phase are affected by pressure gradient, which is closely related to gravity (buoyance). During two-phase displacement under gravity, such as enhanced oil recovery, interfacial tension decrement leads to increment of the Bond number (defined as the ratio of gravitational to capillary force) and the improvement in sweeping efficiency (Xu et al., 2019). During geologic carbon storage, CO_2 is injected into subsurface geological formation. The fate of CO_2 is a combination of processes such as dissolution, bubble ripening, and gravity-driven migration (Huppert and Neufeld, 2014; Celia et al., 2015; Krevor et al., 2015). To date, the gravity factor sees a few investigations of finite-size effects on the pressure-saturation relationship in a given porous medium during slow drainage, while further utilization, especially in hypergravity environment, normally generated via centrifugal acceleration, shows promises in modeling field-scale prototype engineering practices with meter-scale laboratory models (Ayaz et al., 2020; Chen et al., 2022b, 2023). Preliminary experimental results suggest that high gravity results in enhanced fingering given the flow direction is the same as the gravity. In graded porous media, the effect of structural gradient on drainage pattern can be enhanced or reversed by gravity (Vincent-Dospital et al., 2022). A scaled hypergravity model can be used to reproduce long-term and large-scale Ostwald ripening process in a short period. Hypergravity enhances body force, promotes relative motion between phases with different densities, and accelerate the evolution of multiphase transportation. Interplays among hyper gravity, capillary, and viscous force are offset by gravity in a hypergravity environment. The validity of such results to

represent the actual two-phase flow behaviors in a reservoir is yet to be proved. It is also suggested that the validity of the scaling laws should be proved via microfluidic scale models. By the same token, fines transport in porous media under hypergravity condition should also be studied to explore the potential applications in oil industry and carbon neutrality-related engineering practices.

3. Pore-scale simulation coupling direct numerical simulation method and pore network model

Compared with the pore-scale experimental method, the numerical simulation method is more cost-effective and more flexible in variable control. In addition, all the detailed flow information inside the pore space can be obtained. There are mainly two types of pore-scale numerical simulation methods for fluid flow in porous media (Zhao et al., 2019): the DNS and PNM. In the DNS method, to accurately characterize the complex porous geometry, usually a large amount of computing meshes are required. Accordingly, the computational cost is usually high, necessitating high-performance clusters. In the PNM method, the complex porous structures are simplified into regular pore bodies connected by throat bonds, which significantly reduces the computing meshes. In addition, the governing equations in PNM is much simpler than those in DNS method. Therefore, the computational efficiency of PNM is extremely high. However, it fails to describe the detailed flow information as the real complex pore geometries cannot be captured. Developing an accurate and efficient pore-scale model by coupling the DNS and PNM methods is highly meaningful for study fluids flow in porous media. There are two ways to achieve this goal (Zhao et al., 2023).

One way is to incorporate the DNS simulation results into PNM simulation through providing more accurate transport parameters retaining more shape information. For single-phase flow, three improved pore network extraction methods have been developed (Zhao et al., 2020b). The first one keeps the real throat cross section for the throat bond instead of a simplified regular shape (Miao et al., 2017; Rabbani and Babaei, 2019; Zhao et al., 2020b). The second one uses a serial of sub-throat bonds with real cross sections to characterize the cross section variation between two pore bodies (Zhao et al., 2020b). The third one directly extracts the pore-throat-pore element without any shape simplification (Sholokhova et al., 2009; Van Marcke et al., 2010; Zhao et al., 2020b). As the irregular throat geometries are used in these improved pore network models, the DNS method is used to calculate the corresponding single-phase flow conductance. Since more shape information is incorporated into the pore-network model, the accuracy in describing single-phase flow in porous media increases (Zhao et al., 2020b). For quasi-static two-phase drainage flow, the throat information is vital as it determines the invading paths. Therefore, the improved PNM with real throat cross section can provide more accurate prediction results than the conventional PNM (Zhao et al., 2020a). The two-phase flow properties across these real throat cross sections are also determined by the DNS simulations. The machine learning method is a promising predictive tool when finding an exact expression is challenging. It has been successfully used to predict the single-phase and two-phase flow properties across the real throat cross sections (Rabbani et al., 2019; Zhao et al., 2020a), leading to a significant enhancement in computational efficiency.

The other way is to divide the porous medium into two computational domains for DNS and PNM simulations and couple the two methods through the well-designed boundary conditions. For a dual-scale porous medium, the two computational domains can be fixed. For example, for wind driven drying of a porous medium, the DNS method can be used to simulate the velocity field in the open space outside the porous domain, while the PNM simulates the drying process inside the pore structures. The two methods are coupled through boundary condition at the interface of the porous medium (Xu et al., 2016, 2019a). While for a single-scale porous medium, the computational domains can be dynamic. The porous medium can be decomposed into several sub-pore domains based on watershed method. Then the phase distribution can be mapped to the sub-pore domains, leading to three types of pores: the single-invading-phase pore, the single-defending-phase pore, and the two-phase pore. The PNM is used to simulate flow in the single-phase pores and the DNS is used to capture the interface dynamics in the two-phase pores. The two methods are coupled through proper boundary conditions between the two types of pores (Mehmani et al., 2019a; Zhao et al., 2022). As the interface evolves, the computational domain changes dynamically. Such coupling method significantly increases the computational efficiency as the more computationally demanding DNS method is only used to simulate flow in just a portion of the porous medium.

4. CFD-DEM simulations for fines migration

CFD-DEM is a forward modeling method, whereas the motion of fluid and solid particle is solved separately in Euler and Lagrangian frameworks. The fluid motion is controlled by Navier-Stokes equations, while the solid particle motion is controlled by Newton's laws of motion. Coupling of the fluid phase and solid particle is achieved by data exchange, such as momentum and particle position. CFD-DEM can analyze fluid-particle and particle-particle interactions at particle scale, such as drag force, pressure gradient, van der Waals interaction, and Coulombic forces (Liu et al., 2023). As such, CFD-DEM is widely applied in geotechnical engineering, chemical engineering, environmental engineering, and energy engineering. For the instance of ground nano zero-valent iron (nZVI) injection, a coupled of CFD and DEM was adopted to study the transport and retention behaviors of nZVI particles (Liu et al., 2024). Influencing factors on fines transport and clogging behaviors including injection velocity, attraction and repulsive forces, could be quantitatively analyzed. Extreme increment of injection velocity increases the local relative particle concentration, which is not conductive to nZVI migration. Increment of attractive force between particles decreases the surface deposition. Increase of repulsive force between particles increases the dispersion of nZVI. However, extremely high re-

pulsive force forms “membrane repulsion effect”, which hinds nZVI migration in porous media. Temporal-spatial distribution of aggregate size, particle coordination number, and particle transport velocity could also be revealed through CFD-DEM simulation. Depending on the injection velocity and charge, a phase diagram characterizing the particle behavior could be proposed, including clogging zone, non-clogging zone, and membrane repulsion effect zone, which could provide guidance for engineering practice. CFD-DEM is also suitable for other cases of fines migration, such as silty clay migration or sand production during hydrate extraction in sandstone layers under oceans. Furthermore, in petroleum engineering, the CFD-DEM method can be used to simulate problems such as sand blockage during oil extraction, migration of proppants in cracks, and settling of oil droplets in settling tanks. After being combined with the volume of fluid method, it can also be used for simulating the displacement process with adding nanoparticles.

5. Conclusions

Microfluidics emerges as a transformative force in the oil and gas industry, enhancing reservoir characterization, optimizing EOR strategies, and providing unprecedented insights at the pore scale. Its versatile applications contribute to sustainable practices and innovation across various facets of hydrocarbon extraction and recovery. Complementary with microfluidics, the pore-scale simulation method is more advantageous in quantifying the fluid-fluid and fluid-solid interactions, thus revealing the transport mechanisms in porous media. Some new techniques coupling the DNS and PNM methods are developed in recent years, successfully combing the accuracy of DNS and efficiency of PNM. The CFD-DEM coupling method has been widely used to analyze the fluid-solid interactions, especially fines migrations, in porous media, which can provide guidance for engineering applications.

Acknowledgements

This work was supported by the Basic Science Center Program for Multiphase Evolution in Hypergravity of the National Natural Science Foundation of China (No. 51988101), the National Natural Science Foundation of China (Nos. 52174051, 42172159), and the Science Foundation of China University of Petroleum, Beijing (No. 2462023QNXZ001).

Conflict of interest

The authors declare no competing interest.

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