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Invited review

The microfluidic in geo-energy resources: Current advances and future perspectives

Zhao Lu[1], Lizhong Wang[1,2]*, Zhen Guo[1,2], Yi Hong[1,2]*, Limin Zhang[3,4]

[1] *Hainan institute of Zhejiang University, Sanya 572025, P. R. China*

[2] *Department of Civil Engineering, Zhejiang University, Hangzhou 310058, P. R. China*

[3] *HKUST Shenzhen-Hong Kong Collaborative Innovation Research Institute, Shenzhen 518000, P. R. China*

[4] *Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong 000000, P. R. China*

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Abstract:
The development of geo-energy resources plays a crucial role in transitioning towards a sustainable energy future and achieving carbon neutrality. Conventional experimental approaches, constrained by macroscopic-scale observations and high costs, often fail to capture critical microscale mechanisms. In contrast, microfluidic technology offers distinct advantages through high-resolution visualization, high-throughput screening, and precise simulation of practical conditions such as temperature, pressure, pore structures, and chemical reactions, effectively addressing key challenges in geo-energy extraction. This review systematically examines innovative applications of microfluidics in shale gas reservoir, carbon capture, utilization and storage, chemical enhanced oil recovery, enhanced geothermal system, and natural gas hydrate. It further investigates prevailing challenges regarding material compatibility, scale translation, and data extrapolation methodologies. The study demonstrates that microfluidic systems provide innovative experimental methodologies, enabling unprecedented precision in elucidating complex geological processes through enhanced mass transfer efficiency and high-throughput screening capabilities, thereby bridging microscale mechanisms with macroscale phenomena. In the future advancements, the microfluidic technology demands synergistic convergence with materials science, chemical reactions, artificial intelligence, and physical explanation to promote the geo-energy research. This interdisciplinary convergence will provide scientific foundation for developing efficient and sustainable energy solutions.

1. Introduction

The development of Geo-energy sources, including shale gas, carbon capture, utilization and storage (CCUS), chemical enhanced oil recovery (EOR), enhanced geothermal system, and natural gas hydrate, are essential for achieving the energy transition and carbon neutralization goals (Abedini et al., 2022; Lei et al., 2024). Releasing natural gas from tight reservoirs through horizontal drilling and hydraulic fracturing technologies has become an important source of global natural gas supply, which is main technology of shale gas exploitation. CCUS can seal up tens of billions of tons of CO_2 gas emissions for a long period by injecting CO_2 into deep brine or depleted oil and gas reservoirs, significantly reducing greenhouse gas emissions (Abolhasani et al., 2014). The technology of chemical EOR can enhance oil recovery by injecting surfactants or polymers, and realize dual benefits of carbon storage and energy exploitation in combination with CO_2 flooding (Lifton et al., 2016; Alarji et al., 2022). In enhanced geothermal

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*Corresponding author.
E-mail address: zhao_lu@zju.edu.cn (Z. Lu); wanglz@zju.edu.cn (L. Wang); nehzoug@163.com (Z. Guo); yi_hong@zju.edu.cn (Y. Hong); cezhangl@ust.hk (L. Zhang).

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system, engineers can improve geothermal power generation efficiency by enhancing the permeability of underground thermal reservoirs, but the problem of fracture stability under high temperature and high pressure remains to be solved (Porter et al., 2015; Abedini et al., 2022). As a potential alternative energy source, natural gas hydrate requires safe exploitation to overcome the difficulties of phase change control and reservoir stability (Lei et al., 2025). However, the aforementioned geo-energy developments face complex challenges of multi-scale and multi-physical field coupling, such as the flow-diffusion-dissolution behavior in porous media (Bordoloi et al., 2022; Zou et al., 2024), the adsorption-desorption mechanism of shale gas in nanopores and the thermal-hydraulic-mechanical interactions in geothermal reservoirs (Chen et al., 2019; Wang et al., 2025). Traditional experimental methods face limitations in macro-scale observations due to apparatus constraints. Microfluidic technology, dating back to the early 1990s (Gravesen et al., 1993), has evolved into a transformative tool for geo-energy research, offering high-resolution visualization and precise simulation of fluid dynamics in porous media (Sinton, 2014; Abedini et al., 2022). Early studies demonstrated its utility in multiphase flow characterization (Zheng et al., 2017) and CO_2 capillary trapping (Geistlinger et al., 2015), paving the way for modern applications.

Schematic illustration of microfluidics applications in geo-energy research (original figure) is presented in Fig. 1, which includes key domains such as shale gas, CCUS, and geothermal systems, integrating interdisciplinary methodologies (Modified from conceptual frameworks in Sinton (2014); Porter et al. (2015)). In CO_2 sequestration, glass-based and silicon-based microchips are used to simulate capillary trapping, salt precipitation, and mineral reactions of CO_2 in saline aquifers, elucidating microscopic mechanisms of pore clogging and permeability reduction (Gravesen et al., 1993; Geistlinger et al., 2015; Zou et al., 2024). For chemical enhanced oil recovery, fluorescence-labelled microfluidics enable real-time monitoring of CO_2-crude oil miscibility, reducing the measurement time for minimum miscibility pressure from weeks to minutes (Guo et al., 2019). Additionally, microfluidic chips can be utilized to screen high-efficiency nanoparticle stabilizers to optimize the sweep efficiency of CO_2 foam flooding (Guo et al., 2019; Betancur et al., 2024). In geothermal development, high-temperature/pressure microreactors simulate heat and mass transfer of supercritical fluids in fractures, providing insights for enhanced geothermal system design. However, there are limitations in current technologies, such as insufficient gas permeability and pressure resistance of polymer materials (PDMS), which restricts their application in supercritical conditions (Guo et al., 2019; Harshini et al., 2024; Zhong et al., 2025). Further, rock micromodels provide valuable insights, their fabrication costs remain prohibitive, and current etching techniques inadequately capture the multiscale heterogeneity observed in natural reservoirs (Niculescu et al., 2021; Betancur et al., 2024; Cai et al., 2024c). Nevertheless, microfluidics remains pivotal in geo-energy research due to its powerful capabilities (e.g., real-time visualization, multi-physics coupling, high-throughput efficiency). One typical microfluidic testing device for simulating liquid-gas migration is shown in Fig. 2, which mainly includes injection system, microfluidic chip and microscopic observation system. During the microfluidic test, the development of liquid-gas distribution could be captured and analyzed simultaneously by the information acquisition system.

The advancements of microfluidic techniques not only promote the understanding of geo-energy development mechanism from macro to micro, but also provide critical technical support for CCUS scale-up, efficient shale gas exploitation and geothermal system optimization (Golmohammadi et al., 2021; Zhong et al., 2025). This review systematically examines innovative microfluidic applications in all crucial application fields of geo-energy. The prospect of microfluidic integration with interdisciplinary fields and advanced materials are explored.

2. Current advances of microfluidics in geo-energy research

2.1 Microfluidics in shale gas reservoir

Microfluidic technology has shown unique advantages in shale gas reservoir research. It solves the problem of micro-transport mechanism, which is difficult to capture by traditional methods. Microfluidic studies of shale gas emphasizes gas slippage effects, adsorption-desorption equilibria, and microfracture seepage characteristics in nano-pore networks, in contrast to the geological sequestration of carbon dioxide (high-temperature, high-pressure sealing reactions) and chemical-enhanced oil displacement (dependent on surfactants) (Mehmani et al., 2019; Cai et al., 2024b). For instance, silicon-based or PDMS micromodels can simulate the gas migration path of the shale matrix-fracture system, revealing the competing mechanisms between capillary forces and viscous drag (Mehmani et al., 2019; Li et al., 2022c; Zhou et al., 2023; Lu et al., 2025). Unlike geothermal fracture development (focused on heat exchange) and natural gas hydrates (dependent on phase transitions), shale gas research prioritizes gas diffusion coefficient measurement and wettability dynamics under low-permeability conditions (Mehmani et al., 2019; Li et al., 2022b; Cai et al., 2024a). Microfluidic experiments can directly reveal multi-phase flow patterns (e.g., annular flow, stratified flow) and boundary slip phenomena in nanoconfined spaces, whereas traditional core-flooding experiments merely infer microscopic mechanisms through macroscopic measurements.

Recent advancements combine in-situ Raman spectroscopy with high-speed imaging. This integration quantifies the 15%-20% efficiency enhancement of supercritical CO_2 displacement over water flooding (Li et al., 2022b, 2024a). Furthermore, the microfluidic chip can be integrated with a temperature (50-120 °C) and pressure (> 20 MPa) control module to simulate real reservoir conditions, providing experimental validation for optimizing fracturing fluid flowback strategies (Mehmani et al., 2019; Li et al., 2022c). Current microfluidic studies primarily employ PDMS and glass, though PDMS suffers from gas permeability and mechanical instability at pressures > 5 MPa (Xie et al., 2024). Recent advances use silica-glass composites (Zhong et al., 2025) or high-temperature alloys (Porter et al., 2015) to address these constraints. Sub-

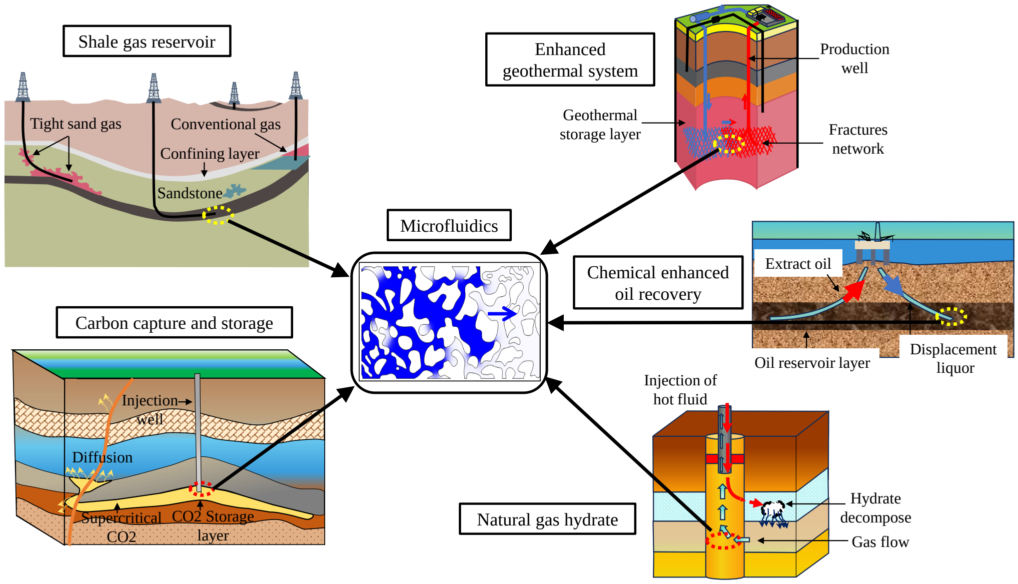

Fig. 1. Microfluidics in geo-energy research.

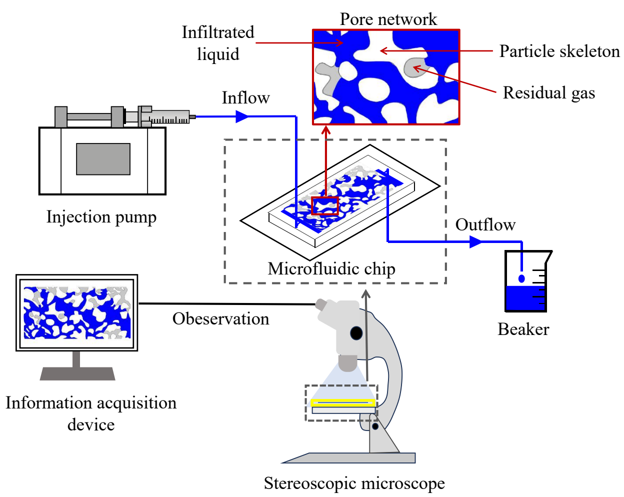

Fig. 2. Typical microfluidic testing device.

stantial gas slippage effects are revealed in nanopores, where permeability exceeds Darcy's law predictions by 3-5 times due to non-continuum flow mechanisms (Mehmani et al., 2019; Wang et al., 2024). Surfactant modification can reduce gas-liquid interfacial tension (72 to 28 mN/m) and enhance recovery (Mukherjee and Vishal, 2023; Li et al., 2024a). To augment microfluidic observations, multiscale computational frameworks (e.g., CFD-DEM) were employed to elucidate diffusion-dominated transport mechanisms, aligning with experimental pore-scale dynamics (Mehmani et al., 2019; Wang et al., 2024). Furthermore, hypergravity microfluidic platforms demonstrate gravity segregation effects on fluid distribution patterns, offering novel insights for optimizing horizontal well placement strategies in shale reservoirs (Zhong et al., 2025). Direct quantification of gas permeability under residual water saturation (10 nm scale) demonstrated nonlinear flow constraints imposed by nanoscale throat structures, which is indistinguishable in conventional macroscopic analyses.

2.2 Microfluidics in CCUS

Microfluidic technology has been widely used in the study of geological sequestration of CO_2, especially in revealing microscale multiphase flow mechanisms and interfacial phenomena, which differ markedly from other energy-related fields (such as shale gas extraction and chemical-enhanced oil recovery). Microfluidics in CCUS builds on early work by Abolhasani et al. (2014) and Sinton (2014), who pioneered real-time visualization of CO_2-brine interactions in micromodels, later expanded to supercritical conditions (Zheng et al., 2017). In contrast to shale gas studies emphasizing nanoscale pore adsorption, microfluidic technologies of CCUS can provide real-time visualization of CO_2 migration, diffusion, and salt precipitation within pore networks through precision-engineered microchannels (e.g., parallel grooves or cylindrical pores) (Ho et al., 2022; Lu et al., 2025). Microfluidics quantify capillary trapping efficiency through dyed brine visualization, while mineral trapping is assessed through on-chip XRD detection of calcite precipitation after hours reaction. Zhong et al. simulated the salt crystallization after injection of CO_2 by microfluidic chip, and found that the salt precipitation rate was nonlinear with CO_2 flow rate (Zhong et al., 2025). Microfluidic control can also be combined with high pressure and high temperature conditions to simulate the behavior of supercritical CO_2 in deep reservoirs, and its dynamic capture capacity is far higher than conventional core experiments (Zheng et al., 2017; Li et al., 2024a). These characteristics make microfluidic technology an indispensable tool for evaluating saline aquifer storage safety (e.g., the Sleipner Project) and resolving salt-clogging challenges (Datta et al., 2023; He et al., 2023). Researchers have employed the microfluidics for investigating the CO_2 trapping mechanisms (Fig. 3), and three principal types of trapping mechanisms are discovered and categorized (structural trapping, dissolution trapping and capillary trapping).

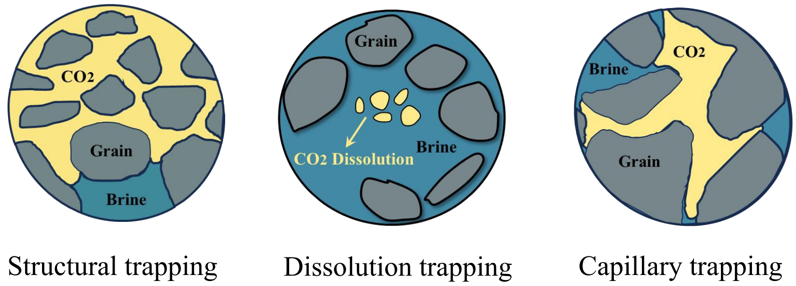

Fig. 3. CO_2 trapping pattern in microfluidic investigations.

Experimental results demonstrated that nanoparticle-stabilized CO_2 foam (e.g., NP-LAPB+AOS) enhanced sequestration efficiency by over 30%, primarily through optimization of capillary number (Ca) and viscosity ratios (Vandu and Krishna, 2005; Guo et al., 2019; Li et al., 2024a). Nanoparticles inhibited foam coarsening, resulting in a more uniform distribution of CO_2 saturation in heterogeneous pore structures (Zheng et al., 2017). In terms of salinity impact, high salinity (> 15% NaCl) can accelerate brine evaporation and cause pore clogging, but this can be mitigated by regulating injection rate (50-1,000 μL/min) (Seo, 2019; Zhong et al., 2025). Researchers have developed innovative approaches in conducting microfluidic tests, including direct observation of acidification using real rock micromodels (e.g., calcite chips), and sealing improvement with microbial-induced calcite precipitation (MICP) (Fu, 2016; Wang et al., 2019; Pan et al., 2023; Ma et al., 2025). Microfluidics focuses on pore-scale dynamics (e.g., salt clogging, nanoparticle-stabilized foam efficiency) but not reservoir-scale leakage. Field-scale validation is proposed in future studies, and hypergravity platform demonstrates a strong potential in simulating large-scale leakage behavior with small-size microfluidic channels in hypergravity centrifugal experiments. In addition, machine learning is used to predict CO_2 diffusion coefficients in deep reservoirs with an error rate less than 5% (Sinton, 2014; Fu, 2016). Employing machine learning technology, microfluidic images have been enhanced from low-resolution (5 μm/pixel) to submicron-scale precision, enabling accurate identification of residual oil morphology in nanochannels. This approach overcomes the limitations of conventional dictionary learning methods in reconstruction efficacy and computational efficiency. Microfluidics enables precise salinity and pressure gradient control, effectively unraveling CO_2-brine interface instability mechanisms (e.g., viscous fingering, Haines jumps). In contrast, conventional core flooding experiments struggle to resolve pore-scale interfacial dynamics due to limited spatial-temporal resolution.

2.3 Microfluidics in chemical enhanced oil recovery

Microfluidics have gained significant attention in Chemical Enhanced Oil Recovery due to the unique capabilities to visualize at the pore scale and the experimental characteristics (Sinton, 2014; Gogoi and Gogoi, 2019). In contrast to geological CO_2 sequestration (requiring supercritical phase transition simulation) and shale gas extraction (focusing on nanoscale adsorption mechanisms), microfluidic chemical EOR studies prioritize interfacial phenomena (e.g., wettability alteration, emulsification) and chemical-crude oil interactions (Sinton, 2014; Deng et al., 2020; Zhao et al., 2022; Yang et al., 2023). For instance, by adjusting the concentration of the salt ions in the low salinity water flooding process, microfluidic technology can track the oil-water exchange process in real-time, revealing a transition mechanism from viscous finger flow to stable displacement (Saadat et al., 2020; Fani et al., 2022). Microfluidic analysis can disclose in-situ coalescence-rupture dynamics of oil-water emulsion droplets during surfactant flooding, whereas the spinning drop method only provides equilibrium interfacial tension measurements under static conditions. In polymer enhanced oil recovery, microfluidic devices are used to simulate reservoir heterogeneity and quantify the impact of permeability on production rate, indicating that the higher permeability zones tend to form preferential flow channels, consequently reducing production rate (Betancur et al., 2024). The synergistic effect of surfactants and nanoparticles have been visualized, demonstrating that nanoparticle-stabilized foams effectively block high-permeability pathways to enhance sweep efficiency. In heterogeneous microfluidic chips, the synergistic application of strong-weak displacement agents demonstrated around 30% improvement in volumetric sweep efficiency. This contrasts with conventional long-core experiments that merely offer macro-scale recovery factors without resolving pore-scale flow mechanisms. The dynamic displacement simulations demonstrated that low-salinity waterflooding (< 5,000 ppm) enhanced oil recovery by approximately 2% through ionic exchange mechanisms, through optimizing injection rates (0.019-100 μL/min) and salinity gradients. However, the presence of divalent ions (e.g., Ca^{2+}) significantly inhibits changes in wettability, leading to a decrease in displacement efficiency (Saadat et al., 2020; Fani et al., 2022; Xiao et al., 2022, 2023). In chemical agent screening, the collaboration between anionic surfactants (e.g., alcohol ether sulfate) and silica nanoparticles results in reducing oil-water interfacial tension to 0.01 mN/m and increasing the recovery rate to 84% (Guo et al., 2019). For multiphase flow regulation, studies highlighted that high molecular weight polymers (e.g., HPAM) tend to accumulate at low-permeable zones, forming blockages. To balance penetration efficiency and mobility, optimizing polymer molecular weight and pore throat size matching is required (Betancur et al., 2024). Surface-modified microchips simulating oil-wet/water-wet pore networks proved that co-surfactant reduces contact angle hysteresis by 94.7%, effectively decreasing residual oil saturation. At the same time, traditional core flooding experiments cannot decouple wettability effects from pore structure influences (Saadat et al., 2020; Lu et al., 2022b). The conventional Wilhelmy plate method introduces measurement errors due to surfactant adsorption on the platinum plate. Microfluidics overcomes this limitation through dynamic contact angle monitoring coupled with interfacial morphology analysis, providing non-equilibrium data that better describe in-situ reservoir conditions.

2.4 Microfluidics in enhanced geothermal system

Microfluidic technologies have rapidly advanced in enhanced geothermal research. The core advantages lie in their capabilities to simulate reservoir conditions (e.g., 10-80 MPa, 80 °C) and direct visualization of fracture-matrix interactions with multiphase flow dynamics (Cai et al., 2024a; Harshini et al., 2024; Wang et al., 2025). Unlike applications in CO_2 sequestration or chemical flooding, geothermal studies with microfluidic technique prioritize micro-scale modelling of complex geological materials (e.g., shale, cement) using three-dimensional microtomographic techniques. This would precisely recreate the realistic fracture networks, thereby addressing critical thermo-hydro-mechanical coupling challenges in reservoirs (Porter et al., 2015). For instance, researchers developed a microfluidic system using an Onconel 600 pressure vessel and a sapphire observation window, enabling the first direct observation of supercritical CO_2 displacement in natural fractures under reservoir-mimetic conditions (Porter et al., 2015; Yew et al., 2019). Additionally, geothermal microfluidic experiments frequently involve three-phase flows (e.g., $scCO_2$-Brine-Oil), requiring simultaneous analysis of miscible/immiscible mass transfer mechanism, which is significantly different from studies focused on nanoconfined flows in shale gas or phase transitions in gas hydrates (Datta et al., 2023; Mukherjee and Vishal, 2023; Wang et al., 2024). In simulating fracture pore-scale flow, fracture surface roughness was observed to significantly modify the fingering behavior of supercritical CO_2 (Porter et al., 2015; Datta et al., 2023; Zeng et al., 2025). The matrix permeability exhibited a nonlinear correlation with thermal exchange efficiency, suggesting complex subsurface interactions. In the field of microfluidics for geological energy research, designing pores with different sizes and geometries (Fig. 4) is necessary for accurately simulating the complex flow behaviors within porous media and for exploring the infiltration mechanisms (Cha et al., 2021; Li et al., 2022a; Lei et al., 2024; Lu et al., 2025). Parameters such as pore diameter, throat diameter, arrangement pattern, connectivity, tortuosity and porosity ratio directly affect fluid permeability and the distribution of multiphase flow. Therefore, the differentiated design of pore structures is crucial for connecting microscopic mechanisms with macroscopic flow laws, providing a scientific basis for optimizing energy extraction efficiency and reservoir prediction models.

Microfluidic technologies also promote the optimization of enhanced geothermal practice through innovative strategies like polymer/gel-based fracture flow control, demonstrating up to 20% thermal transfer efficiency improvements in lab-scale models (Yang et al., 2021; Niculescu et al., 2021). A sapphire-chromium nickel alloy micro-reactor was used to simulate the granite fracture network at 80 °C/30 MPa. Infrared thermal imaging observed that the heat exchange efficiency along the rough fracture surface was 48% higher than that of the smooth surface (Wang et al., 2025). Numerical simulation of fracture development plays an important role in revealing the mechanism of fracture propagation by comparing with experiments. The RFPA software for rock failure process analysis has been widely used in the simulation of rock fracture at the meso scale (Tang and Hudson, 2010), macro scale (Tang et al., 2006), and giant scale (Tang et al., 2020). Geothermal applications place higher demands on material durability to withstand extreme operational conditions (temperatures and pressures), with a preference for geological rock analogues over conventional PDMS or glass substrates (Xie et al., 2024; Zhong et al., 2025).

2.5 Microfluidics in natural gas hydrate

Microfluidic technology demonstrates unique advantages in natural gas hydrate development, emphasizing transient dynamics at the microscopic pore-scale for multiphase flow. Specifically, by simulating the formation and decomposition of hydrates in-situ using microfluidic chips, the critical role of perturbation mechanism in disrupting meta-stable states has been elucidated (Xu et al., 2023; Zhong et al., 2025). In contrast to chemical flooding applications focused on quantitative analysis of low-salinity water-flooding efficiency, hydrate investigations require specialized experimental configurations. Under extreme environmental conditions (temperature ranges from -10 to 10 °C, pressure higher than 10 MPa), PDMS and glass-based microfluidic chips were used to simulate sedimentary pore structures, and the nonlinear impact of hydrate growth on permeability was directly observed (Betancur et al., 2024; Zhang et al., 2024a). Additionally, microfluidics can capture complex interface behaviors, such as methane-water-hydrate triphase distribution and wettability evolution, providing unique insights absent in other geo-energy fields (Betancur et al., 2024; Zhang et al., 2024a). Hypergravity microfluidics (Chen et al., 2025a, 2025c) enables pore-scale simulation of field-scale hydrate dissociation by amplifying gravitational forces, compressing years of sedimentation dynamics into hours while preserving microscale physics (Fig. 5). Because hypergravity can compensate for the shortcomings of the scaled-down model, the microfluidic model in the centrifuge can reveal and reflect large-scale leakage mechanism in the geological field.

The main advantage of microfluidic application in natural gas hydrate lies in the high spatiotemporal resolution, exemplified by quantifying the spatial heterogeneity of the hydrate saturation heterogeneity through microscopic imaging, whereas other fields rely more on macroscopic parameters optimization (Saadat et al., 2020; Zhang et al., 2024b). To

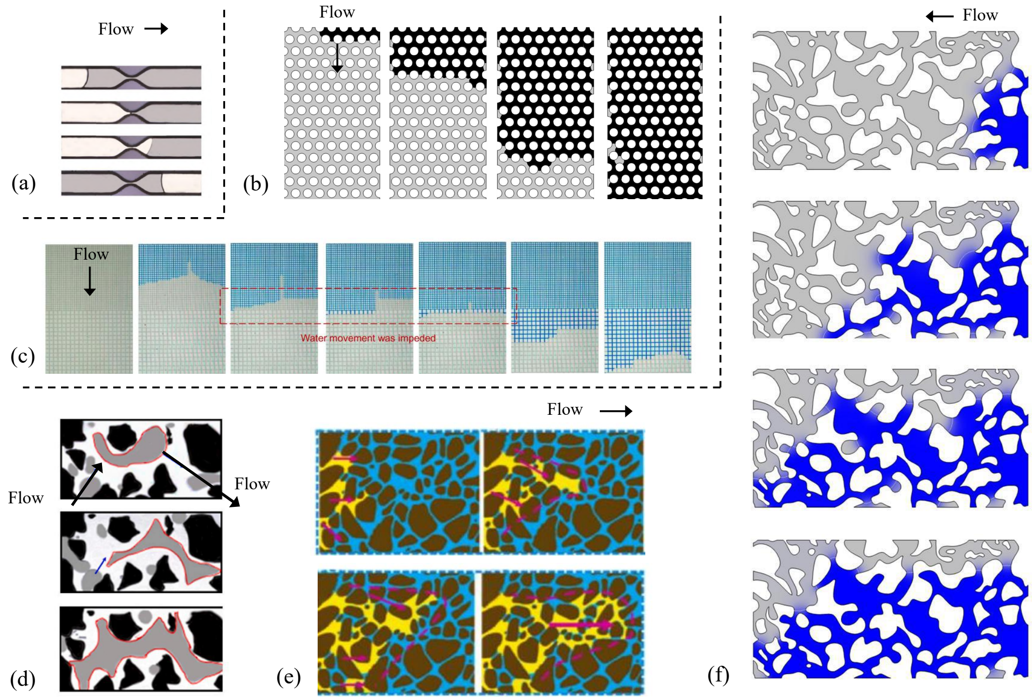

Fig. 4. Various geometrical structures of microfluidic chips: (a) Single channel, (b), (c) homogeneous porous structures, (d), (e) and (f) heterogeneous porous structures.

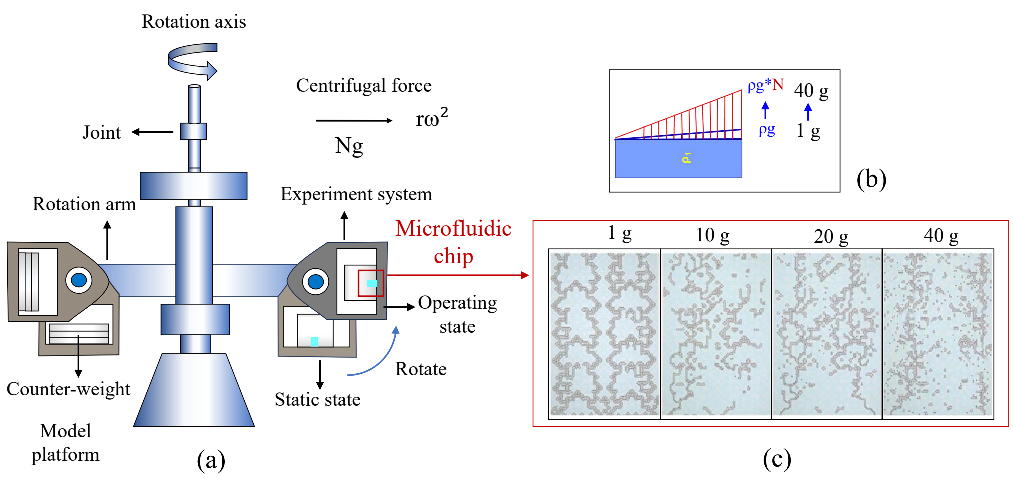

Fig. 5. Microfluidic test under hypergravity centrifugal condition: (a) Illustration of microfluidic test in hypergravity platform, (b) working mechanism of hypergravity, (c) microfluidic observation under hypergravity conditions, 1 to 40 g.

conduct further analysis of hydration development, phase-field numerical simulations were integrated with microfluidic experiments, contributing to understand gas-liquid interface pattern and multiphase coupling interactions (Xu et al., 2023; Gorbunov et al., 2024; Zhang et al., 2024a). Pore structures were specifically designed (e.g., 10-μm microchannels), to reveal the amplification effect of the non-uniformity of pores in increasing the formation rate of hydrate compounds (Xu et al., 2023; Zhang et al., 2024a). The hydrate formation rate under constant pressure was threefold higher than under varying pressure conditions, while hydrate reformation directly correlates with methane's reverse movement (Xu et al., 2023; Zhang et al., 2024a). Silica-glass composite chips can withstand pressure up to 60 MPa, which is suitable for high-pressure nucleation studies. PDMS chips are more applicable for the observation of multiphase flows due to their elasticity that accommodates complex deformation cases (Betancur et al., 2024).

3. Discussions and perspectives

The application of microfluidic technology in the field of geo-energy resources has extended across five major areas, including shale gas, CCUS, chemical EOR, enhanced geothermal development and natural gas hydrate (Porter et al., 2015; Saadat et al., 2020; Nie et al., 2024). In the study of shale gas research, microfluidic chips have been utilized to simulate nanoscale pore structure, revealing methane adsorption-desorption dynamics and slip effects on permeability. These findings provide microscopic insights for optimizing fracturing fluid formulations (Guo et al., 2019; Li et al., 2022b; Ouyang et al., 2023; Zhong et al., 2025). For CCUS development, microfluidic platforms enable real-time visualization of supercritical CO_2 capillary trapping and mineral reactions in saline aquifers (Lu et al., 2025; Zhong et al., 2025). Notably, researchers demonstrated nanoparticle-stabilized foam injection can enhance storage efficiency through bubble transport experiments (Guo et al., 2019; Harshini et al., 2024). In chemical EOR applications, microfluidic visualization has decoded wettability alteration mechanisms during low-salinity water flooding. Swelling of clay minerals was found to enhance oil displacement efficiency, but further experiments need to be conducted with the three-dimensional pore network (Saadat et al., 2020; Zhu et al., 2022). To explore the enhanced geothermal resources, high-pressure microfluidic systems have successfully replicated fracture-matrix interactions and multiphase flow behaviors, generating quantitative datasets informing geothermal fluid circulation optimization (Gravesen et al., 1993; Cai et al., 2024b). In studies of natural gas hydrate, microfluidic techniques have uncovered the interface confinement effect and the inhibitor action mechanism during nucleation (Mehmani et al., 2019). In contrast to conventional core analysis, microfluidic technologies offer distinct advantages including real-time visualization, short test duration, high-throughput capabilities, and low sample consumption, providing particularly invaluable methodology for investigating microscale mechanisms and coupled thermo-hydro-mechanical processes (Lei et al., 2025).

While microfluidics technology demonstrates remarkable potential in geo-energy resources, its development is confronted with several challenges. The quantitative transition between microscopic experimental results and the macro-engineering parameters (e.g., permeability, storage efficiency) still relies on empirical formulas, since a multi-scale mapping framework should be built by combining pore network models with machine learning (Soltanian et al., 2017). Machine learning algorithms address the computational challenges in processing microfluidic big data, while microfluidic platforms provide physically constrained training datasets for algorithm optimization (Mittal et al., 2024). Recent studies show that PINNs trained on microfluidics data (e.g., CO_2 dissolution) can achieve $< 5\%$ error in permeability prediction (Raissi et al., 2018; He et al., 2020), whereas traditional ML models typically exceed 15% (Raissi et al., 2018; Zhong et al., 2025). The CNN used a lightweight ResNet-18 backbone with pruning to reduce parameters by 40%, enabling real-time processing (10 min/experiment vs. 2 hours). Transfer learning from 10,000 microfluidic images reduced training data needs by 50% (McIntyre et al., 2022; Mittal et al., 2024). CNNs (e.g., U-Net) enhanced image resolution from 5 μm/pixel to 0.5 μm/pixel by denoising and feature extraction, reducing analysis time by 90% (Wang et al., 2024). Comparative studies showed > 95% accuracy in identifying CO_2 bubble morphologies versus 70% for conventional methods. The investigation of multi-field coupling mechanisms is still lacking, as existing experiments predominantly focus on single-physical field analysis (e.g., fluid flow, mechanical deformation or chemical reaction), whereas actual engineering practice always involves intricate interactions among fluid-solid-liquid-gas-thermal fields (Lu et al., 2022a; Zheng et al., 2017; Saha et al., 2024). For instance, the dynamic responses of supercritical CO_2 and rock minerals under high temperature and pressure are rarely systematically observed (Abedini et al., 2022). Additionally, the accuracy of three-dimensional pore structure simulation is inadequate, where current microfluidic chips primarily employ two-dimensional etching processes, making it challenging to reproduce the non-homogeneous anisotropic features of the reservoir. While emerging approaches combining 3D printing with in-situ rock imaging have enabled preliminary pore network reconstruction, their resolution and mechanical stability require significant enhancement (Porter et al., 2015; Mehmani et al., 2019; Feng and Chu, 2024). The limitations of image analysis and parameter monitoring technologies further hinder the experimental efficiency. Traditional microscopic imaging lacks sufficient resolution for high-speed micro-interface dynamics (e.g., water hydrate nucleation process), whereas artificial intelligence technologies exhibit transformative potential. Specifically, real-time saturation-level calculation of CO_2 capture process was completed by convolutional neural networks (Porter et al., 2015; Mehmani et al., 2019; Li et al., 2024b), and automatic evaluation algorithms for oil recovery efficiency was developed based on deep learning principle (Wang et al., 2024). The absence of interdisciplinary convergence also requires urgent attention. Biomedical organ-chip technologies could enhance in-situ monitoring of microbial-enhanced oil recovery, while high-temperature-resistant hydrogels from materials science might expand current chip operating limits (Sugioka and Cheng, 2012; Chen et al., 2025b). Furthermore, hypergravity microfluidics (e.g., centrifugal chips simulating strati-graphic pressure gradients) offers novel approaches for advanced geo-energy exploration.

4. Conclusions

Microfluidic technology demonstrates unparalleled advantages in elucidating complex mechanisms of geo-energy resources development due to real-time visualization, instantaneous response, high efficiency, multiphase simulation, and microscale resolution capabilities. For instance, microfluidic chips enable real-time monitoring of residual oil distribution and quantitative analysis of interfacial tension effects, while core displacement experiments struggle to capture viscous fingering during chemical EOR. In contrast to numerical simulations relying on simplified pore structure and experimental assumptions, microfluidic platforms of shale gas exploration uncover spatial heterogeneity in the shale gas slip-off effect through authentic rock replication. The low sample consumption and high-throughput characteristics of microfluidics significantly reduce experimental costs. In rare sample analyses like natural gas hydrate, microliter-scale injection suffices for studying nucleation kinetics and inhibitor screening. Another pivotal advantage lies in its controlled multiphysics coupling capability. Integrated chips equipped with temperature, pressure, and chemical sensors have achieved synchronous monitoring of gas-liquid-solid three phase flows in geothermal fractures, providing direct evidence for optimizing thermal extraction efficiency. Furthermore, the integration of novel materials and manufacturing techniques extends application boundaries of microfluidics. Femtosecond laser processing, for example, enables submicro-scale channel fabrication, facilitating in-situ reaction observation under extreme conditions (e.g. CCUS). The incorporation of artificial intelligence enhances data utilization: machine learning algorithms not only improve extraction accuracy of micro-interface dynamics, but also enable macroscopic seepage model training through microscale datasets.

Microfluidic technology serves as a tool for investigating microscopic mechanisms, and a crucial bridge linking the pore-scale physical laws to macro-scale engineering applications. With the advancement of interdisciplinary studies (geology, chemistry, biology, physics, materials) and the development of extreme-condition simulations (e.g., high pressure, critical temperature, hypergravity fields), microfluidic technology can provide more robust scientific support for promoting geo-energy development and achieving carbon neutrality objectives.

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Conflict of interest

The authors declare no competing interest.

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