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Editorial

Current advances in capillarity: Theories and applications

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Abstract:
As common physical phenomena in porous media, capillarity behaviors exist in many engineering applications and natural science fields. The experimental, theoretical and numerical research on capillarity in porous media has lasted for more than a century, and the research results have been widely used in various fields, such as the development of conventional and unconventional resources. However, although the research has made great progress, the complex imbibition mechanism poses new challenges to us. The 1st National Conference on Imbibition Theory and Application in Porous Media was held in Beijing from April 22 to 24, 2023, to gather researchers who are interested in imbibition research, exchange the latest progress and achievements in the field of imbibition in porous media, and discuss research hotspots and difficulties.

1. Introduction

Spontaneous imbibition refers to the multiphase flow process in which the wetting phase fluid spontaneously enters the porous media under the capillarity and displaces the non-wetting phase fluid, and is of great significance for many scientific and engineering applications such as enhanced oil/gas recovery, geologically sequestrating CO_2, groundwater pollution/remediation, ink-jet printing, penetration of rain drops into building walls, and needleless injection (Gambaryan-Roisman, 2014; Gambaryan-Roisman, 2019; Khalil et al., 2020; Kurotori et al., 2023). Since Lucas (Lucas, 1918) and Washburn (Washburn, 1921) established the classical circular tube imbibition L-W equation in the early 20th century, imbibition behaviors have been studied for over a century through physical experiments, theoretical analysis and numerical simulation. However, due to the influence of multi-physical and chemical factors under various physical backgrounds, the complex imbibition mechanisms and the involved multiphase flow mechanisms have not yet been fully clarified.

During April 22-24, 2023, the 1st National Conference on Imbibition Theory and Application in Porous Media was held in Beijing. This conference provided a platform for experts, scholars and postgraduates to share ideas and exchange studies for new challenges, algorithms, achievements, and ideas of capillarity behaviors in porous media. First, Jianchao Cai, Shuyu Sun and Moran Wang gave an overview of the current development of capillarity-dominated flow behaviors, and discussed the latest developments, issues and challenges. In particular, while unconventional tight geological reservoirs play more roles in energy and environment, there is more need for deeper understanding of capillarity-driven or capillarity-dominated phenomena, as capillarity is stronger in tighter porous media.

Jianchao Cai, from the China University of Petroleum-Beijing, presented a talk entitled "Some key issues and thoughts on spontaneous imbibition in porous media". He pointed out that due to the multi-influencing factors such as petrophysical properties, fluid properties, and boundary conditions in porous media, the microscopic and macroscopic flow mechanisms in spontaneous imbibition are difficult to be

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understood thoroughly. Currently, the spontaneous imbibition process under the influence of multiple factors is widely studied and mainly focused on laboratory experiments, theoretical analysis and numerical simulations (Cai et al., 2021). Then, the key issues and recent progress in spontaneous imbibition were analyzed, and some suggestions and in-depth insights on capillarity in porous media were provided for future work in his talk (Cai, 2021).

Shuyu Sun, from the King Abdullah University of Science and Technology, delivered a lecture entitled "New challenges and new algorithms in the numerical simulation of capillarity-dominated flow in heterogeneous geological formation". A number of existing and new challenges of simulating fluid flow in capillarity-dominated tight porous media were discussed from the Darcy scales (Zhang et al., 2023) to the pore scales (Cui et al., 2022). Prof. Sun first focused the challenges from the multiscale heterogeneity of permeability, the need of phase-wise/component-wise conservative and bound-preserving solution for saturation and concentration, and the numerical preservation of spatial discontinuity for saturation arising from the heterogeneity of capillarity. To address these challenges, Prof. Sun presented some recent work from his team and his collaborators, in particular the physics-preserving IMPES schemes (Chen et al., 2019) and the unconditionally bound-preserving fully-implicit schemes (Cheng et al., 2022b). Prof. Sun then discussed the challenges coming from the CPU-intensive phase behavior calculation within compositional multiphase flow simulation. He also showed how machine learning can help to achieve more robust and faster prediction of phase behaviors by using supervised learning with thermodynamics-informed deep neural networks (Zhang et al., 2020). Prof. Sun further emphasized that, if trained by experimental data, the trained neural network is even more accurate than the commonly-used Peng-Robinson EOS-based models.

Moran Wang, from Tsinghua University, delivered a lecture entitled "Progress of pore-scale modeling of imbibition". Some work on direct numerical simulations of imbibition was first presented. Prof. Wang emphasized that despite its high fidelity of predictions, direct numerical simulations is hard to achieve representative elementary volume-scale simulations, which limits the statistical significance of direct numerical simulations predictions. To overcome this challenge, Prof. Wang introduced their recent work on GPU-parallel computing and pore network models. The lecture presented in detail a pore-throat segmentation method based on local resistance equivalence (Liu et al., 2022), abbreviated as LoREPorTS, which significantly improves the predictive capability of pore network models for single/two-phase flow simulations. Prof. Wang concluded by highlighting the potential of LoREPorTS for other more complex applications, such as fluid-solid coupling and reactive transport in porous media.

The other experts and scholars also conducted exchanges and discussions on their latest achievements of capillarity and fluids flow in porous media. In following three sections, the research topics selected on imbibition in different scales and fields are summarized based on experimental studies, theoretical characterization, and numerical simulations, respectively.

2. Experimental studies on the imbibition in oil and gas reservoirs

Shuangmei Zou, from the China University of Geosciences-Wuhan, presented a talk entitled "Pore scale imaging of wettability effect on water-oil two-phase flow in water-wet and mixed-wet cores". By integrating micro-computed tomography (CT) imaging with laboratory flooding experiment, in situ multiphase fluid distributions at various fractional flows were obtained for water-wet and the altered mixed-wet cores (Zou and Armstrong, 2019; Zou et al., 2020). Consistent with traditional experimental results, relative permeabilities computed from CT images indicated that oil relative permeability is lower in mixed-wet cores. Based on micro-CT images, spatial oil connectivity characterized by Euler characteristics demonstrated less oil connected in mixed-wet.

Fuyong Wang, from the China University of Petroleum-Beijing, delivered a presentation titled "Characterization of formation properties and EOR mechanism of spontaneous imbibition in tight oil reservoirs". The different technologies for characterizing pore structures and formation properties of tight sandstone were introduced. The experiments of spontaneous imbibition of tight sandstone cores without and with fractures were conducted (Yang et al., 2023), and the mathematical models of predicting the spontaneous flow considering pore size distribution, displacement pressure, gravity and surfactant adsorption and diffusion were proposed (Wang et al., 2021).

Lei Li from the China University of Petroleum (East China) presented a talk entitled "Shale reservoir surfactant imbibition oil displacement experiment and analysis of influencing factors". She characterized the pore structure characteristics and surfactant parameters, and conducted shale spontaneous imbibition experiments based on nuclear magnetic resonance technology. By studying the utilization of oil in the micropores of shale during the imbibition process and the relationship between imbibition efficiency and time. Her work explores the effects of petrography, wettability, fracture, porosity, permeability, imbibition solution concentration, and surface tension on the imbibition effect of shale surfactants.

The talk entitled "Influence of $ScCO_2-H_2O$ on spontaneous imbibition characteristics of coal" was given by Yi Du from Northwestern University. The differences in spontaneous imbibition characteristics of coal samples before and after the reaction were introduced and the mechanisms were analyzed. By using nuclear magnetic resonance (NMR) technology, the differences in seepage rate, fluid transport characteristics, and the contribution of different pore sizes to imbibition were identified before and after the reaction. Through in-situ scanning electron microscopy observation, the impact of different mineral changes on pore structure changes was revealed, and the changes in pore structure were found to be the cause of the changes in imbibition characteristics (Du et al., 2020; Fu et al., 2023).

Jiangtao Zheng, from the China University of Mining and Technology Beijing, presented a talk entitled "Investigation of spontaneous imbibition behavior in the porous rock by in-situ X-ray CT". The talk first presented the co-current imbibition weighting data of 100 mD synthetic rock, which showed a two-stage imbibition behavior (Zheng et al., 2018; Zheng et al., 2021). Then in-situ X-ray CT was used to observe the imbibition behavior in the pore space. The imbibed amount of deionized water calculated based on the CT image data is comparable to the imbibition weighting data. The peripheral part of the sample imbibed more water than the central part of the same volume. The heterogeneous distribution of pores and rock matrix in the center part leads to its lower imbibition amount.

Yuxuan Xia, from the China University of Petroleum-Beijing, delivered a presentation on "The characteristics and influencing factors of spontaneous imbibition in the tight reservoir". Based on balance and NMR, the mass change and distribution of imbibed water during spontaneous imbibition experiments in tight sandstone samples were characterized. Meanwhile, he used petrophysical properties and fractal parameters to discuss the factors influencing imbibition in tight sandstone. He concluded that the main controlling factors on the final dimensionless imbibition mass are porosity, fractal dimension, and succolarity (Xia et al., 2021).

Bingbing Li, from Henan Polytechnic University, presented a talk entitled "Research on recovery mechanism and application of two types of surfactant imbibition displacement in low permeability tight oil reservoirs". The microscopic characteristics of spontaneous imbibition of lipopeptide surfactant and Gemini surfactant were studied under reservoir conditions by using 10-60 μm visualized glass capillary as porous medium. Combined with microscopic particle imaging velocimetry, it could be obtained that the Gemini surfactant mainly entered the porous medium through the Marangoni effect induced by diffusion and oil-water interfacial tension gradient to squeeze and replace the oil phase, and the dispersed oil phase flowed in reverse with the surfactant solution, and the uniform dispersion of water in oil droplets formed by emulsification improved the fluidity of oil discharge and migration (Li et al., 2022b).

Xueling Zhang, from the Zhengzhou University of Light Industry, has been committed to the study of the theory and simulation of nanoscale seepage mechanics, gave a presentation "Experimental study and mechanism analysis of spontaneous imbibition of surfactants in tight oil sandstone". Spontaneous imbibition experiments were conducted on tight oil sandstone, the mechanism of different surfactants was revealed, the nonionic surfactants altered the wettability of the core from weakly hydrophilic to strongly hydrophilic and achieved relatively high recovery rate due to the Van der Waals force and hydrogen bonds (Zhang et al., 2019). The enhanced recovery rate of spontaneous imbibition requires a sufficiently low wettability factor and a suitably high interfacial tension factor. The surfactants mixed with 0.03% sodium dodecyl benzene sulfonate and 0.1% Triton X-100 attained an oil recovery of up to 45%. The synergistic mechanism was revealed that the wettability alteration as the nonionic surfactant and the accelerating oil removal from the core by continuously encasing oil droplets in the aqueous phase as the anions.

Hairong Wu, from the China University of Petroleum-Beijing, gave a presentation entitled "The imbibition performance and mechanism of nanoparticle/surfactant system". Firstly, the synthesize route of the amphiphilic nanoparticles was presented (Wu et al., 2020). Next, the enhanced oil recovery mechanism of nanofluid was described (Xu et al., 2023). In particular, the advantages of the nanoparticle/surfactant system in the aspects of imbibition were illustrated. Introduction of the SiO_2 nanoparticles enhanced the oil recovery through both interfacial tension reduction and wettability alteration. Thus, the combination of the surfactant and nanoparticles showed promising potential in enhanced oil recovery.

Yin Chen, from the China University of Geosciences-Wuhan, gave a presentation on "A study on two-phase flow characteristics of mixed-wetting porous media at pore-scale". Based on micro-fluidic experiment, a set of laboratory micro displacements were established. In these experiments, three porous media were fabricated, including oil, mixed and water-wetting porous media. The oil recovery, two-phase distribution, remaining oil distribution, and flow pattern of three porous media during water flooding were analyzed, respectively. Meanwhile, the influence of flow velocity and viscosity ratio were also considered. It can be concluded that mixed wettability can enhance the oil recovery, especially at low capillary number.

3. Theoretical characterization of imbibition in porous media

Chaojun Fan, from Liaoning Technical University, gave a presentation on "The coupling effect of gas infiltration stress damage in coal seam gas injection displacement". Injecting external gases-nitrogen, carbon dioxide, or flue gas, into coal seams can improve gas extraction efficiency through their competitive adsorption and displacement effects. A seepage-stress-damage coupling model in coal seam was constructed, which involves the competitive adsorption of gases on coal, mass transfer in ways of two-phase flow, and deformation and damage of coal seam. The evolution of key parameters in the process of injecting carbon dioxide into coal seams to replace gas was revealed (Yang et al., 2023; Zhou et al., 2023). It is concluded that ignoring the damaging effect will underestimate the efficiency of gas extraction and carbon dioxide injection, resulting in overly conservative drilling arrangements. The multi-field coupling model constructed can be extended to relevant fields, such as carbon dioxide geological storage and underground coal gasification.

Shuheng Du, from the Institute of Mechanics, Chinese Academy of Sciences, delivered a presentation entitled "New characteristics of micro-production by imbibition in shale oil reservoirs of the Lucaogou Formation in Jimusar district". His research team proposed a new model of "ganged imbibition" of shale oil in the Lucaogou Formation (Du et al., 2023). Water will frequently alternate and infiltrate along multi-scale pores. The oil discharge rate is controlled by the size parameters of pores and the activity of the oil discharge process is controlled by the morphological parameters of pores. The evolution characteristics of solid-liquid interface wetting angle during imbibition could provide a key basis for indicating and predicting shale oil and gas production levels from a microscopic perspective. Overall, imbibition plays a role in the effective development of shale oil by disrupting the original oil-water distribution pattern and broadening the lower limit of effective oil utilization (Shi et al., 2020).

4. Numerical simulations of multi-scale imbibition

In the presentation of "Pore-scale simulation of imbibition considering wetting corner film flow", Jianlin Zhao from the China University of Petroleum-Beijing developed a modified interacting capillary bundle model to characterize the corner film dynamics in a strongly wetting square tube, which is used to analyze the competition between main meniscus and corner film flow during the imbibition process (Zhao et al., 2022b). A phase diagram characterizing the importance of wetting corner film flow was proposed, dominated by viscosity ratio and external driving force (Zhao et al., 2022b). The interacting capillary bundle model was further incorporated into a dynamic pore network model to simulate and analyze the imbibition process in strongly wetting porous media (Zhao et al., 2022a).

Haihu Liu, from Xi'an Jiaotong University, delivered a presentation on "Numerical simulation and theoretical prediction of spontaneous imbibition in the porous media micromodels". He first showed the limitations of existing algorithms for spontaneous imbibition simulations (Liu et al., 2021) and the limitations of Lucas-Washburn equation for prediction of spontaneous imbibition in micromodels (Diao et al., 2021; Li et al., 2022a). Then, he presented a quasi-3D color-gradient Lattice Boltzmann Method (LBM) for spontaneous imbibition simulations and developed a theoretical model for predicting compact displacement process in a micromodel by establishing force balance and using the analogy idea. Finally, by comparing with the quasi-3D simulations and micromodel experiment, he demonstrated that the developed theoretical model is able to provide satisfactory prediction of the compact displacement process in porous media micromodels.

Qiang Liu, from Liaoning Technical University, delivered a lecture entitled "Complex wettability behavior triggering mechanism on imbibition". He proposed a characterization method for complex wettability based on a two-dimensional fracture-controlled matrix unit core-scale numerical model and established mixed-wettability models (Liu et al., 2023). He divided complex wettability pores into four types at the core scale: wetting type, sub-wetting type, mixed-wetting type, and non-wetting pore. This complex wettability behavior is triggered by the complex wettability of the pore walls.

Chaozhong Qin, from Chongqing University, gave a presentation on "Image-based pore-network modeling of spontaneous imbibition and its upscaling". He first presented the novelty of the developed model and its validation against direct numerical simulations and lab experiments (Qin et al., 2021). Then, he showed that wetting dynamics significantly deviate capillary pressure and relative permeability away from their quasi-static counterparts. Moreover, a nonequilibrium model for wetting permeability that incorporates flow dynamics was proposed (Qin et al., 2022). Finally, he provides some perspectives on the pore-scale modeling of spontaneous imbibition in multiscale core samples such as shale and tight sandstones.

Guangpu Zhu, from the National University of Singapore, gave an online talk on "Energy capillary number reveals regime transition of imbibition in porous media". He investigated forced imbibition in a heterogeneous porous media over a broad range of wettability conditions and flow rates using the interface capturing method (Zhu et al., 2020; Zhu et al., 2021). An energy capillary number was proposed to identify regime transitions based on the energy balance analysis of imbibition processes, especially the transition from a capillary-dominated regime to viscous-dominated regime. Additionally, he presented a phase diagram, which allows readers to determine the imbibition regime directly from capillary numbers and wettability conditions. The energy capillary number and phase diagram are evidenced by a quantitative analysis of invasion morphologies.

Xiukun Wang, from the China University of Petroleum-Beijing, delivered a presentation on "The coupled pressure driven flow and spontaneous imbibition in shale oil reservoirs". He introduced the in situ coring and imaging result of multi-fractured horizontal wells and presents the deep learning enhanced shale digital rock for oil-water flow simulation (Wang et al., 2023). The enhanced pore size distribution is consistent with the nitrogen adsorption measurement; hence, more representative capillary pressure and relative permeability curves are obtained with essential experimental measurements. Then, an analytical coupled pressure driven (viscous) flow and spontaneous imbibition model, which is based on his previous work (Wang and Sheng, 2018), was derived and proposed to investigate the variations of water profiles and recovery contributions. He concluded that the pressure driven flow is the dominant mechanism for shale oil production instead of spontaneous imbibition. Moreover, the overall oil-relative permeability decreases due to imbibition invasion.

Yu Pu, from Northeast Petroleum University, delivered a lecture entitled "Research on the imbibition law and fluid migration in porous media". She introduced the problems existing in tight oil imbibition recovery and discussed the imbibition laws. She adopted the Quartet Structure Generation Set algorithm to reconstruct the porous structure, and introduced the binary image segmentation method to evaluate the algorithm quantitatively. Lastly, she employed D2Q9 scheme of LBM to simulate the mesoscopic scale migration of fluid in pores (Pu et al., 2020).

Changli Wang, from the Huazhong University of Science and Technology, delivered a presentation on "Contact line pinning and depinning in capillary imbibition". They pointed out that liquid gets imbibed into the capillary tube under the influence of capillary pressure. If the capillary tube is shorter than Jurin height, oscillations of free surface would occur when contact line is confined by the edge of tube. Through numerical simulations and theoretic analyses, he determined the velocity at the tube edge, and identified the morphologies of meniscus at different stages. In addition, he proposed a formula to predict the oscillation period based on scale analysis. Then, through an axisymmetric lattice Boltzmann model, the process of liquid spreading onto the top surface of capillary tube was presented, and several distinct phenomena were observed: depinning up and depinning down, pinning up and depinning down, pinning up and pinning down, pinning below the top edge (Shan et al., 2023).

5. Spontaneous imbibition in nanoporous materials

In a presentation by Bin Pan from the University of Science and Technology-Beijing, he demonstrated spontaneous and electrocapillary imbibition dynamics in nanoporous media. It was found that spontaneous imbibition dynamics follow the classic Lucas-Washburn equation very well even when the pore and pore throat diameter are as small as 22 and 7 nm, respectively (Pan et al., 2021); electrocapillary imbibition could take place even at Faradaic conditions, which depends on the polarity of the voltage (Pan et al., 2023). Finally, he discussed the underlying mechanisms for these interesting physical phenomena.

Junqian Li, from the China University of Petroleum (East China), delivered a presentation on “Microscopic occurrence mechanism and imbibition process of pore water in marine shale matrix”. He proposed that two occurrence states of pore water, namely adsorbed and free water, coexist in the shale matrix pores (Li, 2021). Further, the evaluation model and method of adsorbed and free amounts of water in shale matrix pores were established. He also presented a quantitative evaluation method for the microscopic distribution of pore water in shale matrix and summarized the main controlling factors and mechanisms of micro-occurrence of pore water in shale matrix. Finally, the process and occurrence characteristics of foreign water entering shale matrix pores were presented.

Guanqun Li, from the China University of Petroleum (East China), delivered a presentation on “Mathematical characterization method for the imbibition mechanism of shale oil volume fracturing”. The main forces of microscopic imbibition in a single capillary were analyzed, and the mathematical models of spontaneous/forced imbibition of different micropores were established. Based on fractal theory and capillary bundle model, the semi-analytical imbibition models of porous media considering different forces were constructed. At the same time, the accuracy and effectiveness of the models were verified by indoor experiments. Finally, on the basis of the dual-medium model, the productivity model of shale oil volume fracturing horizontal well considering the imbibition mechanism of the fracturing fluid was established (Li et al., 2023b).

Anqi Shen, from Northeast Petroleum University, delivered a presentation on “Imbibition mechanism in nanoporous media”. She presented the capillary model, network model and matric model for imbibition. The micro-effects which are wall roughness and boundary layer on capillary rise are discussed using momentum conservation (Shen et al., 2017). She concluded that the wall roughness is the main reason that affects imbibition height on nano-micro scale. The acyclic tree-like model is proved for a better description for pore structure as shale reservoir, both the network and matrix imbibition model can give a good estimation of the imbibition efficiency (Shen et al., 2018).

Hui Gao, from Xi’an Shiyou University, delivered a presentation on “Micro- and nano- pore systems and their influence mechanism on imbibition oil displacement for unconventional tight and shale oil”. They summarized the micro- and nano-pore system in the tight sandstone oil and shale oil reservoirs with multi-measurements, and the influence of pore structure on spontaneous imbibition is discussed with a numerical simulation method (Cheng et al., 2022a). A pore radius transform technique with the transversal relaxation time is provided, and the differences in oil produces from the single pore medium and dual pore-fracture medium tight sandstone cores with the spontaneous imbibition measurements were discussed, especially the role of fractures is carried out. Besides, they reported that the pore system features strong stress sensitivity during spontaneous imbibition, and it is essentially for the pores with smaller pore apertures. To quantify the differences in oil displacement in various ranges of pores, the NMR pore classification method with fractal theory was provided, and the roles of the ratio of pores and complexity of pore structure on the imbibition displacement were discussed detailed (Li et al., 2023a).

The talk on “Pore-scale simulations on spontaneous imbibition in shale porous media” delivered by Han Wang, from the China University of Petroleum-Beijing, emphasized the significance of oil-water two-phase flow/imbibition behaviors in shale nanoporous media. He proposed an improved nanoscale multicomponent and multiphase LBM based on the Shan-Chen format to simulate the oil-water two-phase flow/imbibition behaviors in porous media and the shale nanoscale effects of the oil/water-solid slip, oil-water interfacial slip and heterogeneous oil/water density/viscosity were considered (Wang et al., 2022). Then, by fitting the results from molecular dynamics simulations, the oil-water flow/imbibition behaviors in quartz porous media were simulated.

6. Conclusions

Participants believe that this conference is of great significance to the understanding and information exchange of the latest progress and achievements in imbibition behaviors in porous media, exploring the hot and difficult points in imbibition mechanism research, and promoting the application of capillary mechanics engineering, the development of scientific and technological innovation in natural sciences.

At present, the research on capillarity in porous media is mostly limited to a single scale and a single method to study the imbibition and flow mechanisms under the influence of multiple factors. Future works should comprehensively carry out the analysis of molecule-pore-macro multi-scale integration to deeply understand the characteristics of capillarity in porous media, to provide theoretical support for engineering practice.

It is planned that the National Conference on Imbibition Theory and Application in Porous Media, launched by Prof. Jianchao Cai, will be held annually to actively promote the development of capillary mechanics theory and applications in porous media.

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Conflict of interest

The authors declare no competing interest.

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