Advances in Geo-Energy Research

Vol. 9, No. 2, p. 71-75, 2023

Editorial

Recent advances on fluid flow in porous media using digital core analysis technology

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Keywords:
Porous media
multiphase flow
digital rock
transport phenomenon
multiphysics

Cited as:
Yang, Y., Horne, R. N., Cai, J., Yao, J. Recent advances on fluid flow in porous media using digital core analysis technology. Advances in Geo-Energy Research, 2023, 9(2): 71-75.
https://doi.org/10.46690/ager.2023.08.01

Abstract:
The scientific and engineering challenges of research on porous media have gained substantial attention in recent decades. These intricate issues span different disciplines and fields, manifesting in natural and industrial systems like soils, oil and gas reservoirs, tissues, plants, etc. Meanwhile, digital core analysis technology has rapidly developed, proving invaluable not just in oil and gas reservoirs development, but also in geothermal energy, carbon and hydrogen storage. The China InterPore Chapter and the Research Center of Multiphase Flow in Porous Media at China University of Petroleum (East China) have established a conference platform for global scholars to exchange ideas and research in porous media utilizing digital core analysis technology. The 6th International Conference on Digital Core Analysis & the 2023 China Interpore Conference on Porous Media was successfully held in Qingdao from July 5 to 7, 2023. The conference facilitated discussions among 150 participants, including over 20 invited experts from academia and industry, and the recent advances in research of fluid flow in porous media using digital core analysis technology were thoroughly presented.

1. Introduction

Since the 21st century, the scientific and engineering challenges related to porous media have gained significant attention. These intricate challenges span multidisciplinary and multifield, and are reflected in natural and industrial systems such as soils, oil and gas reservoirs, animal tissues and organs, plants, fuel cells, concrete, ceramics and textiles. (Ingham and Pop, 1998; Berkowitz, 2002; Blunt, 2017; Perego and Millini, 2013; Qu et al., 2022; Zhang et al., 2022). The research of fluid flow in porous media focus on five scales (molecular-pore-Darcy-core-field scales) and five physical fields (thermal-hydrological-mechanical-chemical-biological fields) (Yao et al., 2018; Yang et al., 2023).

In recent times, there has been a notable acceleration in the advancement of digital core analysis technology across various fields, which can be used not only for research on flow issues in the development of oil and gas reservoirs, but also for other engineering fields, such as geothermal energy development, geological carbon storage, biological flow research, nuclear waste treatment, and will have a greater prospect for further development (Li et al., 2022; Yang et al., 2022; Wang et al., 2023; Yang et al., 2023).

The China InterPore Chapter and the Research Center of Multiphase Flow in Porous Media at the China University of Petroleum (East China) have established a conference platform. This platform serves as an academic forum, enabling scholars from around the world to engage in the interchange of ideas and the exchange of research on porous media using digital core analysis technology. The primary focus of the

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Received July 15, 2023; revised July 23, 2023; accepted July 28, 2023; available online July 30, 2023.

Research Center of Multiphase Flow in Porous Media is to foster academic exchanges, promote international collaboration, and conduct fundamental and pioneering research. Under the leadership of Prof. Jun Yao, the Research Center has successfully organized five International Conferences on Digital Core Analysis since 2012 (Yang et al., 2021). Additionally, their team has proposed a comprehensive research framework addressing the modern system of multiphase flow in porous media, linked across different fields, as stated by Yao et al. (2018).

From July 5 to 7, 2023, the 6th International Conference on Digital Core Analysis & the 2023 China Interpore Conference on Porous Media was successfully held in Qingdao, China. This significant gathering saw the participation of over 20 distinguished presenters representing both academia and industry. Their contributions provided invaluable insights and perspectives on the research of fluid flow in porous media. The conference gained substantial attention, and attracted more than 150 participants from across the globe who had in-depth discussions during the on-site meeting. The research topics covered in this workshop are concisely summarized as follows.

2. Experiments on porous media via micro-computerized tomography (CT) scanning and nanochips

Hossein Hejazi, from the Calgary University, delivered a presentation on "Corner flow development in porous media". He conducted displacement experiments and obtained three dimensional (3D) confocal images of corner/film flow and the occurrence of isolated water clusters. The results showed that corner flow spreads chemicals into the upswept area ahead of the main two phases (oil-water front), increases the contact of oil and surfactant solutions, and makes oil easier for emulsification and withdrawal. During the hydrogen injection process, the hydrogen invasion into a series of small-large-small pores, referred to as hydrogen jumps, which is followed by the bypass of a series of pores aligned with the direction of the flow, forming so-called water fingers. The recoverable hydrogen is similar in all tests, regardless of the salinity.

Liwei Zhang, from the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, delivered a presentation entitled "Pore structure evolution of cement and concrete induced by CO_2 carbonation". He introduced that CO_2 leakage from wellbores affects long-term safe CO_2 storage of carbon capture, utilization and storage (CCUS) projects and causes environmental concerns. He proposed a characterization method and specific workflow based on micro-CT to study CO_2-induced borehole cement corrosion. Through this approach, Zhang determined the extent of cement corrosion caused by high-pressure CO_2. Regarding concrete, his findings revealed that high-pressure CO_2 reacts with concrete, leading to a decrease in porosity. Additionally, the compressive strength remains unaffected in a dry gas environment but decreases when exposed to a water-rich environment.

Xiaolong Yin, from the Eastern Institute of Technology, delivered a talk entitled "Microfluidic visualization and modeling of polymer induced permeability damage". He presented microfluidic experiments and simulation models to reproduce and measure polymer-induced permeability damage while investigating fluid distribution and evolution. Microfluidic experiments revealed that injected polymer is mostly in channels aligned with the flow. This would generate disproportionately high of permeability damage to subsequent flow, because the post-polymer flow of water/oil must use angled channels and therefore became highly tortuous. Finally, he mentioned that the mathematical model developed to predict the end points using the angular distribution of the fluids as input is reasonably accurate for oil, but tends to overpredict the end points of water and underpredict the end points of polymer.

Lele Liu, from the Qingdao Institute of Marine Geology, China Geological Survey, delivered a presentation titled "Pore fractal characteristics of hydrate-bearing sediments". In his study, he used CT scanning techniques and newly proposed nucleation/growth simulation techniques to investigate the microscale effects of natural gas hydrate with different pore habits on the characteristic of fluid-occupied pores. He determined that the electrical and hydraulic properties of hydrate-bearing sediments largely depend on the pore structure by fitting the relationship curve between hydrate saturation, pore size and fractal dimensions.

Yongfei Yang, from the China University of Petroleum (East China), delivered a presentation entitled "Pore-scale dynamic 3D imaging of CO_2 trapping based on X-ray micro-tomography". A set of laboratory micro-displacement and in-situ scanning systems was established utilizing micro-CT equipment. Based on simple porous medium models, the effects of heterogeneity and wettability on CO_2 capillary trapping in a three-phase fluid system were investigated. Furthermore, based on different types of carbonate rocks, the capillary trapping characteristics of CO_2 and the changes of rock pore structure caused by CO_2 acidified brine were discussed respectively.

Junjie Zhong, from the China University of Petroleum (East China), gave the talk "Nanofluidics: A window into fluid phase and transport behaviors at nanoscale". The talk presented recent advancements in high-pressure and high-temperature nanofluidic system development, as well as nanofluidic experiments that unveiled fascinating insights into shale oil/gas recovery. This cutting-edge setup has proven to be a valuable tool in diagnosing critical processes such as water imbibition, CO_2 miscible injection, and salt precipitation challenges in shale oil recovery. Zhong's work with the nanofluidic setup has extended to measure the intricate phase behaviors of shale gas condensate, revealing fascinating findings that confined dew points deviate from bulk values. In closing, Zhong underscored the immense potential of applying micro/nanofluidics shortly for clean energy resource recovery.

3. Simulations of fluid transport

Guan Qin, from the University of Houston, delivered a presentation entitled "Numerical modeling of subsurface reactive transport processes at multiple length scales", he introduced that the processes such as carbon capture and storage, and enhanced oil recovery (EOR) involve subsurface reactions. Qin

presented his research on competitive adsorption of CO_2 and CH_4. It is noted that compared to CH_4, kerogen and silicalite were easier to adsorb CO_2. The adsorption of CO_2 increased with pressure until it reached its maximum value, at which point CH_4 molecules entered nanopores. Additionally, a multi-physical field coupled numerical simulation model considering free flow in pore regions, permeation in porous media regions, chemical reactions, and the changes of rock property was also developed for linear flooding and radial flooding.

Jianchao Cai, from the China University of Petroleum (Beijing), delivered a presentation entitled "Pore-scale simulations of forced imbibition in natural rocks". By using micro-CT images of rocks, he conducted an assessment of variances in pore structures. Cai utilized the color lattice Boltzmann model to simulate two-phase flow during the imbibition process. Cai's investigation revealed the displacement mechanisms, which proved to be influenced by factors such as wettability, capillary numbers. Additionally, he observed the substantial impact of wettability on displacement behaviors. Cai also analyzed the morphological characteristics of the two-phase interface at different capillary numbers. Moreover, he quantified the distribution and connectivity of the nonwetting fluid post-imbibition.

Li Chen, from the Xi'an Jiaotong University, delivered a talk entitled "Pore-scale study of multiphase reactive transport with solid dissolution in porous media". He introduced a pore-scale model using the lattice Boltzmann simulation. He indicated that the mineral heterogeneity, Peclet number and Damkohler number had strong effect on single-phase reactive transport processes. He further highlighted positive feedback characterizing the relationship between reactive flow and solid behavior in the single-phase case, contrasting with negative feedback in the multiphase case. Multiphase flow can promote the compact mineral dissolution due to the plugging effects of the non-reactive phase. Finally, a new correlation between porosity, saturation and interfacial length was proposed which can be upscaled into the continuum-scale models.

Ke Xu, from the Peking University, delivered a lecture entitled "Bubbles in porous media: Thermodynamics, coarsening, and implications in CO_2 sequestration". He showed theoretical, numerical and experimental approach focusing multiphase dispersed fluids in porous media, which emerge as emulsion, foam, residual ganglia and bubble population in subsurface environments. Pore network modeling is the major numerical method that these approaches adopted. As he concluded, dispersed fluid systems can be thermodynamically stable in subsurface porous media, which is distinct from these in open space. Bubbles need time to go equilibrium by ripening, and the equilibrium time is sensitive to pore size: under low-perm condition, capillary equilibrium is reached immediately; under high-perm condition, equilibrium should not be expected in decades. The interplay between pore size and bubble size shapes bubbles' behaviors, by regulating the free energy–volume correlation and decoupling mass transfer length from bubble size.

Chaozhong Qin, from the Chongqing University, delivered a lecture entitled "Modelling of flow and transport in multi-scale digital rocks aided by grid coarsening of microporosity". Multiscale and across-scale pore structures are ubiquitous in digital rocks. To simulate porous media flow that accounts for both macroscopic and microscopic pores, Qin introduced a hybrid model combining pore-network and continuum methodologies. This model extensively accounts for microporosity heterogeneity and strategically incorporates coarsening of microporosity voxels to strike a balance between accuracy and computational efficiency. Furthermore, the model's reliability and precision were affirmed through single-phase and two-phase flow simulations.

Xingyu Zhu, from the King Abdullah University of Science and Technology, delivered a presentation titled "An energy stable smoothed particle hydrodynamics method for fluid-solid interactions". The presentation introduced smoothed particle hydrodynamics, emphasizing its advantages and potential applications in simulating fluid flow in porous media. Zhu highlighted the critical importance of energy stability in numerical methods, especially in particle-based approaches. He unveiled an innovative energy stable smoothed particle hydrodynamics method with consistent boundary treatment, verified for fluid flow in porous media. This method proves suitable for problems requiring long-term simulations and complex boundary conditions.

4. Novel technology and approach

Oleg Iliev, from the Fraunhofer ITWM in Germany, delivered a lecture titled "Machine learning algorithms for predicting breakthrough curves for reactive flow in porous media and application to parameter identification" He introduced a novel machine learning approach designed to predict breakthrough curves for reactive flow as observed in 3D CT images. This intricate problem encompasses multiple aspects, including convection, diffusion, reaction rate, morphology, and chemical heterogeneity. By employing the proposed machine learning technique, the unknown parameters in the transport equation can be accurately identified once the breakthrough curves are provided.

Morang Wang, from the Tsinghua University, delivered a presentation titled "Gas diffusion and effective diffusivity through saturated or unsaturated microporous media", Wang introduced the gas diffusion and effective diffusivity considering Fick's diffusion in porous media and Knudson diffusion in microporous media, respectively. He presented a robust mesoscopic numerical tool, which follows a strategy from microstructure reproduction using the quartet structure generation set method to simulation based on the lattice Boltzmann method, for predictions of effective properties. The microstructure geometry effect, morphology effect and phase interaction effect on gas diffusion were finally investigated in detail using the presented method.

Kai Zhang, from the China University of Petroleum (East China), delivered a lecture titled "Real-time production optimization for intelligent oilfield based on machine learning" In his presentation, he proposed an innovative approach that combines traditional reservoir engineering methods with artificial intelligence techniques to enhance the efficiency of reservoir development. The lecture introduced four key steps: real-

time data collection, real-time analysis of the reservoir model, real-time production optimization, and real-time control of downhole equipment. Based on these scientific challenges, Zhang presented a technical framework named "Real-time Production Optimization for Intelligent Oilfield".

Yonghao Zhang, from the Chinese Academy of Sciences, delivered a presentation titled "Kinetic modelling of evaporating flows in nano-pores". He proposed a kinetic model based on the Enskog-Vlasov equation and the density-functional theory to accurately predict non-equilibrium evolution at the interface. Compared with the direct simulation monte carlo method, the evaporation coefficient is not a key input parameter for this model. The results also demonstrated that a simplified kinetic model can accurately describe non-equilibrium evaporating flows of both liquid and vapor, as well as their interface.

Huazhou Li, from the University of Alberta, gave a presentation titled "Application of volume translation in cubic equation of state (EOS) and PC-SAFT EOS". His presentation reviewed various volume translation models developed in the literature for the cubic EOSs, and introduced a new volume translation model recently developed by his research group for PC-SAFT EOS. Compared with the existing volume translation models documented in the literature, this new volume translation model in PC-SAFT can not only reproduce the critical density of pure substances, but also predict the density of saturated liquid and single-liquid of pure substances more accurately.

Jian Wang, from the China University of Petroleum (East China), gave the talk "The advances of fuzzy systems in dealing with high-dimensional data". The talk shared the latest developments in fuzzy systems. Wang designed an embedded feature selection and rule extraction method in the framework of adaptive Takagi-Sugeno-Kang (AdaTSK) system, which is FSRE-AdaTSK, where the gate function was used to measure the importance of the feature and rule. Wang introduced a double group of gates based ALETSK system, where ALETSK was a novel adaptive Ln-Exp softmin based TSK model. His work provides the new research direction for fuzzy system in dealing with high-dimensional data and promotes the development of fuzzy model based on feature selection method.

Omar Alfarisi, from the Khalifa University, delivered a presentation on "Digital rock typing a revelation of artificial intelligence geoscience aided physics". He introduced a resolution-independent, sample size-independent, and scale-independent morphology decoder for disentangling heterogeneous textures. This innovative approach was characterized by its efficiency, simulation-free, and integration of machine learning techniques. In the presentation, he demonstrated the ability of machine learning to drive the determination of rock type from its dependent physical properties to have a digital rock typing process.

5. Application on unconventional oil and gas development

Roland N. Horne, from the Stanford University, gave a lecture named "DNA tracers in fractured reservoirs", which was largely the research of Zhang et al. (2022). Focusing on fractures in geothermal systems, three questions, such as where are they, what are their properties, and how will they perform during energy extraction, were discussed. At first, nanosensors (SiO_2 nanoparticles) were investigated to measure pressure and temperature anywhere in the formation and fracture aperture and developed to estimate reservoir parameters and characterize fracture networks based on these measurements. The next, DNA that reflects the microbial community composition in reservoir formation fluids was used to identify interwell connectivity caused by natural fractures. Finally, the effect of fracture activity and advection on fluid-associated microbial community composition was talked about.

Zhejun Pan, from the Northeast Petroleum University, delivered a talk entitled "Experimental study of shale porosity and permeability". The development of shale oil poses challenges to basic experimental technologies such as porosity and permeability testing. He has improved the design principle of helium porosity equipment and the use of differential pressure sensors, which allows for accurate measurement of helium porosity at high pressures. Through experimental studies, he identified a compelling revelation: the equivalent absolute permeability of shale is notably lower - by 1 to 2 orders of magnitude compared to gas permeability, coupled with a significant pore compression coefficient, which means that permeability is more sensitive to changes in effective stress.

Wenhui Song, from the China University of Petroleum (East China), presented a talk entitled "Pore-scale modeling of fluid flow in shale oil and gas reservoir". He proposed a systematic fluid flow simulation method based on pore network modelling, lattice Boltzmann method and level-set method. The pore-scale fluid transport mechanisms in shale oil and gas reservoir were revealed, which laid the theoretical basis for efficient development of shale oil and gas reservoirs.

Yaoze Cheng, from the Research Institute of Petroleum Exploration and Development, delivered a lecture entitled "Confinement effect of nanopores on fluid phase behavior-experimental study and modeling". Due to the confinement effect of nanopores, the traditional methods fail to accurately predict the phase properties and phase behavior of oil and water in nanopores. To address this, he conducted visualized experiments utilizing artificial microfluidic chips to study the change of fluid parameters and properties at the nanoscale, and he also proposed that the existing visualized experiments are limited to artificial microfluidic chips, making it difficult to study the nanopores of oil and water in real reservoir cores.

6. Geological and geophysical applications

Qinhong Hu, delivered a presentation entitled "Porous media in the environment-energy-resources fields: Microscopic pore structure and macroscopic fluid flow". Hu focuses on the micro-scale pore structure and its emergent effects on macro-scale fluid flow and chemical transport in porous and fractured media for geological and engineering applications. Various and integrated experimental approaches are presented on important processes of diffusion, imbibition, and sorption, and associated parameters, as well as ongoing coupled thermal-mechanic-hydrological-chemical processes under reservoir-relevant set-

ting, for the fundamental understanding of pore connectivity in porous media and their confident utilization in the context of the environmental, energy and resources geosciences.

Xiaofan Yang, from the Beijing Normal University, delivered a presentation titled "Multi-scale modeling and simulation of reactive transport in subsurface environments". She provided an overview of current multi-scale models and the small-scale flow and solute transport processes required in large-scale systems. The presentation introduced two sets of state-of-the-art multi-scale models, based on the theories of pore and Darcy scales, respectively. These models utilize the Darcy-Brinkman-Stokes equations and domain decomposition method. Within the presentation, Yang elucidated the framework, numerical algorithms, and advancements in application related to these models.

Zhenhua Rui, from the China University of Petroleum (Beijing), delivered a talk entitled "Status and prospect of carbon dioxide capture, utilization and storage". He provided a comparative analysis of the developmental status of CCUS internationally. Six technological advances were introduced, which were CO_2 capture from coal-fired power plants, negative carbon, CO_2 corrosion protection, CO_2 transport characterization and measurement, monitoring and verification, rapid mineralization and storage of CO_2, and CCUS-EOR. Finally, Rui pointed out the challenges facing CCUS technology and industry, and emphasized the importance of strengthening policy guidance and international cooperation in the future development of CCUS.

Chi Zhang, from the University of Vienna, gave a presentation entitled "Pore to watershed: Unveiling the critical zone through geophysical applications". She explained the concept and importance of critical zone research and described the geophysical methods for studying critical zone research. She recognized that the critical scientific questions regarding the study of critical zones in carbonate rocks are manifested in two main aspects: spatial scale and temporal scale.

Acknowledgements

We would like to express appreciation to the following financial support: National Key R&D Program of China (No. 2022YFE0203400). We also like to thank all the volunteer students for their contributions to this conference: Hongfeng Zhang, Ziwei Liu, Chunyu Tong, Junming Liu, Jinlei Wang, Yingwen Li, Zhuocheng Hu, Chao Liang, Jiawei Li, Huaisen Song, Zhenxiao Shang, Fugui Liu, Chaoyang Zhao, Mingxin Liu, Jinye Wang, Haoyun Li, Weichen Sun, Tonghui Liu, Can Yang, Yongchun Zhu, Zhihao Xing, Wenxin Yang, Rupeng Zhang, Huapeng Jing, Tianhao Li, Boyu Liu.

Conflict of interest

The authors declare no competing interest.

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