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Perspective

Digital rock physics and fluid flow in the context of the energy transition

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Abstract:
On November 16, 2025, the editorial office of Advances in Geo-Energy Research (AGER) successfully held the 100th AGER Forum, jointly supported by several academic partners, and attended by more than 10,000 people online. With the theme focusing "Digital rock physics and fluid flow in the context of energy transition", the event gathered renowned experts from UK, Belgium and China to discuss frontier progress in fluid flow, pore-scale simulation, and geo-energy storage research. The forum emphasized that digital rock physics and multiscale imaging technologies are becoming essential research tools in next-generation low-carbon energy systems. The AGER forum included expert lectures and interactive discussions, enhancing the influence of AGER within the global geo-energy field. The 100th Forum marks an important milestone in the development of the journal. In the future, the AGER Forum will continue serving as a platform for advancing science and technology in the field of geo-energy.

1. Introduction

The AGER Forum is an important online, non-profit scientific exchange platform initiated by Advances in Geo-Energy Research (AGER), held approximately once a week. It serves as a key complement to the "one-journal-one-forum mode" first proposed by Prof. Jianchao Cai (Cai et al., 2024). On November 16, 2025, the AGER Forum celebrated its 100th event, marking a significant milestone in global geo-energy dialogues. To commemorate this landmark, Prof. Jianchao Cai, together with Prof. Liwei Zhang, designed and organized this academically influential event. This forum demonstrates the commitment of AGER to foster cutting-edge research and international collaboration.

To reflect the academic excellence and global influence of forum, three internationally distinguished scholars were invited to deliver keynote lectures. Among them was Prof. Martin Blunt from Imperial College London, renowned as an authoritative figure in porous media and energy systems; Dr. Marijn Boone, a senior scientist at TESCAN in Belgium, known for his contributions to high-resolution digital rock imaging and microstructural characterization; and Prof. Shuyu Sun from Tongji University, highly recognized for his influential work in computational modeling and numerical simulation of fluid flow in porous media.

The presentations addressed the forefront of geo-energy research in the context of global energy transition. Through a multidisciplinary perspective, the speakers explored advanced

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characterization and simulation techniques for understanding fluid flow in porous media, including digital rock physics, multiscale computational modeling, fast algorithms for pore-scale simulations, and real-time imaging. They emphasized the crucial role of digital rock physics in enhancing the utilization of underground resources and underground gas storage security.

The forum brought together scholars from around the world through both online and in-person participation. More than 10,000 online attendees participated in the forum. The event highlighted influential position of AGER in the global geo-energy research community. By convening global experts and promoting international cooperation, the forum contributes to the advance of energy science, supporting the goals of technological independence and sustainable development.

2. Flow in porous media in the energy transition

In the lecture titled "Flow in porous media in the energy transition", Prof. Martin Blunt presented his perspective on the key role of flow in porous media under the global drive toward low-carbon energy systems. He began by emphasizing that porous media play a crucial role in both natural and manufactured geo-systems. Many innovative R&D directions of the 21st century—including subsurface CO_2 storage, groundwater remediation, geothermal energy production, hydrogen storage, electrolyzers and batteries—involve flow in porous media (Boot-Handford et al., 2014; Blunt et al., 2024).

Using high-resolution 3D CT imaging of porous materials, Prof. Blunt demonstrated how CO_2 injected into sandstone preferentially flows through larger pore channels. As water flows into the sandstone, the CO_2 becomes disconnected into isolated clusters, forming residual trapping structures. This trapping under the action of capillary force ensures long-term CO_2 storage. He then discussed steady-state flow experiments in mixed-wet carbonate reservoir, showing that long-term exposure to crude oil creates complex mixed wettability (Spiteri et al., 2008). It enhances oil connectivity and allows oil to flow over a wide saturation range.

Geological hydrogen storage presents new complexities compared to CO_2 due to high diffusivity and extremely small molecular size of hydrogen (Hematpur et al., 2023). Prof. Blunt particularly focused on Ostwald ripening, where differences in pressure among trapped gas clusters lead to dissolution–diffusion exchange and gradual reorganization of interfaces, ultimately altering connectivity over time (Hashemi et al., 2021). This mechanism requires updated modeling strategies and adjustments to residual saturation estimates for long-term hydrogen storage security.

Throughout the lecture, Prof. Blunt highlighted the value of multiscale characterization, combining synchrotron-based fast scanning, lab-based micro-scale CT imaging, and pore-scale fluid mechanics with dynamic computational modeling (Blunt et al., 2013). He illustrated how different research teams enable accurate quantification of pore structures, interface curvature, wetting behavior, and saturation evolution. These insights are increasingly interfaced with machine learning techniques to generate porous materials and make predictions.

In summary, digital rock physics is now widely used in oil and gas industry and has important applications in the energy transition, including CO_2 and hydrogen storage, and the design of electrochemical devices, as well as packed bed reactors and heterogeneous catalysts. It also offers huge potential for aiding the management carbon capture and storage, especially when experiments and multiscale modeling are used together. The focus should be on using these tools to study displacement processes, improve storage performance, and develop new materials and workflows, rather than simply comparing digital results with experiments. Machine learning methods can further support this work by improving image analysis, model generation, and process simulation.

3. Algorithms for digital core technology and their applications in geological H_2 storage and CO_2 sequestration

In the lecture "Advances in algorithms for digital core technology and their applications in geological H_2 storage and CO_2 sequestration," Prof. Shuyu Sun discussed recent progress in numerical methods for multiscale porous media flow. He first noted that geological gas storage problems require modeling at multiple scales, which ranges from sub-atomic scales, molecular scales, nano-pore scales, micrometer-pore scales, all the way to the Darcy scales (centimeter scales to kilometer scales). These challenges include understanding relative permeabilities, capillary pressure, immiscible two-phase flow, and pore-scale simulations supported by high-resolution images. These topics are central to both H_2 storage and CO_2 sequestration.

Prof. Sun then presented work on direct numerical simulation using smooth particle hydrodynamics. He introduced pore-space construction methods, diffuse interface NS–CH modeling, and energy-stable smooth particle hydrodynamics algorithms that preserve physical conservation laws (Dawson et al., 2004; Feng et al., 2023). Demonstrations of droplet evolution, deformation, and coalescence illustrated the capability of smooth particle hydrodynamics to capture transient interface dynamics relevant to hydrogen storage and CO_2 sequestration (Feng et al., 2023).

Pore network modeling is a great tool to tackle the problems in porous media. Prof. Sun summarized recent progress on pore-network parameter extraction methods (Cui et al., 2022), highlighting new non-pixel-based approaches with the detailed workflow for network connection and extraction, including geometrical simplification and fast computation. The algorithms enable accurate, continuous, and pore throat network extraction from 3D CT images to build reliable pore-network models for efficient multiphase flow and capillary process simulations.

Prof. Sun briefly noted the role of the lattice Boltzmann method as one of the mesoscopic tools used in multiscale modeling of porous media flow. Although this part was not expanded, he included it as an important link between pore-scale and reservoir-scale models. At the molecular scale, he discussed molecular dynamics and Monte Carlo molecular simulation. Together with kinetic-theory models and Boltzmann-transport formulations, these molecular-scale tools help describe fundamental behaviors that influence hydrogen storage and carbon dioxide sequestration.

In short, digital core simulation is steadily advancing toward first-principle-based models capable of describing porous-media flow across molecular, pore, and Darcy scales. Future work will strengthen adaptive mobility-coefficient formulations, develop linear and unconditionally energy-stable orthonormal schemes for density-functional-theory modeling (Wang et al., 2024), and improve the mathematical foundations of the robust gradient flow framework (Feng et al., 2023). These developments aim to provide more efficient multiscale tools for applications such as geological hydrogen storage and CO_2 sequestration.

4. Multi-scale, spectral and dynamic micro-CT imaging of flow processes in porous media

In a lecture titled "Multi-scale, spectral and dynamic micro-CT imaging of flow processes in porous media," Dr. Marijn Boone presented dynamic micro-CT scanning technology and its application in revealing the mechanisms of pore scale fluid flow. He highlighted how multi-scale imaging enables consistent characterization of cores from full-size to the micro-scale (Rücker et al., 2020). Using a sandstone core, he compared medical CT with micro-CT and showed that although medical CT provides stable calibration, its limited true spatial resolution can mask critical pore features (Mascini et al., 2021). Higher-resolution micro-CT revealed cementation patterns, open pore networks, and flow-conductive pathways that explained the difference between laboratory permeability and medical CT interpretations.

Subsequently, dynamic *in-situ* CT imaging was discussed. It captures real-time fluid flow by integrating *in-situ* flow equipment into a fast micro-CT scanner. This configuration achieves temporal resolutions of a few seconds, enabling visualization of rapid pore-filling events, flow field determination using tracer particles, and multi-phase invasion processes (Bultreys et al., 2024). Incorporating the time dimension into the analysis compresses large dynamic datasets into intuitive spatiotemporal flow maps that clearly distinguish early and late pore-scale fluid displacement events.

The spectral micro-CT is an emerging technique that can record energy-resolved X-ray data to differentiate minerals through their K-edge imaging. A reactive-flow experiment involving $PbCO_3$ demonstrated how acid dissolution, CO_2 generation, and localized $PbCO_3$ precipitation can be monitored simultaneously. By detecting the characteristic K-edge of Pb at 88 keV, spectral imaging enables direct, *in-situ* quantification of dissolved ions, opening new possibilities for studying mineral dissolution, metal leaching, and chemically driven flow processes within pores.

In summary, the latest generation of micro-CT scanners now integrates multi-scale structural imaging, dynamic flow visualization, and spectral CT analysis within a unified system. Together with high-quality, high-resolution CT scanning, these advances enhance digital rock physics and deepen understanding of flow, transport, and reaction processes in porous media across scales.

5. Dialogue and open questions in digital rock physics

Regarding questions from the audience on the main challenges in digital rock physics, the speakers offered complementary perspectives. Prof. Blunt noted that the multiscale nature of porous media makes it inherently difficult to capture pore-scale mechanisms with sufficient physical fidelity, highlighting the importance of integrating detailed imaging with predictive models. Prof. Sun emphasized that strong heterogeneity at every scale—Darcy, pore, and molecular—creates significant complexity for developing efficient and robust algorithms for multiphase flow. From the imaging viewpoint, Dr. Boone pointed out that real reservoir samples, especially samples of fractured or ultra-tight formations, span wide pore-size ranges, requiring improved high-resolution imaging and advanced structural characterization techniques.

Regarding the question from the audience on how digital core technology encounters scale-related issues when applied to real oil fields and how these challenges can be overcome in the future, the speakers agreed that bridging scales remains a central scientific task. Prof. Blunt noted that pore-scale measurements of relative permeability and capillary pressure must be connected to reservoir-scale models through appropriate upscaling strategies. Prof. Sun added that multiscale coupling frameworks offer practical ways to transfer micro-scale parameters to larger scales, enabling more coherent cross-scale descriptions of flow. Dr. Boone emphasized that accurate scale bridging relies on both wider field-of-view imaging and refined detection of fractures and pore networks, ensuring that micro- and macro-scale structures are consistently represented.

Regarding the question from the audience on the integration of artificial intelligence (AI) with digital rock technology, the speakers expressed optimism about future opportunities. Prof. Blunt highlighted AI's potential to accelerate pattern recognition and physical prediction in multiphase flow modeling. Prof. Sun noted that AI can learn high-dimensional relationships from molecular simulations, offering powerful tools for force-field development and multiscale model acceleration. Dr. Boone described AI growing role in imaging, particularly in improving dynamic CT data through denoising, segmentation, and super-resolution reconstruction, which enables clearer visualization of complex pore structures and time-dependent flow behavior.

During the live Q&A session, the three speakers offered complementary insights into audience questions spanning CO_2 behavior, digital core modeling, and imaging technologies. Prof. Blunt explained that CO_2 in oil–water–gas systems often remains disconnected due to wettability contrasts, leading to low relative permeability even under steady-state conditions, and noted that although his work focuses on conventional reservoirs, the same pore-scale imaging and modeling approaches can be extended to fractured shale systems. Prof. Sun responded to questions on pore-network modeling by emphasizing that future developments will increasingly integrate microscopic methods such as molecular simulation, with pore-network models serving as a mathematically consistent reduced-order framework. He also highlighted that computational demands depend strongly on model complexity, and addressed the distinct challenges of hydrogen storage, where leakage risks and microfracture interactions must be carefully considered. Dr. Boone provided valuable insights into the evolving capabilities and practical challenges of dynamic and multiscale micro-CT imaging for porous media research. He noted the balance between temporal and spatial resolution must be controlled through careful experimental design. He explained that current techniques still face limits in extracting velocity fields and managing large dynamic datasets. He also pointed out the additional requirements for multiscale imaging workflows for shale and fractured reservoirs. He further discussed the management for a large amount of dynamic data experiments. He highlighted the advantages for spectral CT to distinguish minerals and fluid composition that conventional absorption CT cannot, which especially promising for understanding reactive flow. Dynamic CT data can support physics-informed neural networks machine learning if diverse, well-labeled datasets are available. Reliable imaging requires careful sample preparation that preserves native pore structure.

6. Conclusion

The 100th AGER forum demonstrated how advances in porous-media science, numerical algorithms and imaging technologies are reshaping research for the energy transition. Fundamental studies of multiphase flow clarified the mechanisms controlling CO_2 trapping, hydrogen migration and wettability-driven displacement. Developments in digital core algorithms also showed that stable numerical schemes and faster molecular simulations can provide a solid basis for investigations in CO_2 sequestration and hydrogen storage.

In addition, developments in multiscale, dynamic and spectral micro-CT imaging offer powerful capabilities for visualizing flow, transport and reactive processes directly within pore structures. The dialogue after the lectures emphasized that bridging scales, integrating imaging with computation and applying data-driven approaches are primary directions for future work. These efforts are shaping a more quantitative and physically grounded framework for understanding and optimizing porous media processes essential to low-carbon energy systems.

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Conflict of interest

The authors declare no competing interest.

References

Blunt, M. J., Bazylak, A., Brook, M., et al. Research needs in porous media for the energy transition. InterPore Journal, 2024, 1(1): ipj260424-2.

Blunt, M. J., Bijeljic, B., Dong, H., et al. Pore-scale imaging and modelling. Advances in Water Resources, 2013, 51: 197-216.

Cai, J. AGER launches one-journal-one-forum mode to achieve a leading geo-energy exchange platform. Advances in Geo-Energy Research, 2024, 13(2): 81-82.

Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., et al. Carbon capture and storage update. Energy & Environmental Science, 2014, 7(1): 130-189.

Bultreys, T., Ellman, S., Schlepütz, C. M., et al. 4D microvelocimetry reveals multiphase flow field perturbations in porous media. Proceedings of the National Academy of Sciences of the United States of America, 2024, 121(12): e2316723121.

Cui, R., Hassanizadeh, S. M., Sun, S. Pore-network modeling of flow in shale nanopores: Network structure, flow principles, and computational algorithms. Earth-Science Reviews, 2022, 234: 104203.

Dawson, C., Sun, S., Wheeler, M. F. Compatible algorithms for coupled flow and transport. Computer Methods in Applied Mechanics and Engineering, 2004, 193(23-26): 2565-2580.

Feng, X., Qiao, Z., Sun, S., et al. An energy-stable smoothed particle hydrodynamics discretization of the navier-stokes-cahn-hilliard model for incompressible two-phase flows. Journal of Computational Physics, 2023, 479: 111997.

Hashemi, L., Blunt, M., Hajibeygi, H. Pore-scale modelling and sensitivity analyses of hydrogen-brine multiphase flow in geological porous media. Scientific Reports, 2021, 11(1): 8348.

Hematpur, H., Abdollahi, R., Rostami, S., et al. Review of underground hydrogen storage: Concepts and challenges. Advances in Geo-Energy Research, 2023, 7(2): 111-131.

Mascini, A., Boone, M., Van Offenwert, S., et al. Fluid invasion dynamics in porous media with complex wettability and connectivity. Geophysical Research Letters, 2021, 48(22): e2021GL095185.

Rücker, M., Bartels, W. -B., Garfi, G., et al. Relationship between wetting and capillary pressure in a crude oil/brine/rock system: From nano-scale to core-scale. Journal of Colloid and Interface Science, 2020, 562: 159-169.

Spiteri, E. J., Juanes, R., Blunt, M. J., et al. A new model of trapping and relative permeability hysteresis for all wettability characteristics. SPE Journal, 2008, 13(3): 277-288.

Wang, X., Chen, H., Kou, J., et al. An unconditionally energy-stable and orthonormality-preserving iterative scheme for the Kohn-Sham gradient flow based model. Journal of Computational Physics, 2024, 498: 112670.