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Perspective

Exploring the prospects and challenges of petrophysics research from the perspective of materials physics

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Abstract:
Rocks are the most prevalent material on solid planets, and using physical methods is the most practical and feasible way to explore planetary resources. This is also one of the most commonly used methods for oil and gas exploration on the Earth. However, many challenges remain to be addressed in practice. Based on the practice of oil and gas physical exploration, rock physicists need to answer several questions. This work aims to address these issues by exploring similarities between materials physics and petrophysics. There are some special phenomena in rock physics that can be explained by principles borrowed from materials physics. This work also examines the similarities of porous media in different physical methods, conducts comparative studies on the physical properties of porous media, and analyzes the potential for future exploration using comparative physical property methods. In addition to being applied in petroleum engineering logging and core analysis, petrophysics can also provide insights for the development of new energy and materials, offering valuable guidance for upgrading the energy structure.

1. Introduction

Rocks are the most common substances on the Earth and solid planets, often composed of porous media with complex mixtures of mineral components. Utilizing the differences in various physical properties of rocks is a primary method for detecting solid and fluid minerals. Analyzing the physical properties of rocks saturated with different fluids is currently the main means of assessing rock fluid properties in oil and gas exploration. Traditional well logging methods include electrical logging and acoustic logging (Shi et al., 2023), while oil and gas field development focuses on permeation in petrophysics, and geothermal research involves the thermal properties of rocks (Chekhonin et al., 2018).

Digital core technology is utilized to determine properties such as permeability, electrical conductivity, thermal conductivity, and acoustic characteristics by using digital information about a rock's pore structure, mineral composition, and fluid distribution. This has become a crucial method in current petrophysics research. The advantage of this approach is its ability to continuously simulate the factors affecting rock physical parameters, compared compare with the limited number of tests in experimental methods.

Rock physicists currently have three tasks to address, all of which require the integration of engineering problems with the analysis of material physics: (1) Utilize the physical characteristics of composite materials, rock physicists aim to clarify the understanding of petrophysics mechanisms. Through theoretical analysis, numerical simulations, and experimental verifi-

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cation, the physical reasons are sought to reveal behind these anomalous phenomena and identify the main contradictions. (2) Analyze the physical properties of rocks, utilize new interpretative models, and invert to obtain the desired pore structure and fluid saturation distribution parameters. (3) Analyze the same material with different physical characteristics, and find methods that can explain specific phenomena. By theoretically identifying feasible approaches, the researchers aim to enrich to enrich the selection of engineering practices.

This work aims to provide a technical approach for better conducting petrophysics research by reviewing petrophysics methods and comparing the similarities with materials physics, ultimately summarizing the research paradigms of petrophysics.

2. Petrophysics and material physics

With the availability of equipment like CT scanning and nuclear magnetic resonance that offers a wider range of scales and higher resolutions, it has become possible to determine the physical properties of rocks based on pore structure, mineral composition, and fluid distribution. By characterizing the microstructure of the research object and utilizing numerical simulations based on the distribution characteristics of different materials, the physical properties of the entire system can be determined. This approach is the concept of digital petrophysics and is also a common research approach in material physics. Many fundamental aspects of petrophysics are derived from other disciplines. Petrophysics originates from materials science and faces many similar problems and involves many similar problems and models (Aminzadeh and Dasgupta, 2013). Recently, research on effective physical parameters of non-homogeneous media has repeatedly appeared in various disciplines with different perspectives.

2.1 Rock is a “special” composite material

The numerical simulation methods for studying the physical properties of porous medium rocks based on the distribution characteristics of constituent minerals are the same research strategies as that for composite materials (Hull et al., 1996). The study of various physical properties of composite materials is well-established. Apart from the Archie formula in rock electrics, the fundamental content of petrophysics is widely derived from other disciplines. Compared to composite materials, petrophysics delves more into features like heterogeneity.

Composite materials encompass almost all structures and materials, whether they are wood, metals, polymers, or porous media like bones, ceramics. In a sense, rocks can be considered a type of composite material, and it is natural to study petrophysics from the material perspective. The approach to studying digital rock cores is not fundamentally different from studying digital polymers (Katsuhiko et al., 2024).

2.2 Representative elementary volume and “atoms” in metamaterials

In numerical simulations concerning the physical properties of porous media, researchers often utilize the concept of the representative elementary volume (REV). The REV represents the minimum volume where characteristics tend to stabilize, aiming to balance computational costs while ensuring that the numerical simulation results align with reality (Mehmet et al., 2021). This concept bears similarities to metamaterials, which are artificially engineered materials possessing extraordinary physical properties not found in natural materials (Xiang et al., 2023). The properties of metamaterials primarily stem from their artificial structures rather than the materials composing them. Democritus once proposed the “atomic hypothesis”, where in the context of metamaterials, these “atoms” refer to the material constructed from artificial building blocks. The characteristics of metamaterials depend on the overall properties of their “functional units” rather than the microstructure of the material components (Michael et al., 2011). When using digital rock cores to calculate various physical properties, the overall properties often play a crucial role, sometimes relying on macroscopic features whose scale is larger than the microstructure within the REV.

2.3 Percolation phenomenon

Percolation refers to a process in which a system undergoes a “phase transition” due to the increase of a certain substance to a specific proportion. In this system containing two types of spheres: insulating and conducting, and the percolation threshold is determined by observing the appearance of electrical currents as the percentage of different spheres is altered. If a certain threshold is exceeded, the physical properties of the system exhibit a sudden, cliff-like change, known as “percolation” (David et al., 2008). In petrophysics, the relationship between the physical properties of fluids and porous media is frequently discussed, especially concerning the electrical resistivity of reservoir rocks with fluid-saturated pores. Typically, the physical properties of a particular portion may be masked by a larger portion of physical properties. Apart from electrical properties, this phenomenon also involves the permeability of porous media and thermal conductivity characteristics.

2.4 Macroscopic and microscopic scales

In petrophysics research and engineering practices, a common challenge is the difficulty in matching the scales of core samples and well logging. Large fractures and cavities can alter the overall physical properties of rocks, leading to macroscopic situations different from the properties of the matrix. Even small-volume, low-resistivity bands can significantly change the overall resistivity of shale, causing a sharp decrease in resistivity in specific directions (Xie et al., 2022). In such cases, the porous media occupying a larger volume have minimal influence on the overall physical properties. This undoubtedly poses difficulties for well logging analysts who aim to analyze rock physical properties and invert parameters for pore structure and fluid saturation distribution.

It is challenging to match laboratory-scale simulations with engineering scales, a phenomenon commonly encountered in civil engineering practices as well. Like the issue of defects in materials science research, the presence of defects often serves as the primary determinant of the physical properties

Table 1. Similarities and differences of physical mechanism in porous media.

Elements	Physical properties		
	Flow	Electric conduction	Thermal conduction
Grain	Play no role	Almost non-conductive	A good conductor of heat
Fluid	Pore structure determines more	The main channel of the carrier	Usually lower than that of skeleton
Vug/Cave	Makes flow better	Matrix porosity determines more	Impairs heat conduction
Vertical fracture	Little effect on single-phase flow	Saturated water almost no difference, but saturated gas impedes it	Saturated water and methane both inhibit it
Parallel fracture	Greatly improve	Saturated water enhances it, but saturated gas almost no effect	Little effect at rest, closer to fluid properties while flowing
Conductive substance	Same properties as the grain	Facilitated conduction	Promote heat conduction
Time	Takes time to reach a balance	Instantaneous completion	Takes considerable time to reach equilibrium

under study, overshadowing the intrinsic physical properties of the material. This is an unavoidable objective reality.

3. Multiple physical properties in porous media

Matrix porosity provides vast storage space for underground oil and gas reserves. If the macroscopic structure masks the physical properties of matrix rocks, it undoubtedly presents a pessimistic outlook for researchers aiming to reveal fluid saturation in matrix pores using geophysical methods. However, insights from digital rock and polymer methods suggest that digital approaches involve assigning different materials to various spatial locations within the "research system" , each with distinct physical properties. Leveraging these diverse physical properties can facilitate the inversion and interpretation of the "research system".

3.1 Similarities

The Fourier's law, Ohm's law, and Darcy's law are respectively used to describe heat conduction, electrical conduction, and fluid flow in porous media. The physical essence of these three fundamental laws lies in depicting linear relationships between energy or substance flow rate per unit time under certain potentials, the conductivity of a specific energy or substance, and the geometric dimensions of objects. Mathematically, they are unified, as the heat conduction equation, Ohm's law differential equation, and the flow differential equation can all be expressed as $\partial u/\partial t = \alpha\nabla^2 u$, In heat conduction, electrical conduction, and fluid flow in porous media, u represents temperature, electric potential, and pressure respectively, t represents time. α is a constant that is directly proportional to the diffusion coefficient, for example, in heat conduction, it is the square root of the ratio of the thermal conductivity to the product of specific heat and density.

Due to the similarities in the aforementioned physical laws, it was conducted that experiments in simulating permeability by using electricity (Nokken and Hooton, 2008). In the early stages of research in oil and gas field development, when computer performance could not meet the demands of numerical simulations, electrical stimulation of permeability was a common method employed by many engineers. For the radial permeability testing method of cylindrical samples, Muskat proposed relevant schemes (Muskat et al., 1937), and later the similarities in different physical properties were utilized to introduce methods for radial electrical resistivity and thermal conductivity testing (Aboozar et al., 2021; Panja et al., 2021).

3.2 Different mechanisms

For porous media with developed cavities and fractures, the characteristics based on different physical properties are summarized in Table 1.

3.3 Application and prospects

Looking at a single physical property alone may not be sufficient to reflect a certain pore structure present in different porous media. However, by comparing multiple physical properties, these differences can be revealed to some extent. Such comparisons are beneficial for understanding the anomalies in well logging interpretations, aiding well logging engineers in making better judgments. Comparative studies on the diverse physical characteristics of porous media are also of significant importance for the discovery of new energy sources and materials. For instance, in the case of thermoelectric materials that trouble low-temperature geothermal power generation, the aim is to find a substance that simultaneously meets the criteria of low thermal conductivity and high electrical conductivity. Exploring porous media structures that fulfill this condition is also a valuable research direction.

4. Conclusions

Although the "peak carbon" and "carbon neutrality" policies may influence the ultimate development of traditional energy industries such as oil and gas, petrophysics research remains paramount. The evolution of petrophysics follows a trajectory similar to that of materials physics. Petrophysics deals with porous media that possess more complex pore structures and are predominantly composed of mixtures, inheriting many physical research methods from materials physics. The achievements of materials physic always provide insights for the development of petrophysics. Concepts such as "atoms" in metamaterials, REV, percolation threshold, and macroscopic scales all stem from materials physics.

In addition to studying the individual physical properties of porous media, an increasing number of comparative studies on multiphysical fields are crucial for understanding the nature of porous media and grasping the essence of different physical phenomena. These studies not only find applications in petroleum engineering well logging and core analysis but also hold inspirational significance for the preparation of new energy sources and materials. On one hand, petrophysics researchers can comprehend the reasons behind these physical phenomena from a materials science perspective based on their differences. On the other hand, by following the approach of petrophysics research, new perspectives and application scenarios can be provided for materials science research.

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Conflict of interest

The authors declare no competing interest.

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