Original Research Article

Sensitivity analysis of pore structure factors and permeability in carbonate reservoirs

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Abstract: This article delves into the pore structure factors of carbonate reservoirs and their impact on permeability sensitivity. Through detailed experimental analysis and theoretical research, the characteristics of pore structure, determination methods of related factors, and their relationship with permeability were elucidated. Further analysis of the mechanisms by which different factors affect permeability sensitivity provides important theoretical basis and practical guidance for the effective development and management of carbonate reservoirs.

Keywords: Carbonate reservoir; Pore structure factor; Permeability sensitivity

1. Introduction

Carbonate reservoirs play an important role in global oil and gas resources, and their complex pore structure has a significant impact on the permeability of the reservoir. The in-depth study of pore structure factors and permeability sensitivity is of great significance for optimizing oil and gas extraction strategies and improving recovery rates.

2. Pore structure characteristics of carbonate reservoirs

The pore types of carbonate reservoirs exhibit significant diversity, covering various forms such as pores, caves, and fractures. These different types of pore spaces exhibit significant differences in size, shape, distribution, and connectivity, collectively constructing extremely complex pore structures.

Pores, as a common type of pore in carbonate reservoirs, typically have relatively small sizes. The size of these pores is relatively uniform, and their distribution in the reservoir is also relatively uniform. They are often scattered inside rocks like fine networks, providing a certain space for fluid storage and slow flow.

In sharp contrast, karst caves are usually larger in scale. The size and shape of karst caves exhibit significant uncertainty and variability, some may present wide spaces, while others may have irregular shapes. The significant size differences and irregular shapes result in strong heterogeneity in the distribution of karst caves in the reservoir, making the flow and storage of fluids more complex and difficult to predict.

Cracks play a crucial role in carbonate reservoirs. They are like narrow channels that connect isolated pores and caves to each other. The presence of cracks greatly improves the connectivity of the reservoir, allowing fluids to flow more smoothly in the reservoir. Meanwhile, the direction, length, and width of cracks also have a significant impact on the flow characteristics of fluids. For example, longer and wider cracks can provide larger fluid flow channels, thereby significantly improving the permeability of the reservoir; Shorter and narrower cracks may create some resistance to fluid flow.

In short, the unique properties of pores, caves, and fractures, as well as their interactions, make the pore structure of carbonate reservoirs highly complex and diverse, which also brings many challenges and opportunities for the exploration, development, and evaluation of oil and gas resources.

3. Determination and Analysis of Pore Structure Factors

3.1. Porosity measurement

Porosity is an important indicator for measuring the richness of reservoir pore space, and its measurement methods are diverse.

The commonly used methods for measuring porosity include helium porosity measurement and liquid saturation method.

The helium porosity measurement method is based on Boyle's law and utilizes the low compressibility and good diffusivity of helium gas to measure pore volume. In the experiment, a rock sample of known volume is placed in a closed container and then helium gas is injected. By measuring the pressure changes before and after injection, combined with the gas state equation, the pore volume in the rock sample can be accurately calculated, thereby obtaining the porosity. This method has the advantages of fast measurement speed and high accuracy, and is suitable for various types of rock samples.

The liquid saturation rule is to immerse the rock sample in a certain liquid (usually water or kerosene) to fully fill the pore space of the rock sample. Then, by measuring the mass change of the rock sample before and after saturation, combined with the density of the liquid, the pore volume and porosity are calculated. This method is relatively simple to operate, but may be affected by factors such as liquid adsorption on the rock surface and incomplete filling of micropores inside the rock, resulting in certain deviations in measurement results.

Both the helium porosity measurement method and the liquid saturation method can provide us with information on the proportion of reservoir pore space to the total volume, which is of great significance for evaluating the reservoir's storage capacity and oil and gas resource potential.

3.2. Aperture distribution analysis

It is crucial to accurately obtain the distribution of pore size in order to gain a deeper understanding of the microscopic characteristics of pore structure.

Mercury intrusion porosimetry is a widely used technique for pore size distribution analysis. The principle is to use mercury under non wetting conditions, which requires a certain amount of pressure to enter the pores. The magnitude of pressure is inversely proportional to the diameter of the pores. By gradually increasing the pressure and measuring the amount of mercury injected, the pore volume distribution within different pore sizes can be obtained. The mercury intrusion method can measure pores with a larger pore size range (usually from a few nanometers to several hundred micrometers), but its application is limited due to the potential harm of mercury to the environment and the damage it may cause to certain pores.

The nitrogen adsorption method is mainly used to measure the distribution of micropores and mesopores (pore size less than 50 nanometers). Nitrogen undergoes physical adsorption on pore surfaces at low temperatures (usually liquid nitrogen temperature). By measuring the adsorption amount at different relative pressures and using appropriate theoretical models (such as BET equation, BJH model, etc.), the pore size distribution can be calculated. The nitrogen adsorption method has high resolution and accuracy, but its ability to measure large pore sizes is limited.

The comprehensive use of mercury intrusion porosimetry and nitrogen adsorption methods can achieve a comprehensive understanding of the pore size distribution over a wide range of pore sizes, providing strong support for in-depth research on the microscopic characteristics of pore structures.

4. The relationship between pore structure factor and permeability

4.1. Theoretical Model

In order to quantitatively describe the relationship between pore structure factors and permeability, many scholars have established a series of mathematical models based on in-depth research on pore structure characteristics. Among them, the Kozeny Carman equation and its improved forms play an important role.

The Kozeny Carman equation was initially proposed based on theoretical analysis of fluid flow in porous media. It links permeability with pore structure parameters such as porosity and specific surface area. However, the original Kozeny Carman equation has certain limitations in practical applications, so later researchers have continuously improved and perfected it.

The improved form takes into account more pore structure characteristics, such as irregularity of pore shape, non-uniformity of pore size distribution, and complexity of connectivity between pores. By introducing more correction coefficients and parameters, these improved models can more accurately reflect the quantitative relationship between actual pore structure and permeability, providing a powerful theoretical tool for predicting and evaluating permeability.

4.2. Experimental research

In order to further explore the complex relationship between pore structure factors and permeability, extensive research has been conducted through actual core flow experiments.

In the core flow experiment, carefully select core samples with different pore structure conditions. Then, in a strictly controlled experimental environment, the flow rate of fluid through the core under different pressure gradients is measured to calculate the corresponding permeability. By conducting experiments on a series of rock cores with different porosities, pore size distributions, pore shapes, and connectivity, rich data can be obtained.

These experimental data are not only used to verify the predictive relationship established based on theoretical models, but also to further reveal the more complex and subtle interactions between pore structure factors and permeability. For example, experiments have found that an increase in porosity alone does not necessarily mean a linear increase in permeability. The uniformity of pore size distribution and good connectivity between pores also play a crucial role.

A large number of research results have shown that when the porosity is higher, it means that there is more space available for fluid storage and flow, which helps to improve permeability. The more uniform the pore size distribution, the lower the flow resistance of the fluid in the pores, which can smoothly pass through the reservoir and thus improve the permeability. The more regular the pore shape, the less turbulence and energy loss occur during fluid flow, which is beneficial for improving permeability. Good connectivity provides a smoother flow channel for fluids, resulting in a significant increase in permeability.

In summary, through the establishment of theoretical models and practical experimental research, a more comprehensive and in-depth understanding of the relationship between pore structure factors and permeability has been obtained, which provides important theoretical support and practical guidance for fields such as oil and gas field development and reservoir evaluation.

5. Sensitivity analysis of permeability

5.1. Stress sensitivity

In geological environments, reservoirs typically bear enormous pressure from overlying rock layers. When this pressure changes, the pore structure of the reservoir will inevitably undergo deformation. Specifically, as pressure increases, rock particles may be compressed more tightly, pore spaces may shrink, and communication channels between pores may also be blocked or narrowed. The deformation of this pore structure will directly lead to a decrease in permeability.

Therefore, in-depth analysis of the relationship between stress and permeability changes is of great significance. By establishing precise mathematical models and conducting extensive experimental research, the impact of stress changes on permeability can be quantitatively described. This is crucial for accurately predicting the performance changes of reservoirs during the mining process. For example, in the process of oil and gas extraction, if the influence of stress changes on permeability cannot be fully considered, it may lead to prediction bias of production, affecting the formulation and optimization of extraction plans.

5.2. Fluid sensitivity

When a reservoir comes into contact with fluids with different chemical and physical properties (such as acids, bases, saltwater, etc.), it may trigger a series of complex physical and chemical changes, leading to changes in pore structure.

For example, acidic fluids may undergo chemical reactions with certain minerals in rocks, dissolving some minerals and changing the size and shape of pores. Alkaline fluids may cause clay minerals in rocks to expand and block pore channels. Saltwater may alter the wettability of rock surfaces and affect the flow characteristics of fluids in pores due to its high ion concentration.

These changes in pore structure caused by the interaction between fluids and reservoirs will ultimately be reflected in changes in permeability. Therefore, in the process of reservoir development and utilization, fluid sensitivity must be fully considered, and appropriate injection fluids and extraction methods must be selected to avoid or reduce adverse effects on reservoir permeability.

5.3. Temperature sensitivity

Temperature, as an important environmental factor, can have a significant impact on the physical properties of rocks and fluids. For rocks, an increase in temperature may cause thermal expansion, thereby altering the volume and shape of pores. Meanwhile, temperature changes may also affect the mechanical properties of rocks, such as hardness and strength, indirectly affecting pore structure.

For fluids, changes in temperature can cause variations in physical parameters such as viscosity and density. For example, an increase in temperature usually leads to a decrease in fluid viscosity and an increase in fluidity. On the other hand, temperature changes may also alter the interaction between fluids and rocks, such as affecting adsorption and desorption processes.

These changes in the physical properties of rocks and fluids caused by temperature fluctuations will ultimately affect pore structure and permeability. In some special geological environments or industrial applications, such as geothermal resource development or high-temperature and high-pressure oil and gas reservoir exploitation, the impact of temperature sensitivity on permeability is particularly significant and requires detailed research and evaluation.

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