Research progress in damage assessment methods for tight sandstone gas reservoirs

Guangxu Zhou¹, Yan Ye¹,* , Fujian Zhou¹

¹State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China.

* Corresponding author email: yeyan@cup.edu.cn

Abstract. In the process of oil and gas development, the perfect reservoir damage evaluation method is an important condition to realize the economical and efficient development of the reservoir. At present, great progress has been made in the exploration of tight oil and gas. However, due to the characteristics of low porosity, low permeability and low water saturation of tight sandstone gas reservoirs, conventional reservoir damage evaluation methods are not applicable to it, and no systematic evaluation method has been formed yet. The damage evaluation methods of tight sandstone gas reservoirs mainly include the steady-state method and the unsteady-state method. The steady-state method is mainly the high temperature and high back pressure method, while the unsteady-state methods are the pressure attenuation method and the pressure transmission method which are widely applicable. Visualization technology, microfluidic technology, flow rate evaluation method and recovery evaluation method are the new methods to evaluate reservoir damage, which are in the further research. This paper summarizes the research progress of reservoir damage evaluation methods for tight sandstone gas reservoirs, analyzes the main evaluation methods, experimental equipment and improvement measures, and points out the problems that need to be paid attention to and solved, in order to provide reference for efficient and accurate evaluation of reservoir damage in tight sandstone gas reservoirs.

1. Introduction

Unconventional oil and gas resources, especially tight oil and gas, are widely developed in China, which have good prospects for exploration and development. At present, great progress has been made in the exploration of tight oil and gas. Tight gas has become an important contributor to the increase of natural gas storage and production, with an average annual increase of $3110 \times 10^8$ m³ of natural gas geological reserves, accounting for about 52% of the increase of proven natural gas reserves in the same period. Compared with conventional reservoirs, tight sandstone gas reservoirs are characterized by low porosity, low permeability and ultra-low water saturation, so conventional reservoir damage evaluation methods in the industry standard are not applicable [1-3]. In recent years, many scholars have carried out researches on damage evaluation methods and experimental equipment according to different reservoir damage mechanisms, and it is of great significance to optimize drilling fluid and realize reservoir protection.

The damage mechanism of tight sandstone gas reservoir mainly includes fluid sensitivity damage, pressure sensitivity damage, liquid phase trap damage and solid phase invasion damage. Among them,
fluid sensitivity damage and liquid phase trap damage are important forms of damage in tight sandstone gas reservoirs [4-7]. Reservoir damage evaluation methods mainly include steady-state method, unsteady-state method and other evaluation methods combined with new technology. This paper summarizes the research progress of reservoir damage evaluation methods for tight sandstone gas reservoirs, analyzes the main evaluation methods, experimental equipment and improvement measures, and points out the problems that need to be paid attention to and solved, in order to provide reference for efficient and accurate evaluation of reservoir damage in tight sandstone gas reservoirs.

2. Steady-state method

For fluid sensitivity damage evaluation methods, the conventional steady-state method mainly conforms to SY/T 5358-2010 "Experimental Evaluation Method of Reservoir Sensitivity Flow", and its applicable scope is clastic rock samples with air permeability greater than 1 mD. For tight sandstone gas reservoirs, this method has some problems, such as not establishing initial saturation, unreasonable selection of media, not considering the influence of temperature, and forming pressure suppression at the inlet end of low permeability rock samples, which will lead to long experiment time and low accuracy of experimental results. Therefore, the evaluation methods of fluid sensitivity based on industry standards need to be improved.

Yuan Xuefang [8] made improvements on the basis of industry standards, using nitrogen as the intermediate medium and test medium to test permeability under the condition of original water saturation of the reservoir, and at the same time ensuring that the pressure difference and water saturation of permeability test before and after the experiment were within an appropriate range. This method can keep the evaluation process in line with the characteristics of gas reservoir and eliminate the effects of gas slippage and water lock damage, but this method does not take into account the influence of temperature and does not solve the problem of long experiment time.

In view of the difficulty in outlet flow detection and long experimental time in the conventional steady-state method, Yang Hao [9] adopted the steady-state method with high temperature and high back pressure.

By adding back pressure in the process of core displacement, the method can promote the participation of small pore channels in the flow and compress the thickness of water film to increase the cross-sectional area of seepage and reduce the stress sensitivity at the outlet end of rock samples, so as to improve the permeability of rock samples and shorten the experimental period. Kang Yili [4] used the steady-state method of high temperature and high backpressure to evaluate the rock samples of ultra-deep tight sandstone gas reservoir in Tarim Basin, proving that the damage of fluid sensitivity under high temperature condition was higher than the experimental results under normal temperature condition. By simulating the reservoir temperature at high temperature, the method can be used to evaluate the fluid sensitivity damage more accurately, and the high backpressure can increase the boiling point of the fluid and reduce the experimental error caused by the boiling of the fluid at high temperature.

Fig. 1 shows the Nano-Perm permeability tester designed using the steady-state method, which is suitable for measuring the permeability of ultra-low permeability shale cores of conventional size. In the measurement process, the rock sample is put into the holder and the confining pressure is applied to the predetermined value. Extremely low pressure gas is applied above the rock sample, and the flow rate is tested by the downstream highly sensitive gas flowmeter. After the gas flow is stable, the gas flow rate and the pressure difference between upstream and downstream of the rock sample are tested, and the permeability is obtained by Darcy's law. The equipment is automatically collected and recorded by the computer and the permeability is automatically calculated. The measurement is stable, accurate and easy to operate. The permeability test range is 0.001mD-0.1nD.
3. Unsteady-state method

3.1. Pressure attenuation method
You Lijun and Kang Yili [10] proposed the pressure attenuation method. In this method, a certain flow pressure is added to the inlet end of the core, and the fluid flows along the core under the action of pressure. The flow of the fluid reduces the flow pressure at the inlet end gradually, and the sensitivity can be evaluated according to the change of the flow pressure with time when the fluid passes through the core. Compared with conventional fluid sensitivity evaluation methods, this evaluation method has a wider application range, higher accuracy and shorter experimental time. However, for ultra-low permeability reservoirs, the evaluation time is still relatively long. Yang Hao [9] improved the pressure attenuation method and pre-increased the back pressure when changing the working fluid type, so as to improve the fluid replacement efficiency. The experimental error caused by the evaporation of the working fluid can be reduced by keeping the high back pressure at the outlet during the pressure attenuation.

PDP-200 permeability tester is designed by pressure pulse attenuation method for conventional low and ultra-low permeability core permeability, as shown in Fig. 2. The test range is 1mD-10nD. During the test, the tight rock sample is placed in the core holder, and the pressure pulse is applied at both ends. The permeability of the tight rock sample is calculated by detecting the change of the upstream and downstream pressure. The measurement time is short, the speed is fast and the measurement process is automatic. The computer automatically collects and records the data and calculates the permeability.
3.2. Pressure transmission method
To solve the problem of ultra-low permeability, China University of Petroleum independently designed and developed a pressure transmission instrument on the basis of research on pressure transmission methods [11-13]. Fig. 3 shows the physical model of core permeability measured by the transient pressure transmission method. The pressure in the container under the rock sample at the initial time is $P_0$. During the experiment, constant pressure $P_m$ is used to displace fluid flow above the rock sample. The upstream fluid percolates through the core to the downstream, causing the downstream pressure to change. Permeability can be calculated from the data of downstream pressure changes over time.

![Figure 3. Schematic diagram of pressure transmission permeability measurement.](image)

The measurement of core permeability by pressure transmission method is a one-dimensional saturated seepage problem along the vertical direction, which can be modeled according to the mathematical model of seepage:

$$\frac{\partial^2 P}{\partial x^2} = \frac{1}{\eta} \frac{\partial p}{\partial t}$$  \hspace{1cm} (1)

Where, $\frac{\partial p}{\partial t}$ is the change of downstream pressure of pressure transduction meter with displacement time; $\eta$ is coefficient of pressure conductivity, cm$^2$/s

$$\eta = \frac{k}{\phi \mu C}$$  \hspace{1cm} (2)

Initial conditions:

$$p(x, 0) = p_0', 0 < x < L$$  \hspace{1cm} (3)

Boundary conditions:

$$p(0,t) = p_m, t \geq 0$$  \hspace{1cm} (4)

$$\frac{\partial p(L,t)}{\partial x} = \frac{q \mu}{kA}$$  \hspace{1cm} (5)

Since there is no velocity monitoring at the location $x = L$ of the core outlet in the experiment, (5) is modified by the compression coefficient:

$$\frac{\partial p(L,t)}{\partial x} = -\frac{CV \mu}{kA} \frac{\partial p}{\partial t}$$  \hspace{1cm} (6)
Where, \( k \): permeability of core sample, \( 10^{-3} \, \mu m^2 \); \( \mu \): viscosity of measuring medium, \( mPa\cdot s \); \( C \): compressibility factor of experimental system, \( MPa^{-1} \); \( \phi \): porosity of the core; \( A \): cross-sectional area of the core sample, \( cm^2 \); \( V \): volume of the downstream sealed chamber, \( ml \).

The Laplace method is used to solve the model. Before solving, Equation (1) needs to be transformed into Laplace space, as shown in Equation (7).

\[
\frac{\partial^2 p}{\partial x^2} - \frac{sp}{\eta} = -\frac{p_0}{\eta}
\]  

Equation (7) is the second-order inhomogeneous equation, and its general solution can be obtained:

\[
p(x, s) = C_1 e^{\frac{L}{\eta}} + C_2 e^{-\frac{L}{\eta}} - \frac{p_0}{s}
\]

In Equation (8), the values of \( C_1 \) and \( C_2 \) depend on the boundary conditions of the model, so the boundary conditions of the model need to be transformed into Laplace form:

\[
\begin{align*}
p(0, s) &= \frac{P_m}{s} \\
\frac{\partial p(L, s)}{\partial x} &= -\frac{C V \mu}{kA} (s p - p_0)
\end{align*}
\]

Substituting the transformed boundary condition (9) into (8), the expressions of coefficients \( C_1 \) and \( C_2 \) can be obtained:

\[
\begin{align*}
C_1 &= \frac{(p_m + p_0) \left( \frac{s}{\eta} e^{-\frac{L}{\eta}} + \frac{CV \mu}{kA} s (sp - p_0) \right)}{\sqrt[3]{s^3 - \frac{L}{\eta}} e^{-\frac{L}{\eta}} + \sqrt[3]{s^3 - \frac{L}{\eta}} e^{\frac{L}{\eta}}} \\
C_2 &= \frac{(p_m + p_0) \left( \frac{s}{\eta} e^{\frac{L}{\eta}} + \frac{CV \mu}{kA} s (sp - p_0) \right)}{\sqrt[3]{s^3 - \frac{L}{\eta}} e^{-\frac{L}{\eta}} + \sqrt[3]{s^3 - \frac{L}{\eta}} e^{\frac{L}{\eta}}}
\end{align*}
\]

Substitute the values of \( C_1 \) and \( C_2 \) into (8), and the expression of the general solution of the diffusion equation can be obtained:

\[
p(x, s) = \frac{(p_m + p_0) \left( \frac{s}{\eta} e^{\frac{L}{\eta}} + \frac{CV \mu}{kA} s (sp - p_0) \right)}{\sqrt[3]{s^3 - \frac{L}{\eta}} e^{\frac{L}{\eta}}} - \frac{p_0}{s}
\]

According to Carslaw pressure transmission formula:
\[
\frac{p(x,s) - p_0}{p_m - p_0} = 1 - 2\sum_{n=1}^{\infty} e^{-\frac{\phi_n^2}{L^2}} \sin\left(\frac{x\phi_n}{L}\right) \frac{(\cos \phi_n \sin \phi_n + \phi_n)}{(\cos \phi_n \sin \phi_n + \phi_n)}
\]  
(12)

\[
\phi_n \tan \phi_n = \frac{AL\phi}{V}
\]  
(13)

Parameter \( \Phi_n \) is mainly affected by the ratio of core pore volume to downstream volume. As its value approaches 0, the model can be expressed in the form of Equation (13) at \( x = L \).

\[
\frac{p(L,s) - p_0}{p_m - p_0} = 1 - e^{-\frac{AL\phi}{V}}
\]  
(14)

Permeability can be obtained by simplification:

\[
k = -\frac{\xi\mu CVL}{A}
\]  
(15)

Where, \( \xi \) is the slope of the curve between \( \lambda \) and time.

\[
\lambda = \ln \left[ \frac{p_m - p(L,s)}{p_m - p_0} \right]
\]  
(16)

The pressure transmission method does not need to measure the stable outlet flow, and the experiment cycle is shorter and the accuracy is higher. Zhang Lufeng used this method to evaluate the water sensitive damage caused by fracturing fluid to Keshen tight sandstone gas reservoir in Tarim, and also evaluated the water locking damage and solid phase damage. This method is suitable for reservoir damage evaluation of tight and low permeability reservoirs with permeability as the standard. However, the influence of temperature on the experiment is not considered in the pressure transmission device at present, so the corresponding accuracy can be improved.

4. Other methods

4.1. Microfluidic technology

Microfluidic technology, also known as laboratory on a chip, is a science and technology for studying and controlling fluids on the space of micron and nanometer scales. It can integrate the basic functions of laboratory such as sampling and testing into a chip of several square centimeters, and has been introduced into various fields such as biology, chemistry and environment at present [14-16]. In recent years, microfluidic technology has been applied to the petroleum field. Srikanth [17,18] studied the invasion and backflow characteristics of fracturing fluid through microfluidic technology, so as to study the water lock damage caused by hydraulic fracturing. At the same time, the effect of surfactant reducing reservoir damage can be analyzed visually and intuitively. Wen Song [19] visualized fine grain migration and its damage to reservoir by using this technique. Geng Xiangfei [20] carried out online and visual simulation evaluation of oil displacement performance of nano-fluidity modifiers in tight reservoirs through three kinds of microfluidic models independently designed.

Microfluidic technology has the characteristics of high accuracy, high sensitivity, transparent visualization, low cost and so on. The current research shows that this technology has a broad prospect in oil recovery, reservoir damage evaluation, tight reservoir and other related fields.

4.2. Visualization Technology

Visualization technology is a new method applied to reservoir damage evaluation in recent years. This method does not harm the sample and has a visual display of results. At present, CT scanning technology and nuclear magnetic resonance imaging technology are widely used.

CT is a cross-sectional virtual anatomy technology, which transmits rays through the section of the sample from multiple directions. The ray information attenuated by the sample is detected by the
detector. The collected data is reconstructed by the computer, and the density distribution of the detected section is presented in the form of two-dimensional image. CT scanning technology has been widely used in core heterogeneity evaluation, fracture quantitative analysis, real-time online measurement of fluid saturation and core flow experimental research. Zhang Fuxiang [21] used industrial CT to quantitatively describe the three-dimensional spatial distribution characteristics of cores contaminated by drilling fluids. He established a test method to quantitatively judge the filtration depth of drilling fluid, and obtained the three-dimensional spatial distribution graphs of drilling fluid pollution under different conditions. According to the basic principles of CT scanning, Leng Zhenpeng [22] established the water-sensitive damage evaluation method and put forward the formulas for calculating the porosity and relative porosity of water sensitive damage. By carrying out the design of water flooding experiment and combining with CT scan evaluation method, the quantitative evaluation of water sensitive damage was realized.

Magnetic resonance imaging (MRI) is a mature, fast, nondestructive, high-resolution detection technology that can display fluids in porous media. At present, the core displacement visualization experimental method of MRI is relatively mature, Di Qinfeng [23] combined MRI visualization technology with core displacement experiments to observe the distribution characteristics and migration rules of weak gels in cores. MRI can reflect various properties of fluid in the pore of the core. The core skeleton almost does not generate signals, so the core structure with millimeter or even micron resolution in any selected section can be obtained quickly and nondestructively, and the distribution state of oil and water can be determined, as well as the core physical property parameters such as porosity, permeability, oil and water saturation and capillary pore diameter can be estimated [24].

4.3. Flow evaluation method
For fractured reservoirs, including artificial fractured reservoirs represented by reformed tight sandstone and shale, Zheng Lihui [25] proposed to use flow instead of permeability to quantitatively characterize the extent of reservoir damage. In this method, the relationship between flow damage rate and permeability damage rate is derived from Darcy’s law, and the permeability damage rate is calculated from the flow damage rate and the inlet and outlet pressure of the core at different flow rates before and after being damaged by the working fluid. The experimental results show that the permeability damage rate is basically the same as the steady flow damage rate when the single layer is exploited. The permeability damage rate cannot quantitatively characterize the overall damage degree of the reservoir when the two layers and three layers are exploited together, but the flow damage rate can be used to characterize the overall damage degree. This method solves the problem that permeability is used as a single evaluation index of reservoir damage, realizes the evaluation of the overall damage degree of fractured reservoir, and provides a new idea for reservoir damage evaluation. However, this method cannot explain the damage mechanism at present, and the evaluation indexes and methods need to be further optimized.

4.4. Artificial fractures
For fractured tight strata, artificial fractures can be used to improve the accuracy of evaluation. In fluid sensitivity damage evaluation, Xu Peng [26] used artificial fracture to evaluate rock sensitivity in Dabei Block. In order to fully consider the influence of fracture width and ensure the stability of filling material, Zhou Yicheng [27] proposed a new method to simulate artificial fracture width, and selected copper sheet as filling material to more accurately evaluate reservoir damage. Aiming at fractured tight sandstone gas reservoirs, the optimization and improvement of artificial fracture technology is of great significance to reservoir damage evaluation and reservoir protection.

4.5. Recovery rate evaluation method
Xu Jiafang [28] introduced the improved recovery experiment into the evaluation of reservoir sensitivity. In this method, the relationships between the recovery rate of samples in different solutions
and the changes of permeability caused by acid sensitivity, alkali sensitivity and salt sensitivity are established, and the classification standard of reservoir sensitivity index is obtained, so as to realize the sensitivity evaluation of reservoir. This method provides a new idea for the sensitivity evaluation of unconventional oil and gas reservoirs.

4.6. Model calculation method
In addition to laboratory experiments, model calculation method can also be used to evaluate the damage of water phase trap. The related methods include water phase trap index method, total water volume method, phase trap coefficient method, phase trap index method, regression analysis method, grey prediction method, neural network method [5,29-32].

5. Conclusion
At present, the damage evaluation method of tight sandstone gas reservoir is not perfect. Forming an accurate and efficient reservoir damage evaluation method is the key to the realization of reservoir protection, and also one of the important conditions for the realization of economic and efficient development of gas reservoir. Through the analysis of the relevant research progress of reservoir damage evaluation methods in recent years, the conclusions are as follows:

1. For tight sandstone gas reservoir damage evaluation, the main methods include steady state method and unsteady state method. In recent years, the steady state method has been improved by increasing the back pressure, adjusting the gas medium and establishing the original water saturation conditions. For the unsteady state method, the pressure attenuation method and the pressure transmission method are widely applicable. The pressure attenuation method is mainly improved by increasing the high back pressure, while the pressure transmission method is an improved method which does not need to measure the stable outlet flow rate, and has shorter experiment cycle and higher accuracy.

2. In addition to the conventional steady-state and unsteady-state methods, there are many new techniques applied to reservoir damage evaluation. Visualization techniques, including CT scan and MRI, have been applied in reservoir damage evaluation. As new methods of reservoir damage evaluation, microfluidic technology, flow evaluation method and recovery rate evaluation method provide new ideas for the sensitivity evaluation of unconventional oil and gas reservoirs, which need to be further studied.

3. The current damage evaluation methods of tight sandstone gas reservoirs mostly take permeability as the evaluation index, so there is the problem of too single evaluation index and a multi-scale evaluation method needs to be established. Furthermore, in addition to the evaluation according to different damage mechanisms, the comprehensive results caused by multiple mechanisms should also be evaluated, and a multi-scale comprehensive evaluation method with reservoir productivity as an index should be established.

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