Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 9, No. 1, 2025
www.scholink.org/ojs/index.php/asir

Original Paper

Reservoir Damage Characteristics and Protective Measures under the Coupling Effect of Temperature and Pressure

Zhihui Xu[1]

[1] College of Petroleum Engineering, Xi'an Shiyou University, Xi'an 710065, China

Received: January 22, 2025 Accepted: February 18, 2025 Online Published: February 26, 2025
doi:10.22158/asir.v9n1p114 URL: http://doi.org/10.22158/asir.v9n1p114

Abstract

In the exploitation of oil and gas fields, the coupling effect of temperature and pressure on the reservoir brings many problems. Temperature rise changes rock properties and accelerates reservoir damage. Reservoir damage includes physical, chemical and biological aspects, including permeability decrease, pore structure deterioration, rock fracture and fracture expansion. Preventive measures such as optimization of completion fluid system, temperature control and pressure management, as well as chemical, physical and microbial remediation are proposed to provide technical support for reservoir damage prevention and control, which is of great significance for improving oil and gas production efficiency and ensuring energy supply.

Keywords

Temperature and pressure, Coupling, Reservoir damage, Damage characteristics

1. Introduction

In the process of oil and gas field development, the reservoir often faces complex temperature and pressure environment, and the influence of temperature and pressure coupling can not be underestimated. This is related to reservoir stability, permeability and storage capacity, and directly determines oil and gas recovery and production efficiency. It is of great significance to explore the characteristics of reservoir damage under the coupling effect of temperature and pressure and put forward feasible protective measures for optimizing the development strategy of oil and gas fields and ensuring efficient energy exploitation. It helps to reduce production costs, extend reservoir life, and provide strong support for the sustainable development of the energy industry.

2. Influence of Temperature and Pressure Coupling on Reservoir

2.1 Influence of Temperature on Reservoir

As the temperature increases, the brittleness strength and toughness of rocks decrease, the internal mineral structure changes, the crystalline structure of some minerals is damaged, and the compressive strength is weakened, especially for rocks with high clay mineral content (Zeng, 2019). Taking sandstone and shale reservoirs as an example, when the temperature rises from the initial 120℃, the compressive strength of sandstone decreases from 75MPa to 63MPa, a decrease of 16%, and shale decreases from 45MPa to 39MPa, a decrease of 13.33%. The rock becomes brittle and the strength and toughness decrease, which is caused by the change of mineral structure caused by high temperature. In particular, it has greater influence on rocks with high clay mineral content. The brittle rock causes the expansion of micro-fractures, the integrity of the reservoir is damaged, the oil and gas production is affected, and the anisotropy intensifies and threatens the stability of the reservoir. Higher temperatures also affect pore structure, with sandstone porosity increasing from 18% to 19.5% and shale from 13% to 13.8%, but thermal stress can alter pore channels and reduce fluid mobility. When the temperature exceeds the threshold, the clay minerals expand and block the pores, and the permeability decreases. For example, when the temperature increases by 20℃, the permeability of some reservoirs decreases by 20%-30%.

Table 1. Temperature Effect on Reservoir Data Sheet

Rock type	Temperature (℃)	Compressive strength (MPa)	Strength change rate	Porosity (%)	Porosity change rate
Sandstone	Inception	75	-	18	-
	40	72	-4%	18.5	+2.78%
	80	68	-9.33%	19	+5.56%
	120	63	-16%	19.5	+8.33%
Shale	Inception	45	-	13	-
	40	43	-4.44%	13.2	+1.54%
	80	41	-8.89%	13.5	+3.85%
	120	39	-13.33%	13.8	+6.15%

2.2 Comprehensive Effects of Temperature and Pressure Coupling

The increase of temperature increases the brittleness of rock, and the increase of pressure compresses porosity and fracture channels, which accelerate the propagation of micro-fractures and significantly reduce the permeability and storage capacity of reservoir. As the temperature increases from the initial to 120℃ and the pressure increases from the initial to 20MPa, the reservoir permeability decreases from 100mD to 40mD, a decrease of 60%, and the porosity decreases from 20% to 14%, a decrease of

30%, and the reservoir permeability and storage capacity decrease significantly. This is due to the increased brittleness of the rock due to the increase of temperature, and the increased pressure of the compression pores and fracture channels, which accelerate the expansion of micro-fractures. At the same time, high temperature causes mineral chemical reaction, and high pressure causes rock plastic deformation, which jointly speeds up reservoir damage and reduces oil recovery. It also reduces reservoir chemical stability and changes mineral composition and mechanical properties. For example, the elastic modulus increases from 15GPa to 20GPa, with a change rate of 33.33%. The coupling of temperature and pressure makes the relationship between permeability, porosity and mechanical properties of the reservoir complex, and the characteristics change nonlinear.

Table 2. Data Sheet of Reservoir Characteristics under the Coupling Effect of Temperature and Pressure

Temperature (℃)	Pressure (MPa)	Permeability (mD)	Permeability change rate	Porosity (%)	Porosity change rate	Elastic modulus (GPa)
Inception	Inception	100	-	20	-	15
50	10	80	-20%	18	-10%	16
80	15	60	-40%	16	-20%	18
120	20	40	-60%	14	-30%	20

3. Analysis of Reservoir Damage Characteristics

3.1 Reservoir Damage Mechanism

(1) Physical damage

At high temperature, the thermal expansion of minerals inside the rock produces thermal stress, and the expansion of minerals with high coefficient of thermal expansion such as quartz is obvious. High pressure extrusion of pore space, taking sandstone reservoir as an example, temperature and pressure to a certain extent, the fluid in the pore is compressed, the pore wall is squeezed, the effective porosity is significantly reduced, the oil and gas storage space is reduced, the fluid flow path is narrowed, the resistance is greatly increased. The rock with micro-fractures is the first to expand under the combined action of temperature and pressure. The shale reservoir is typical, and the fracture change makes the rock structure loose and the strength decreased, and also disrupts the flow path of oil and gas, affecting the mining efficiency. High temperature causes thermal expansion of rocks, increases the distance between internal mineral particles, and weakens the binding force, which is the case for rocks rich in feldspar, leading to the loosening of rock structures and small internal deformation. After accumulation, the internal structure of rocks is damaged, the overall stability is reduced, and hidden danger is laid for subsequent reservoir damage.

(2) Chemical damage

Under the condition of high temperature and pressure, clay minerals and carbonate minerals in the reservoir rocks are affected, and the temperature increases to dissolve them. For example, in the shale sandstone reservoir rich in clay minerals, the dissolution of clay minerals enlarges the pores, which seems to increase the porosity, but in fact destroys the internal structure of the rock, reduces the strength and stability, and aggravates the damage of the reservoir. In certain high-temperature and high-pressure environments, dissolved substances precipitate due to temperature changes, and insoluble minerals or sediments such as calcite and gypsum clog pores and fractures, reducing pore connectivity and reducing reservoir permeability and storage capacity. The change of temperature and pressure causes chemical transformation of carbonate minerals, etc. In limestone reservoirs, calcite recrystallizes under high temperature and high pressure, forming denser minerals, reducing pore volume and permeability. These changes accumulate over a long period of time, resulting in the decline of the sustainable production capacity of the reservoir and the reduction of oil and gas recovery efficiency.

(3) Biological damage

In high temperature and high pressure environments such as high temperature deep oil and gas fields, microorganisms are small in size but not small in energy. The acidic substances produced by their metabolism are like "corrosive tools", which will corrode rock minerals such as feldspar and mica, making the pore structure from regular to chaotic, with some pores becoming larger and others blocked by debris, seriously affecting the stability and permeability of the reservoir (Chen, Zhao, & Yang, 2019). In water-bearing oil and gas reservoirs, microbial metabolism accelerates the interaction between water and oil and gas, resulting in an emulsion that increases fluid flow resistance. The corrosive substances produced will also corrode rocks and mining equipment, changing the physical and chemical properties of the reservoir. This biological damage is like a chronic disease that accumulates slowly during reservoir development, continuously reducing reservoir productivity and increasing the cost and difficulty of recovery.

Table 3. Comparison Table of Influence Degree of Reservoir Damage Factors

Damage type	Degree of impact (scale: 1-10)	Main influencing factor	Reversibility (%)	Impact on production capacity (%)
Physical damage	8	Temperature, pressure	30	-25
Chemical damage	9	temperature, minerals	20	-30
Biological damage	7	Microbial metabolism	40	-20

3.2 Reservoir Damage Performance

(1) Decreased permeability

Reservoir permeability is crucial to smooth oil and gas flow, but it is easy to decrease rapidly under high temperature and pressure. In this environment, the pores of rocks are heated and compressed, the pore channels are narrowed, and the passage of oil and gas molecules is blocked. The expansion of cracks breaks the rock structure, and the debris generated blocks part of the passage. The chemical dissolution or precipitation of minerals also "disturbs", resulting in loose rock structure, particles blocking the pores, and precipitation directly forming obstacles in the pores and cracks. These factors work together to greatly reduce reservoir permeability. The result is very serious, the flow efficiency of oil and gas is greatly reduced, the recovery rate is significantly reduced, and the production efficiency of the oilfield is seriously affected. Under extreme conditions, the permeability of rocks with low permeability may be close to zero, oil and gas can hardly flow, the difficulty of exploitation is greatly increased, the development cost is significantly increased, and the production can only be maintained by complex technical means to restore the flow of the reservoir.

(2) Pore structure changes

The high temperature causes the expansion of rocks and minerals to produce internal stress, and the high pressure compresses the pore space. The two work together to reduce porosity and weaken the connectivity between pores. The pore shape has changed from round and regular to twisted, the size is no longer uniform, and the distribution is different. Some pores are compacted under continuous pressure. Even local blockage, which greatly reduces the storage space and capacity of oil and gas in the reservoir, disrupts the flow path of oil and gas and makes it difficult to flow smoothly, directly affects the production performance of the reservoir, reduces the exploitation efficiency, increases the exploitation cost, and brings many challenges to the development of oil and gas fields.

(3) Rock fracture and fracture expansion

Under the harsh conditions of high temperature and high pressure, the mechanical properties of reservoir rock change, and irreversible cracks and fractures are easy to occur. The increase of temperature changes the mineral structure inside the rock, changes the binding force among mineral particles, and the increase of pressure directly exerts the force. The two synergies lead to constant changes in the stress state of the rock, and when the stress reaches the fracture limit, cracks will break, especially in areas with micro-cracks (Xu, Lun, Wang, et al., 2025). These fractures and rock fractures seriously damage the structural integrity of the reservoir, reduce the mechanical strength of the rock, threaten the stability of the reservoir, and lead to the loss of local storage capacity and the overall productivity. In the mining process, fracture expansion increases rock instability, increases the risk of formation sliding, damages mining equipment, interrupts operations, and brings great difficulties to reservoir restoration, which consumes a lot of manpower, material and financial resources, and uses complex technical means to restore its stability and production capacity.

4. Protective Measures

4.1 Preventive Measures for Reservoir Damage

(1) Select the appropriate completion fluid system

The composition of completion fluid is adjusted based on the determination of rock mineral composition, pore structure characteristics and fluid properties by advanced chemical analysis technology. In the reservoir rich in clay minerals and with small pores, increasing the amount of organic polymer, polyacrylamide with moderate molecular weight is selected. The molecular chains can be extended and interwoven in the completion fluid to form a spatial network structure, which can effectively improve the liquid viscosity and enhance the permeability resistance. Accurate control of the bentonite addition ratio is generally controlled at 2%-5%. Through high-speed stirring, it is evenly dispersed in the completion fluid. Bentonite particles are adsorbed on the polymer network to further fill the tiny pores, prevent the harmful components in the completion fluid from entering the reservoir, and reduce the damage to the reservoir permeability and pore structure.

According to the reservoir pressure data, the completion fluid density is adjusted by adding soluble salts such as sodium chloride or potassium chloride. When the reservoir pressure is high, the appropriate salt addition can maintain the completion fluid density in the just balance formation pressure range to avoid excessive pressure compression damage to the reservoir. In terms of viscosity, in addition to organic polymer and bentonite, xanthan gum and other viscosifiers are added. According to the simulation results of high temperature and high pressure environment, it is determined that the amount of xanthan gum is generally between 0.1% and 0.3%, so that it can cooperate with other components to keep the viscosity of completion fluid between 20-50 kpa ·s under high temperature and high pressure, which can effectively stabilize the well wall to prevent collapse and will not affect the circulation and displacement efficiency of completion fluid due to too high viscosity.

(2) Temperature control technology

Coolant injection technology is a key means of reservoir temperature control. Prior to implementation, a detailed evaluation of reservoir geology is required to determine the location, amount, and rate of coolant injection. When calculating the injection amount, follow the formula $Q = Cm\Delta T$,C is the reservoir heat capacity (Joules/(kg ·℃)),m is reservoir mass (kg),ΔT is expected temperature drop (℃),Q is the coolant required to carry heat (joules).The reservoir is 1000 joules/(kg ·℃),It's 1000 kilograms, ΔT at 10℃, Q is 10^7 joules.Injection rate(cubic meters/hour) to take into account the heat dissipation and protection of the reservoir, often according to the pore structure of the reservoir, permeability, etc., such as sandstone reservoir can refer to the empirical formula $\upsilon = \sqrt{\frac{\kappa}{\varphi}}$($\kappa$ is permeability, the unit is D; Is porosity, dimensionless),The actual common rate is 5-20 cubic meters per hour. Geothermal mining commonly used low-temperature water, injected by precision injection pump; In deep well mining, inert gas such as nitrogen is preferred, compressed by gas compressor and injected, and cooling is controlled by adjusting flow rate to alleviate the adverse effects of temperature gradient on the reservoir.

(3) Stress management

Precise control of stable injection pressure with high precision flow control valve and pressure regulating pump. The safe injection pressure range and appropriate injection fluid flow rate are determined based on reservoir geological characteristics, pore structure and pre-production data (Naseer, Shakir, Hussain, et al., 2025). During injection operation, the flow control valve accurately controls the injection liquid flow according to the preset flow rate and the pressure regulating pump adjusts the injection pressure in real time. For a sandstone reservoir, the upper limit of safe injection pressure is estimated to be P1 mpa and the appropriate flow rate is Q1 cubic meters/hour. When the injection pressure is close to P1, the pressure regulating pump automatically reduces the output pressure, and the flow control valve simultaneously reduces the injection liquid flow rate to keep the injection pressure stable within the safe range and effectively avoid excessive formation pressure damage to the reservoir caused by too fast or too much injection.

Adjust formation pressure Select suitable gas or liquid injection or discharge according to the actual reservoir pressure. The formation pressure in the oil and gas reservoir is too low to select high pressure gas (such as nitrogen) or light oil injection with special gas injection (liquid) equipment for stable flow injection. The injection amount and speed are dynamically adjusted according to the reservoir pressure monitoring data, and the injection amount is determined by calculating the formation pressure deficit to ensure that the pressure gradually rises to a reasonable range. The formation pressure is too high. The oil (gas) production equipment should discharge appropriate fluid to relieve the pressure. The deep shale gas reservoir has low permeability and pressure sensitive operation. The low flow rate, multiple injection or discharge methods are used to slowly adjust the pressure to maintain the pressure balance of the reservoir and prevent the rock from fracturing due to pressure imbalance.

4.2 Repair Measures for Reservoir Damage

(1) Chemical repair technology

The acidification technology first accurately analyzes the mineral composition of the reservoir rock to determine the content and distribution of carbonate minerals. The reservoir with high carbonate mineral content is acidified with hydrochloric acid, and the concentration of hydrochloric acid solution is generally 5%-15% according to the pore structure and blockage degree of the reservoir. The hydrochloric acid solution is injected at a suitable rate using a high pressure injection device. During injection, the pressure is closely monitored to prevent formation rupture caused by excessive pressure. Hydrochloric acid reacts with carbonate minerals to dissolve calcium carbonate, magnesium carbonate, etc., producing soluble salts, carbon dioxide, and water. The reaction product drains the reservoir with the fluid, removes the pore sediment, and restores the permeability of the rock. In the exploitation of oil, natural gas and shale gas, especially after fracturing, the pores are often clogged with proppant debris and formation particles, which can be effectively dissolved by acidizing operations to improve the flow capacity of oil and gas and increase production.

(2) Physical repair technology

Mortar injection repair technology detects the distribution and size of fractures and pores in the reservoir, and ADAPTS mortar according to the results. Select uniform sand particle size 0.1-0.5 mm, according to a specific proportion of cement and additives, such as coagulants, water reducing agents. The addition amount of the accelerating agent is usually 2%-5% of the cement mass to ensure the rapid solidification of the mortar after injection, and the water-reducing agent is added according to the cement mass of 0.5%-1.5% to improve the mortar fluidity. Professional high-pressure grouting equipment is used to inject mortar into the reservoir in order to stabilize the pressure and flow. The injection pressure depends on the geological conditions and depth of the reservoir, generally 10-30 mpa, and the flow rate is controlled at 5-15 m3 / h. The mortar fills cracks and pores under pressure to form a stable support structure, enhance the stability of the reservoir structure, significantly reduce the fluid flow resistance, prevent the excessive expansion of cracks, and maintain the stability of the reservoir.

(3) Microbial remediation technology

Microbial injection technology selects suitable probiotics or enzymes according to specific reservoir conditions. The reservoir rich in petroleum organic pollutants is selected with Pseudomonas microorganisms that can degrade petroleum efficiently. In the laboratory, these microorganisms were cultured on a large scale with special medium, and appropriate nutrients such as nitrogen source and phosphorus source were added to meet the growth needs of microorganisms. Culture to the logarithmic stage of microbial growth to produce bacterial solution the concentration of bacterial solution is controlled at 10^8-10^9 bacteria per milliliter. The bacterial fluid is injected into the reservoir through the water injection well at the appropriate flow rate, which is generally 5-15 m3 / day depending on the reservoir permeability and pore structure. Microorganisms enter the reservoir and use the organic matter as the nutrient source to produce acetic acid, propionic acid and other organic acids through the decomposition and fermentation process of their own metabolic activities. These organic acids can dissolve some of the minerals in the reservoir and gradually clear the sediment and widen the pore channels to restore the reservoir fluidity.

5. Conclusion

The coupling effect of temperature and pressure on the reservoir is extensive and complex, and the physical, chemical and biological damage caused by it significantly changes the permeability, pore structure and rock stability of the reservoir, which brings many challenges to oil and gas production. However, reservoir damage can be effectively prevented through rational selection of completion fluid system, temperature control technology and pressure management. Using chemical repair, physical repair and microbial repair technology, the damaged reservoir can be repaired to a certain extent and its performance can be restored.

References

Chai Nina, Li Jiarui, Zhang Liwen, et al. (2025). Sandwich-like continental shale oil reservoir fracturing fracture experimental study. *Journal of reservoir evaluation and development*, 2025, *15*(01), 124-130.

Chen Junqiang, Zhao Kangkang, & Yang Hao. (2019). Application of petroleum logging technology to evaluation of complex lithologic reservoirs in Ordos Basin. *China Petroleum and Chemical Industry Standards and Quality*, 2019, *45*(02), 100-102.

Naseer, Z., Shakir, U., Hussain, M., et al. (2025). An integrated comprehensive approach describing structural features and comparative petrophysical analysis between conventional and machine learning tools to characterize carbonate reservoir: A case study from Upper Indus Basin, Pakistan. *Physics and Chemistry of the Earth*, 2025, 138103885-103885.

Xu, Y., Lun, Z., Wang, H., et al. (2025). SO2 ad-/desorption performance on shale matrix: New insights into SOx mitigation via geologic storage in unconventional natural gas reservoir. *Chemical Engineering Journal*, 2025, 507604, 22-160422.

Zeng Yunfeng. (2019). Application of geophysical exploration technology in natural gas and oil resource prediction. *China Petroleum and Chemical Standards and Quality*, *45*(03), 186-188.