

Current Status of Research on Seepage Mechanism in Tight Sandstone Gas Reservoirs

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Abstract: China's tight sandstone gas reservoirs have a large amount of resources, which is an important part of future energy. At present, one of the main problems facing the production of tight sandstone gas reservoirs is water production, and the water production of gas wells is a key influence factor restricting the stable and increased production of gas reservoirs. Firstly, the research status of reservoir characteristics of tight sandstone gas reservoirs is summarized, then the seepage mechanism of tight sandstone gas reservoirs is analyzed, and finally the relationship between gas and water in tight sandstone gas reservoirs is reviewed, which provides a basis for further research on the seepage mechanism of tight sandstone gas reservoirs and the law of gas and water production.

Keywords: Gas-water distribution; Tight sand gas; Formation water.

1. Introduction

With the rapid and stable development of China's society, the country's demand for oil and gas resources has increased dramatically, and the contradiction between energy supply and demand has become a key factor restricting development. Due to the decline in production of conventional oil and gas fields and the demand for environmental protection, natural gas as a clean energy source has gradually become a research hotspot. As unconventional energy sources, tight gas, shale gas and coal bed methane have been highly valued and rapidly developed. China's tight gas resources are widely distributed and rich in reserves, mainly concentrated in Ordos, Sichuan Basin, Bohai Bay and Songliao Basin. In recent years, the development of tight gas reservoirs has made remarkable progress with the advancement of tight gas reservoir development technology, including the breakthrough of fracturing technology for straight and horizontal wells. Improvements in fracturing and reforming technology have substantially increased single well production and the degree of gas reservoir utilization has also been significantly enhanced.

Regarding the definition of tight sandstone gas reservoirs, no uniform standard has been formed in the international arena yet. Kazemi et al [1] defined gas reservoirs with a gas permeability less than $1 \times 10^{-3} \mu\text{m}^2$ as low permeability or tight reservoirs, while reservoirs with a gas permeability greater than $1 \times 10^{-3} \mu\text{m}^2$ are categorized as conventional reservoirs. Holditch et al [2] defined tight gas reservoirs from the perspective of natural gas production, and concluded that tight gas reservoirs are not a common reservoir, and that tight gas reservoirs can be used to produce natural gas. Holditch et al. defined tight gas reservoirs from the perspective of natural gas production, and considered that tight gas reservoirs should be "natural gas reservoirs that can only be commercially effective if they are exploited by large-scale hydraulic fracturing, horizontal well fracturing, or multi-branching well technology". In China, the concept of tight sandstone gas reservoirs was only gradually and clearly studied and specified in the early 1990s. Yuan Zhengwen et al [3] and Xu Huazheng et al [4] defined a tight sandstone

reservoir as having a porosity of less than 12% and a permeability of less than $0.1 \times 10^{-3} \mu\text{m}^2$ by studying tight sandstone gas reservoirs in the Dongpu depression area, and classified the reservoirs into a general layer, a near-tight layer, a tight layer, a very tight layer, and a super-tight layer based on the size of the permeability. Zou Cai Cai et al [5] defined dense sandstone gas reservoirs as sandstone-like reservoirs with overburden matrix permeability less than or equal to $0.1 \times 10^{-3} \mu\text{m}^2$.

2. Reservoir Characteristics of Tight Sandstone Gas Reservoirs

The microscopic pore structure characteristics and distribution characteristics of tight sandstone gas reservoirs will directly affect their storage performance and gas seepage ability, and therefore also determine the difference in the production capacity of the gas reservoir and the final recovery effect of the gas reservoir [6]. Tight sandstone gas reservoirs are mostly fine sandstone - siltstone, colluvium and mud content are high, the depth of burial is not the same, the reservoir temperature and the original formation pressure can be high or low, can be lenticular distribution or block or layer distribution, Lei Qun, Li Xizhe, etc. [7] based on the reservoir production characteristics of China's tight sandstone reservoirs are subdivided into block gas reservoirs, layered reservoirs, and lens-shaped gas reservoirs. gas reservoirs.

The type of tight sandstone trap is dominated by lithologic trap, and there are also tectonic-lithologic traps in some areas [8], and its genesis mainly includes three kinds of proximal deposition, remote deposition, and diagenesis, and generally the deposition process will be accompanied by diagenesis. Sedimentary reservoir compaction and cementation during diagenesis will lead to the reduction of primary pores in reservoir rocks, especially those with relatively low maturity, and the large reduction of pores will turn the reservoir into a low-permeability reservoir, or even a very dense non-reservoir [9]. Dissolution in the later stages of diagenesis will lead to the generation of secondary porosity, which will increase the porosity of the dense layer and turn it back into a

low-permeability reservoir. Due to the low permeability of tight sandstone reservoirs, the long-distance transportation and large-scale aggregation and storage of natural gas can not rely on gas buoyancy alone, so natural gas is generally widely endowed in tight sandstone reservoirs regionally, and there is no significant gas-water interface, and the distribution of gas reservoirs has obvious root gas characteristics.

Due to its own low permeability, low abundance and other characteristics, tight sandstone gas reservoirs have different development characteristics from other conventional gas fields.

(1) Low permeability and dense reservoir with strong non-homogeneity

Dense sandstone reservoir space mainly has two categories: pore-type and fracture-porosity type. Sedimentation and diagenesis during reservoir formation make the pore structure extremely complex [10], in addition to a large number of developed clay minerals significantly reduce the permeability of the reservoir, resulting in a complex reservoir microstructure. Tight sandstone gas reservoir reservoirs usually include high porosity and high permeability layer, low porosity and low permeability layer, and high porosity and low permeability layer [11], the reservoir is non-homogeneous, and its porosity is generally 3% to 12%.

(2) Secondary pore development and high capillary pressure

Dense sandstone reservoirs have strong diagenesis, the reservoir is dominated by secondary pores and accompanied by a large number of micropores, the throat is thin and tortuous, the fluid is not easy to flow, and the pore throat connectivity is poor. Secondary pores account for 70%~80% of the total volume of pores. The pores in dense sandstones are distributed in multiple scales with a variety of pore types, and the pores in dense sandstones are categorized into nanopores ($<0.5 \mu\text{m}$), micropores ($0.5\text{-}1.5 \mu\text{m}$), and mesopores ($>1.5 \mu\text{m}$) based on the difference in pore connectivity and the contribution to the reservoir and seepage flow [12]. Reservoir pore types can be subdivided into reduced intergranular pores, intergranular dissolution pores, and dissolution-enlarged intergranular pores [13], and pore throats can be categorized into lamellar, curved lamellar, and tubular, while fracture structures, such as microfractures, disintegration joints, and facies joints, are developed. The gas flow in the reservoir shows double pore and seepage media seepage characteristics, and due to the differences in permeability properties, storage properties and pressure propagation speed of the two media in the gas reservoir, the fluid flow between the matrix pores and cracks is easy to occur. The pore throat is narrow in the dense reservoir, the capillary pressure is high, the discharge and drive pressure is between 1~2MPa, and the capillary pressure will reach 7.0MPa under 50% water saturation.

(3) High water saturation of reservoir

The pore throat and fracture conduction diameter of tight gas reservoir is small, the capillary pressure is high, the water saturation is high, and the gas phase flow ability is weak. The residual gas saturation of water-driven gas increases, which is an important reason for the low recovery rate of tight gas reservoirs.

(4) Complex reservoir gas-water relationship

Tight sandstone gas reservoirs generally have high water saturation, complex gas-water relationship, and the side and bottom water drive is not obvious. During the primary mining period, the type of gas reservoir drive is characterized by

elastic drive and dissolved gas drive, and the primary recovery rate is generally low. The distribution law of gas and water in the gas reservoir is not controlled by tectonic pattern as a whole, but only in a single connected sand, it will be controlled by both tectonic pattern and lithology.

3. Current Status of Research on Seepage Mechanism

3.1. Slippage effect

Gas in the rock pore medium of low velocity seepage characteristics are different from the liquid, the gas in the rock pore wall does not produce adsorption thin layer, the flow rate of the gas molecules in the center of the pore and the pore wall has no obvious difference, this wall of the flow rate is not 0 microscopic movement embodied in the macroscopic is the gas in the seepage process of sliding off the effect.

Jones et al [14] through experimental research: the degree of influence of the sliding effect on gas reservoir seepage mainly depends on the permeability and reservoir pressure, in general, the lower the permeability of the reservoir, the lower the reservoir formation pressure, the more significant the sliding effect. Rose et al [15] think that in a certain bound water conditions, the sliding effect and the water saturation is negatively correlated with the degree of water saturation, and at high temperature when the sliding effect is more significant. Gao Shusheng et al [16] combined the laboratory results with the actual gas reservoir development conditions, and concluded that in the development stage of gas reservoir depletion, when the wellbore flow pressure reaches the abandonment pressure, the reservoir still exists in a higher formation pressure, so it is not necessary to consider the effect of the slippage effect on the production in the process of the actual exploitation of gas wells.

3.2. Starting pressure

Starting pressure is the critical value of the pressure difference between the two ends of the core when the gas in the core starts to flow, also called the threshold pressure, which reflects the sudden change and time lag phenomenon of the gas from the static state to the flow state in the reservoir. Wang Xibin simulated the formation conditions for the start-up pressure gradient test, the experiment studied the relationship between the initial permeability and water saturation of the core and the start-up pressure gradient, and found that there is a negative correlation between the permeability and the start-up pressure, and there is a positive correlation between the water saturation and the start-up pressure gradient [17]. Zheng Xiaomin conducted a study on the change rule of initiation pressure and movable water, which showed that for Changqing Surig tight gas reservoir, the higher the water saturation of the reservoir, the higher the gas phase initiation pressure [18].

3.3. Stress sensitivity

Stress sensitivity of reservoir refers to the phenomenon that rock permeability or porosity decreases with the increase of effective stress, which is expressed by rock volume coefficient and pore compression coefficient, which quantitatively indicates the change of pore volume due to the change of pore pressure. At present, about the quantitative characterization of reservoir stress-sensitive features there are a variety of evaluation criteria, can be classified for stress-sensitive intensity, and now the main use of indoor physical

simulation experiments using the target block of natural rock cores to obtain permeability with the effective stress of the formation between the change rule.

3.4. Gas-water two-phase flow

John Cousins [19] concluded through equivalent experiments that as the temperature rises, the gas expands and the liquid evaporates, resulting in accelerated gas molecular movement and increased viscosity. Ren Xiaojuan [20] through indoor experiments on the influence of gas-water phase permeability factors, the results show that the physical properties of the core and the pressure gradient on the gas-water phase permeability have different degrees of influence. Shanley et al [21] gas-water two-phase seepage “permeability barrier” theory that the porosity and permeability of dense sandstone reservoirs is low. According to the theory of “permeability barrier”, the porosity and permeability of dense sandstone gas reservoirs are low, and the two-phase co-permeability zone almost does not exist, that is, the dense sandstone gas reservoir will not produce gas or water in a certain interval. According to Tian Wei et al [22], for tight reservoirs, the gas-phase permeability decreases substantially with the increase of water saturation, and when the water saturation reaches 80%, the gas-phase permeability is approximately 0, which reduces the gas well capacity and causes a significant decrease in the gas recovery rate. It can be seen that the water saturation has a very unfavorable effect on the two-phase seepage law of gas and water, and many scholars have only qualitatively described the two-phase seepage law. It is very important to quantitatively characterize the effect of water saturation on gas-water seepage and on gas well productivity for the theoretical development of tight sandstone gas reservoirs.

4. Gas-water Relationship Study in Tight Sandstone Gas Reservoirs

4.1. Stratigraphic water endowment state

The original water in the depositional process, after compaction, diagenesis, metamorphism and other effects, together with the water released during the formation of hydrocarbons from organic matter, form formation water [23]. For tight sandstone gas reservoirs, the water phase is generally a wetting phase, formation water is mainly distributed in the micropore throat and the rock surface, the gas is stored in the pore space, and the micropore throat surrounds and controls the pore body, forming a gas-water mutual sealing state. Microscopic pore structure characteristics determine the original water saturation level, the development of small pore throats leads to high water saturation in the reservoir, and the gas content is poor.

According to the state of formation water in the formation, combined with the non-homogeneity of the reservoir, pore throat structure, etc., the formation water is divided into three categories: bound water, capillary water, and movable water [24]. Bound water is the formation water that is bound in the contact corners of rock particles, in micropores or adsorbed on the surface of rock skeleton particles and cannot move. Capillary water refers to the formation water developed in the micro - fine pore throat in the reservoir with strong non-homogeneity, which can be subdivided into dense lens capillary water and residual capillary water formed by insufficient filling strength. Movable water refers to the formation water that can move freely under the effect of

gravity, generally developed in reservoirs with good physical properties, and can be subdivided into low-part stagnant water, residual movable water formed by insufficient filling strength, and isolated lenticular body water. The identification methods of gas well water production sources include the identification of the production dynamic data of gas wells, the identification of gas production profiles [25], the identification of water-gas ratios, the identification of water properties, and the identification of unstable test wells [26], and many other methods.

4.2. Gas-water distribution law of tight gas reservoirs

In recent years, with the scale up production of tight sandstone gas reservoirs, the study of gas-water law has become a top priority. Pang Xiongqi used physical simulation experimental methods to study the formation process of tight sandstone gas reservoirs and the distribution law of gas and water. It is pointed out that the non-homogeneity of the reservoir is the main reason for the complexity of the gas-water relationship. Zhu Yadong et al. concluded that the complexity of gas-water relationship in tight sandstone gas reservoirs is mainly related to the incomplete gas-water replacement in low-permeability reservoirs, the lenticular sands formed by fluvial deposition, and the concentration of catchment water caused by the change of stratigraphic tendency from westward-dipping to eastward-dipping. Through the study of groundwater in Surig West District, it is believed that groundwater can be divided into four categories according to the types of seepage barriers, namely: the first category is the water-rich river type, the second category is the water type of the local side bottom of the river sands, the third category is the water type of the “lenticular body”, and the fourth category is the water type of the residual water type of the dense layer. It was also concluded that microstructures play an important role in controlling the spatial distribution of water. Zhang et al. concluded that the hydrocarbon intensity controls the general pattern of gas and water distribution, and the lateral inhomogeneity of the reservoir controls the local gas and water distribution in the reservoir. Dou Weitan et al. analyzed the formation water chemical characteristics, formation water properties and formation water genesis, and concluded that the formation water in tight sandstone gas reservoirs is not controlled by regional tectonics, but mainly controlled by the intensity of hydrocarbon production and reservoir inhomogeneity.

5. Summary

(1) The reservoirs of tight sandstone gas reservoirs have low permeability, high tightness, significant inhomogeneity, developed secondary porosity, high water saturation, and complex gas-water relationship.

(2) Compared with conventional gas reservoirs, tight gas reservoirs often have the problems of early reservoir water sighting and short stable production time during the development process, and there are the phenomena of stress sensitivity, start-up pressure gradient, gas sliding effect, and high-speed nondarshi, etc., which will affect the development effect of tight gas reservoirs.

(3) According to the endowment state of formation water in the formation, formation water in tight sandstone gas reservoirs is categorized into bound water, capillary water and movable water. The complexity of gas-water relationship is

mainly affected by reservoir inhomogeneity, hydrocarbon intensity and low permeability conditions, while formation water distribution is closely related to formation inhomogeneity and hydrocarbon intensity.

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