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Technique Progress of Improving Gas Recovery in Conventional Gas Reservoirs

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Abstract

Conventional natural gas reservoirs are the main force of natural gas production and the "ballast stone". In order to promote the continuous improvement of the development level of conventional gas fields, the gas reservoir recovery evaluation model and the main influencing factors are surveyed and analyzed. Then the difference between improving gas and oil reservoir recovery and the core concept of gas reservoir are compared and analyzed. And two core problems of unbalanced gas utilization and heterogeneous water intrusion are analyzed with technical methods for improving or enhancing gas recovery (IGR or EGR). Then two efficient development examples are analyzed with guidance on balanced development theory in Sulige dense sandstone gas reservoir in Ordos Basin and Longwangmiao Formation gas reservoir in Anyue gas field in Sichuan Basin. Finally, some proposals are put forward to greatly improve gas reservoir recovery by increasing pressure drop ripple coefficient and pressure depletion efficiency, which provides a basis for the top-level design and technology research of using CO_2 and chemical methods to improve gas reservoir recovery.

Subject Areas

Petrochemistry, Petroleum Geology

Keywords

Conventional Natural Gas, Balanced Development, Improve Gas Recovery, Technical Countermeasures

1. Introduction

Sinopec natural gas development has experienced preliminary development, steady production and rapid development in three stages, and annual industrial gas production exceeds 30 billion cubic meters with conventional gas industrial production of 21.4 cubic meters, accounting for 70%. Therefore, the scientific and efficient development of conventional natural gas reservoirs has a positive role in enhancing China's natural gas development level and ensuring national energy security [1]-[6]. The conventional gas reservoirs of Sinopec mainly include five types: carbonate rock gas reservoirs, low-permeability dense sandstone gas reservoirs, condensate gas reservoirs, volcanic rock gas reservoirs, and medium-high permeability sandstone gas reservoirs, among which large and medium-sized carbonate rock gas reservoirs and low-permeability dense sandstone gas reservoirs are the main types. The carbonate gas reservoirs represented by Puguang gas field and Yuanba gas field are in the stable production stage, and the Zhongsheng gas field and Zhongjiang gas field are in the upper production stage in the low permeability tight sandstone gas reservoir, while the Daniudi gas field is in the stable production period. The key development technologies of gas reservoirs in different development stages need to be solved urgently: 1) Fine residual gas characterization, improved gas recovery, and moisture pressurization extraction technology of high sulfur carbonate gas reservoirs; Key technologies such as water control and sulfur control. 2) Fine description of fracture pore reservoir and "dessert" prediction, gas and water identification and gas content prediction technology, low cost and fast drilling and completion, reservoir transformation, and protection technology. 3) Fine characterization and gas content prediction technology of strong heterogeneous reservoir in tight sandstone gas reservoir, residual gas quantitative tracing technology, engineering technology of improving oil recovery at low cost, key technologies for the development of water-bearing tight gas reservoir, etc. The utilization rate of explored reserve conventional gas reserves is low, and the recovery rate of developed reserves is low, and the calibration recovery rate of different types of gas reservoirs varies greatly, which has the potential of production and recovery improvement. Through the techniques and methods of improving gas recovery through systematic investigation and analysis of conventional gas reservoirs at home and abroad [7] [8] [9] [10], we guide the development and adjustment for different types of gas reservoirs, which provides a basis for the top-level design and technology research of using gas injection and chemical methods to improve gas reservoir recovery.

2. Gas Reservoir Recovery Rate and Main Influencing Factors

2.1. Implications of Gas Reservoir Recovery and Enhanced Gas Recovery

The recovery rate of the gas reservoir refers to the ratio of the amount of natural gas produced from the gas reservoirs to the proved geological reserves or verified geological reserves with the development evaluation under the existing engineering and technical conditions. The geological conditions of gas reservoir and the existing development technology level determine the recovery rate of gas reservoir. Gas reservoir recovery is an important index to measure the level of gas field development, and it is the foundation and basis for designing development technical indicators, formulating development technical plans and formulating development technical policy.

Enhanced gas recovery in gas reservoir refers to a series of development efforts to increase recoverable reserves and increase the cumulative yield under certain economic and technical conditions based on the development scheme or the expected recovery under the existing development state. The ratio of newly added recoverable reserves to proved geological reserves is the added value of oil recovery. The higher the enhanced recovery range of the gas reservoir, the larger the new recoverable reserves, and the more recoverable natural gas, and the higher the final recovery rate of the gas reservoir.

2.2. Difference in Enhancing Recovery between Gas and Oil Reservoirs

The driving force of the natural gas reservoir exploitation is different from that of the oil reservoir. The reservoir is generally used for supplementary energy development, and crude oil is a weak compressible fluid with small elastic energy. After the elastic energy is depleted, there is still a large amount of crude oils stored underground, requiring artificial injection of water, gas, chemical agent, heat and other media to supplement the energy to extract the remaining oil. The oil recovery rate has obvious stages, which can be divided into primary recovery with natural elastic energy development, secondary recovery with water injection development, tertiary recovery with gas injection or chemical injection development, etc., and the oil recovery rate is continuously improved through the transformation of development methods in different stages. With the continuous increase of the cumulative amount of crude oil production, the oil saturation of the reservoir continues to decrease, so the reservoir development is the process of "continuously oil saturation decreasing" of the reservoir. The reservoir recovery technology includes chemical displacement, gas displacement, thermal oil recovery and other technologies. By changing the physical and chemical properties of the displacement phase or crude oil, the impact degree and efficiency of displacement phase can be improved, and the crude oil recovery can be increased by 5% - 30% again on the basis of the conventional secondary recovery rate of 30% - 40%.

Natural energy depletion development and the maximum use of formation elastic energy are the basis of gas reservoir development. The driving force of gas reservoir development is the gas elastic energy determined by the pressure level. Therefore, gas reservoir development is the process of "continuously gas pressure depletion". The natural attribute of the strong gas compressibility determines the economic benefit and technical feasibility that all gas reservoirs except the gas reservoirs with high condensate oil are developed by natural energy exhaustion rather than supplementary energy development. Natural gas has strong compressibility and large elastic energy. According to the different gas reservoir temperature, pressure and gas components, the volume of gas extracted from underground to the ground can be expanded by hundreds to thousands of times. Most of the natural gas can be produced by relying on the gas itself and rock elastic energy. Theoretically, for dry gas reservoirs, if the abandoned formation pressure is 10% - 20% of the original formation pressure, the cumulative produced gas can generally reach 70% - 80% of the used geological reserves.

2.3. Evaluation Model of Gas Reservoir Oil Recovery

The gas reservoir recovery rate is the ratio of the final cumulative gas recovery to the geological reserves. The gas reservoir recovery is the product of geological reserve utilization degree, pressure drop ripple coefficient and pressure depletion efficiency.

The utilization degree of geological reserves is the basis of calculating the recovery rate, and the utilization degree of geological reserves refers to the ratio of the geological reserves of natural gas to the proved geological reserves or the verified geological reserves in the production construction area/section designed in the development scheme. The degree of reserve utilization is different from the traditional degree of reserve producing, which refers to the ratio of the geological reserves of natural gas to the proven geological reserves or verified geological reserves in the plane production area or longitudinal reserves designed in the development scheme. Meanwhile, it is known from the ideal gas state equation that under a certain temperature condition, the amount of the gas matter is proportional to the pressure and the volume of the gas. During the development of depletion, the amount of gas produced is proportional to the gas reservoir pressure drop and the volume of pressure drop. Therefore, the proportion of natural gas reserves in the production construction area/section is affected by the ripple coefficient of pressure drop and pressure depletion efficiency.

The ripple off coefficient of pressure drop is defined as the ratio of dynamic reserves of gas field/gas reservoir and the geological reserves in the plane construction area or the longitudinal development section, or the static reserves ratio. Pressure depletion efficiency is defined as the proportion of cumulative production to dynamic reserves constrained by waste production (waste formation pressure). Pressure depletion efficiency depends on the gas reservoir waste conditions. Waste gas production rate refers to the production rate when the gas well production rate decreases to the production rate in which operation cost is equal to the net sales income. When the gas well production decreases to waste production, the corresponding formation pressure is the waste formation pressure.

2.4. Main Affecting Factors of Gas Reservoir Recovery

The geological factors affecting gas recovery refer to the relevant geological parameters that affect the recovery calculation parameters such as reserve utilization degree, pressure drop impact coefficient and pressure depletion efficiency. The geological parameters of gas reservoir including reservoir physical property, heterogeneity and connectivity, fluid characteristics and driving mode are the primary geological factors affecting gas reservoir recovery. Reservoir physical properties, heterogeneity and connectivity determine the gas flow capacity, single well discharge area and gas well production capacity, and are highly sensitive to pressure drop impact coefficient and pressure depletion efficiency. The fluid characteristics of gas reservoir mainly include fluid types and fluid occurrence states, and fluid types contain dry gas, wet gas and condensate gas, and the fluid occurrence states contain adsorption state, free state, and dissolution state. According to the fluid type and drive mode, gas reservoir can be divided into dry gas reservoir, wet gas reservoir and condensate gas reservoir. According to the drive mode, gas reservoir can be divided into gas drive gas reservoir and water drive gas reservoir. In general, the fluid type of dry gas reservoir is dry gas, and the drive type is elastic gas drive. The recovery rate of this type of gas reservoir is mainly determined by the waste pressure, and usually the pressure drop impact coefficient is high. For water displacement gas reservoir, water invasion affects dynamic reserves and waste pressure, resulting in the significant reduction of pressure drop impact coefficient and pressure depletion efficiency. Therefore, the geological factors affecting the recovery of water displacement reservoirs are not only the reservoir physical properties, heterogeneity and connectivity characteristics, but also the distribution characteristics of water and the size of water energy.

Engineering factors affecting gas recovery mainly refer to the drilling and completion techniques and development technical parameters that affect the recovery parameters. In general, the adverse factors causing the production loss or capacity decline of gas reservoir development are engineering factors affecting the gas reservoir recovery, including the dynamic reserves decrease of the reservoir caused by the damage of the reservoir, the dynamic reserves loss caused by the gas reservoir, the dynamic reserves decrease caused by the closure of the artificial cracks, the cumulative gas loss caused by the ground gathering and transportation system, the low drainage gas production efficiency and the cumulative gas production loss.

The economic factors affecting the gas reservoir recovery rate mainly refer to the external factors that affect the waste yield. In general, the factors affecting the economic indicators of gas reservoir development mainly include: gas price, labor cost, price level and exchange rate, etc. Gas price has the most direct impact on the economic lower limit coefficient, and the gas price directly determines the sales income of output natural gas. When the sales revenue is not enough to offset the rising operating cost caused by labor cost, price level and exchange rate, the gas reservoir development reaches the critical point of economic benefit, and the corresponding gas reservoir recovery rate is the economic limit recovery rate.

2.5. Core Concept of Improved Gas Reservoir Recovery

1) Gas oil recovery improvement should run through the whole life cycle of gas reservoir development. To some extent, there is no clear stage of gas reser-

voir development and the IGR accompany the whole process of gas reservoir development. The development and production process of monotonous pressure drop in gas reservoir determines that the utilization degree of gas reservoir reserves and the utilization efficiency of formation energy must be improved to obtain a high final recovery rate. In the development process of water drive gas reservoir, due to the ogeneity of the reservoir and crack development, the separation of the water causes the formation of "water seal gas" in the gas reservoir, resulting in a large number of geological reserves can not be extracted, and then the final recovery of the gas reservoir is reduced. Microscopically, in the process of water invasion, gas and water form two-phase flow in the seepage channel, and the water phase flow reduces the gas phase permeability, increases the energy loss of gas reservoir, leading to a significant reduction in the pressure depletion efficiency of gas reservoir, increases the waste pressure, and serious damage to the gas reservoir recovery. Therefore, the core of improving EOR is to reduce uneven water intrusion, improve the efficiency of gas reservoir pressure depletion, and reduce the waste pressure. In the development process, the concept of balanced use of the whole life cycle should be followed to minimize the loss of gas reservoir pressure depletion efficiency, and thus reduce the damage to gas recovery.

2) To avoid or reduce recovery damage early in development is more important than improving recovery later in development. The gas reservoir recovery damage mainly comes from the reservoir damage in the process of drilling and completion, reservoir damage caused by excessive production pressure difference (speed sensitivity and pressure sensitivity, etc.), water sensitivity and residual gas storage caused by water intrusion, etc. The reservoir transformation can improve the reservoir damage to some extent, but it is difficult to restore to the original state, and the reservoir transformation increases the development cost. For the water displacement gas reservoir, the formation water will cause the water locking effect or the water sealing gas, and the residual natural gas within the water flooded range is difficult to be extracted economically and effectively. Therefore, in the process of natural gas exploitation, it is often more important to avoid or reduce the reservoir damage and premature water recovery damage than using other technical means to improve the recovery in the later stage, which is also an important principle for the economic benefit development of natural gas reservoir.

3. Methods for Improving Gas Recovery in Conventional Gas Reservoirs

3.1. Main Development Problems in the Conventional Gas Reservoirs

The practice of conventional natural gas development at home and abroad [11]-[16] shows that the two key factors affecting the recovery rate and development effect of conventional natural gas reservoir are reservoir physical properties and connectivity, the size of formation water and water intrusion mode.

On the whole, the development of conventional natural gas reservoir mainly faces two problems: one is the unbalanced utilization. The problem is mainly for conventional anhydrous gas reservoir, especially the strong heterogeneous conventional gas reservoir, which is blocked by poor lithology or physical fomation, and gas reservoir is not fully connected and separated into multiple gas reservoir units. In the same unit, internal reservoir quality, reservoir type, reservoir pore structure combination characteristics are not the same. Because the strong heterogeneous distribution of effective reservoir itself and 3D seismic and geological accuracy, part of the gas reservoir unit reserves cannot be effectively developed. So from the perspective of the whole gas reservoir, reserves in plane and longitudinal imbalance affect the final recovery of gas reservoir. Second is Inhomogeneous water intrusion. This problem is mainly aimed at the conventional water displacement gas reservoirs, especially gas reservoirs with the side and bottom aquifer. The key to development is to deal it well with the contact relationship between gas and water and water energy utilization, and to maximize the elastic energy of natural gas itself. The energy of the bottom water of the conventional natural gas storage can be divided into three levels: 1) The most ideal "positive energy", that is, through the deployment of scientific well network density and the development of a reasonable gas well production system, uniform water propulsion is maintained, and slow replenishment of formation energy is empowered for the gas reservoir, which extends the gas reservoir without water and gas production period and continuous high yield. 2) "Zero energy", that is, through effective water plugging or drainage measures, the core area is ensured or in no water or water influx as late as possible, to maximize the elastic energy of the gas reservoir itself; 3) Worst "negative energy", that is, premature water breakthrough is caused in gas wells due to the unreasonable deployment or development strategy. On the one hand, the water seal gas is formed in the reservoir pores, hindering the energy play of the gas itself. On the other hand, gas and water flow occurs in the reservoir and the wellbore, consuming the gas elastic energy in the reservoir. The process of efficient development of gas reservoir with water is to pursue the "positive energy" of formation water, to achieve the "zero energy" and avoid the "negative energy" of formation water. The key is to accurately understand the contact relationship between gas well, natural crack or high seepage channel and the bottom water, and formulate a scientific and reasonable well network and production system on this basis. If the uneven water invasion of the formation water causes premature water observation in the gas well, the gas production period of the gas reservoir will be greatly shortened, which will cause irreversible damage to the gas reservoir and affect the final recovery rate and development effect of the gas reservoir.

3.2. Methods for Improving Gas Recovery in Conventional Gas Reservoirs

Methods for improving gas recovery in conventional gas reservoirs contain: 1) Well network encryption, well type optimization, old well side drilling and three-dimensional well network, which increase the utilization level by well pattern optimization. 2) Reservoir transformation, well layout optimization and production system optimization, which improve sweep coefficient by balanced development. 3) Gas drainage, ground pressurization or other technical measures, which improve stress exhaustion efficiency by pressure boost *et al.*

It can be seen from the evaluation model of oil recovery of gas reservoir that the technical method of improving oil recovery of gas reservoir should carry out the research and practice from 3 aspects, including improving the utilization degree of reserves, improving the ripple coefficient of pressure drop and improving the efficiency of pressure depletion.

The technical methods to improve the utilization degree of reserves include well network encryption, well type optimization, old well side drilling and three-dimensional well network. Well network encryption is the most direct technical method to improve the reserve utilization degree, which refers to the addition of adjustment wells on the basis of the original well network to reduce the impact of gas reservoir plane heterogeneity on the development of gas reservoirs, and effectively drive the remaining unused reserves between wells. Old well side drilling, well type optimization and stereo well network are effective ways to increase the longitudinal unused reserves. Through the side drilling open longitudinal unused layer or well type optimization adjustment for directional well, large slope and horizontal well increase contact area, and multiple set well network development vertical different layers increase the unused reserves effective utilization.

The technical methods of increasing pressure drop ripple coefficient include technical measures such as reservoir transformation, well layout optimization and production system optimization. Reservoir transformation is to improve the physical property of the reservoir by artificial means to increase the discharge area. Optimization of distribution well and production system is mainly aimed at the adverse effects of water intrusion on the development effect during the development of water displacement gas reservoir, and realizes the balanced development by optimizing well deployment, which realizes uniform pressure decrease by optimizing production system, and increases dynamic reserves to improve the ripple coefficient of pressure drop.

Technical methods to improve the efficiency of pressure depletion include gas drainage, ground pressurization or other technical measures to reduce waste production. The production time of gas wells are increased by increasing the lifting effect of gas wells. Reducing the waste pressure can further improve the efficiency of formation energy and pressure depletion by the gas drainage. Labor cost is reduced by improving digitalization and intelligence, and the final production gas volume is increased as much as possible in the gas reservoirs.

Technical countermeasures are suggested for the balanced development of different types of gas reservoirs. Influenced by the differences in the development mechanism of the whole process of gas reservoir, the influencing factors of the balanced development of different types of gas reservoirs are quite different, and the development ideas and core technologies and methods have different priorities. For the strongly heterogeneous gas displacement reservoir with the bottom water, the core is to improve the impact coefficient and pressure depletion efficiency to realize the balanced utilization of reserves. For the water displacement reservoir, the core is to improve the impact coefficient and maximize the macroscopic water flooding efficiency and realize the balanced pressure drop of gas reservoir (Table 1).

4. Balanced Development Examples of Conventional Gas Reservoirs

4.1. Longwangmiao Formation Gas Reservoir in Anyue Carbonates Gas Field

The Longwangmiao Formation gas reservoir in Anyue gas field is a typical example of water flooding development of side-bottom water gas reservoir [17] [18] [19] [20]. It is the largest super-large Marine monomer carbonate gas reservoir discovered in China. The geological conditions of gas reservoir in Longwangmiao Formation are complex, and the gas reservoir structure amplitude is low, the gas water transition zone reaches 37%. The reservoir porosity is low with only 4.3% of the average porosity and is easy water lock. The reservoir has strong inhomogeneity, and permeability difference is up to 450 times, which is prone to uneven water invasion. And the elastic expansion energy of overpressure water body is strong, the estimated water volume is over 25×10^8 m^3. In 2022, the water intrusion substitution coefficient is from 0.15 to 0.4, which is the subactive water flooding gas reservoir.

Table 1. Technical direction, means and mechanism of EOR improvement in gas reservoir.

Technical direction	Technical methods	Mechanisms
Improve pressure depletion efficiency	Boosting wellhead pressure	Reduce wellhead pressure
	Water withdrawal	Reduce formation seepage and wellbore pipe flow resistance
	Pumping or plunger	Reduce pipe flow resistance
Increase the pressure drop ripple coefficient	Well types optimization	Improve the degree of utilization of unused reserves between wells
	Sidetracking	
	Well network encryption	
Optimize the water invasion coefficient	Horizontal well development	Change the form of water invasion and increase the impact coefficient of water invasion
	Arrange wells in high areas	Increase the height of water avoidance and increase the coefficient of water invasion
	Remove blockage and water blocking	Change or expand the water invasion path and increase the water invasion coefficient during abandonment
	Optimize production allocation	Control water cone to increase water invasion coefficient
Improve macro water drive gas efficiency	Injecting carbon dioxide and other gases (New technologies)	Enhance energy and replace natural gas
	Unseal and release water seal gas	Produce water seal gas

According to the characteristics of gas reservoir, using the balanced development concept with highlighting the whole gas reservoir and balanced pressure drop of different well areas, relying on water channel characterization, production system optimization, water dynamic early warning, the whole life cycle of progressive type water control development mode is integrated and formed, that is "early prevention and control of water intrusion, mid-term prevention and control of watered out, and late prevention and control of water sealing". 1) In the early stage of development, the gas reservoir in this stage was characterized by overpressure. Through well network optimization and mining speed optimization, "side control and internal release" was achieved to prevent the bottom water from invading the gas reservoir prematurely, so as to improve the impact coefficient of pressure drop and pressure depletion efficiency in the pure gas area, and realize the balanced pressure drop within the range of gas reservoir. 2) In the mid-term stage of development, the stage of gas well can fully carry liquid, which is mainly through the production system optimization and production well function transformation. On the one hand, it's necessary to control the rapid invasion of formation water into the wellbore at the front edge of the water invasion channel. On the other hand, the rational use of gas reservoir energy is need to keep a part of the gas wells with liquid normal production and prevent gas well shutdown due to watered out, so as to further improve the efficiency of pressure depletion and macro water gas efficiency, and realize the pressure drop in different well area. 3) In the late stage of development, a large amount of formation water invades into the gas reservoir, it's necessary to focus on optimization of water withdrawal technology in gas production, which is water withdrawal in low position drainage well and optimized gas production in high position, to prevent the formation of water seal gas, so as to improve the water invasion impact coefficient, and continuously improve the efficiency of macro water displacement, and further realize the balanced pressure drop of gas reservoir pressure.

Under the guidance of the concept of improving oil recovery in the whole life cycle and the development countermeasures, the impact coefficient of pressure drop and the efficiency of pressure depletion are continuously improved, the gas reservoir of Longwangmiao Formation has realized the technology upgrade from emergency and localized water control to full lifecycle water control and management, and realizes the pressure balanced pressure drop in different development stages. According to the comprehensive evaluation, the original formation pressure of the gas reservoir in Longwangmiao Formation is 76 MPa, and the deviation factor is 1.36. The average abandoned formation pressure in the main development unit is 15 MPa, the corresponding deviation factor is 1.42, the impact coefficient of the whole gas reservoir is 83%, and the pressure depletion efficiency is 71%. According to the numerical simulation results of gas reservoir in Longwangmiao Formation, the water intrusion impact coefficient is 60%, and the macro water flooding efficiency is 81% considering the residual gas saturation. According to the recovery model, the calculated recovery rate of gas reservoir in Longwangmiao Formation will reach 64%.

4.2. Sulige Tight Sandstone Gas Field

The Sulige gas field is a typical representative of the highly heterogeneous gas reservoir by depletion development [21] [22] [23] [24] [25]. More than 17,000 gas wells have been put into production, and the annual gas production is 30.2 billion m^3, which is the largest reserves and output scale natural gas field in China. The gas field has deposited widely distributed river phase sand body on the background of gentle basin slope. The effective sand body is mainly medium coarse quartz sand rock deposited in core beach. The gas-bearing sand body is lens-like dispersion, with thickness between 2 - 5 m, width between 100 - 500 m and length between 300 - 700 m, and more than 70% gas-bearing sand body is not connected. Overall, there were many relatively independent gas reservoir units (single sand body) constitute the complex geological features of the gas field.

According to the development characteristics of gas reservoir, starting from the gas reservoir recovery model and according to the balanced development concept, the development unit division, well network optimization and ground pressurization are mainly used to improve the impact coefficient of pressure drop and pressure depletion efficiency. Because of the development of gas reservoir is a gradual process, and the understanding of sand body size, scale, physical distribution characteristics is also a deepening process, in essence, the gas reservoir development is a dynamic balance process between gas reservoir recovery and economic benefits. The main development way mainly depends on continuous encryption well network density to improve the pressure drop ripple coefficient and pressure depletion efficiency. The adjustment of well network density roughly goes through three stages: 1) The early stage of development. Due to the great difficulty in predicting the sand body distribution, the gas field adopts vertical well network with 600 m × 800 m, which is affected by the insufficient control range of the single well and the sand body control degree, and the pressure drop impact coefficient at this stage is only about 35%. At the same time, the surface of Sulige gas field adopts medium and low pressure gas collection, and the common use of ground pressurization. The pressure depletion efficiency in the actual dynamic control range can reach 85%, so the recovery rate at this stage is about 30%. 2) At present, with the implementation of several dense well network pilots and the gradual deepening of geological understanding, the well spacing is gradually adjusted to 500 m × 650 m, and the pressure drop ripple coefficient in the average area of a single well is increased to 51%, and gas recovery rate was correspondingly increased from 30% to 43%. 3) In the future, with the progress of development technology, development cost, sales gas cost and other economic benefit indicators, the development well network is expected to be further optimized and encrypted to 4 wells/km^2, and the impact coefficient of pressure drop in the average area of the whole gas reservoir well will exceed 63%, and the implementation of drainage gas production and surface pressurization in the middle and later stage of development will further reduce the pressure of waste formation, improve the efficiency of pressure drop depletion, and the recovery rate of the gas field will exceed 50%.

4.3. Kela-2 Block Side-Bottom Water Sandstone Gas Reservoir

Kela-2 gas reservoir is a typical side-bottom water sandstone gas reservoir [26] [27], and the height of the gas reservoir is 500 m. The water intrusion of the gas reservoir is mainly vertical along the large fault. The key to improve the recovery is to reduce the waste pressure, improve the efficiency of macroscopic water flooding and the pressure depletion in the flooded area. The main technical measures include: 1) In the development design stage, to move away from the side water to the structure, and the production wells occupy the high structure position to minimize the risk of gas wells. 2) During the production construction process, to adjust the production system, optimize the production of distribution, control the uneven propulsion speed of the advance edge water intrusion, improve the efficiency of pressure depletion. 3) In the mid-late stage development plan adjustment stage, the technical measures are conducted combining horizontal wells with water invasion advantage channels for drainage and blockage at the top of the gas reservoir, and to implement drainage and blockage of water flooded sections on the water invasion path to reduce the water flooding energy and further improve the efficiency of pressure depletion. On the one hand, to ensure the production capacity of the gas field and extend the stable production period. On the other hand, to optimize the water intrusion form to further improve the pressure depletion efficiency of the gas reservoir, extend the production life of the gas well, and increase the final cumulative gas production of the gas field. In the initial stage of gas field development, the linear well moves along the structure to realize the reserve balance, and the impact coefficient of pressure drop is close to 100%. From 2011 to 2020, the relative abandonment pressure is 0.39, and the pressure depletion efficiency increased to 0.45 by optimization of production system, control of non-uniform advancing speed of water invasion leading edge, and full utilization of formation energy with breaking through the lower limit of abandoned pressure in active water drive gas reservoirs. In 2021, the development adjustment plan adopts a combination of top deployment of horizontal wells and water invasion path for water blockage and drainage, and the pressure depletion efficiency is further increased from 0.45 to 0.48, and the predicted cumulative gas production can increase by 8.05 billion m^3 with increased gas recovery by 3.4%.

4.4. Sebei Multi-Layer Side-Bottom Water Sandstone Gas Reservoir

Sebei gas field in Qaidam Basin is a multi-layer edge bottom water gas reservoir, with multiple sets of layers and multiple gas and water systems [28] [29]. The development of multiple sets of well networks to improve gas recovery is mainly based on layered management and balanced exploitation, and improves the ripple coefficient of pressure drop and pressure depletion efficiency. The technical practice of improving EGR mainly includes: 1) To evaluate the contribution of different layers through gas profile test, determine the water yield of different levels and accurately "identified water"; 2) To adopt the strategy of combining water control of different layers, and deploy the water control well and side drainage well on the water invasion channel to realize "water control" and "water governance" of gas reservoirs; 3) Balanced exploitation is crucial to improve the recovery of such gas reservoirs, including regional balance, plane balance and longitudinal balance. Regional equilibrium mainly improves the gas production speed in weak water invasion blocks, reduces the gas production speed in strong water invasion blocks, and realizes the balanced exploitation between different blocks in the region by analyzing the production dynamics of different blocks and dividing the annual and monthly output of different blocks. Plane balanced exploitation is to implement the active water control strategy in the medium and strong water intrusion area, control water and tap the potential in the weak water intrusion reservoir area. Within a single gas reservoir, it's to increase the production output, form the pressure low value area in the high area, thus forming the high pressure water resistance barrier in the side, and realize the plane balanced exploitation by methods such as well opening and closing, reasonable production allocation, and operational measures. For longitudinal balanced production, the principle of differentiated mining of different layers is adopted. The water plugging and the aquifer are avoided during perforation. By reducing the gas production of high water penetration and extraction degree, the gas production of the water intrusion and low level group is increased, and the output of each layer group is optimized and adjusted to realize the longitudinal balanced production between layers.

5. Understanding and Suggestions

The recovery of gas reservoir is affected by the combination of natural gas development technology, development cost and economic environment. From the recovery evaluation model and equilibrium development theory, improving the degree of reserve utilization, pressure drop impact coefficient and pressure depletion efficiency are the three aspects of improving the recovery. Conventional water displacement gas reservoir further improves the pressure drop ripple coefficient and pressure depletion efficiency by reducing the area of water invasion area and reducing the macro water sealing gas and micro water lock gas of water invasion. Some technical measures are used for tight gas such as deploying encrypted well networks to improve reserve utilization, multi-stage and multi-stage fracturing to increase pressure drop sweep coefficient, and boosting production to improve pressure depletion efficiency.

It's necessary to strengthen the research on the mechanism of natural gas recovery, and explore new methods and materials to improve oil recovery, accelerate the research and development and field test of gas reservoir recovery technology, and form a theoretical technical system of natural gas recovery adapted to the geological characteristics of gas reservoirs in China. And we need to study the water invasion mechanism for conventional water displacement reservoir, explore the method of actively regulating crack water flow to improve the ripple coefficient of pressure drop in water displacement reservoir, and solve the physical and chemical methods and materials. Meanwhile, it's also to study the mechanism of increasing seam height, seam length, crack turn and so on, and clarify the mechanism and technical approach of improving the ripple coefficient and pressure depletion efficiency. At the same time, the research on forward-looking technical methods of gas reservoir enhanced recovery, such as gas injection energy replacement and chemical agent injection to increase permeability and reduce resistance, would be carried out.

6. Conclusions

1) Oil reservoir development is the process of continuously oil saturation decreasing, but gas reservoir development is the process of continuously gas pressure depletion, this is the main difference in enhancing recovery between gas and oil reservoirs.

2) The gas reservoir recovery is the product of geological reserve utilization degree, pressure drop ripple coefficient and pressure depletion efficiency, which are interrelated and influential.

3) Main affecting factors of gas reservoir recovery contain the geological factors, engineering factors and the economic factors, which decided the size of improving oil recovery.

4) Gas oil recovery improvement should run through the whole life cycle of gas reservoir development, and recovery damage early should be avoided or reduced in development which is more important than improving recovery later in development, this is the core concept of improved gas reservoir recovery.

5) Main development problems are the unbalanced utilization and inhomogeneous water intrusion in the conventional gas reservoirs, which can be solved by 3 aspects, including improving the utilization degree of reserves, improving the ripple coefficient of pressure drop and improving the efficiency of pressure depletion.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Ma, X. (2009) Natural Gas in CNPC Is Coming in a Stage of Leapfrogging Devel-

opment. *Lecture Collection of the First Global Think Tank Summit*, Beijing, China Center for International Economic Exchanges, 3-4 July 2009, 172-173.

[2] Jia, A.L., He, D.B., Wei, Y.S., *et al.* (2021) Predictions on Natural Gas Development Trend in China for the Next Fifteen Years. *Journal of Natural Gas Geoscience*, **37**, 709-715. https://doi.org/10.1016/j.jnggs.2021.04.005

[3] Li, J.Z., Zhen, M., Guo, Q.L., *et al.* (2019) Fourth Assessment for Oil and Gas Resource. Petroleum Industry Press, Beijing.

[4] Ma, X.H., Chen, J.J. and Tang, J.W. (2003) The Natural Gas Development Characteristics and Strategy in China. *Journal of Natural Gas Geoscience*, **14**, 15-20.

[5] Oil and Gas Department of National Energy Administration, Resource and Environmental Policy Research Institute of the Development Research Center of the State Council, Oil and Gas Resources Strategic Research Center of the Ministry of Natural Resources (2022) Natural Gas Development Report of China. Petroleum Industry Press, Beijing.

[6] Zou, C.N., He, D.B., Jia, C.Y., *et al.* (2021) Connotation and Pathway of World Energy Transition and Its Significance for Carbon Neutral. *Acta Petrolei Sinica*, **42**, 233-247.

[7] Li, S.L., Wang, Y., Liu, T.Y., *et al.* (2008) Good Experiences Learned from Home and Abroad to Develop Large Gas Fields in China. *Natural Gas Industry*, **28**, 7-11.

[8] Sun, Y.P., Lu, J.L., Wan, Y.J., *et al.* (2016) Enlightenments of Lacq and Meillon Gas Fields in France to the Development of Longwangmiao Fm Gas Reservoirs in the Anyue Gas Field, Sichuan Basin. *Natural Gas Industry*, **36**, 37-45.

[9] Jia, A.L. and Yan, H.J. (2014) Problems and Countermeasures for Various Types of Typical Carbonate Gas Reservoirs Development. *Acta Petrolei Sinica*, **35**, 519-527.

[10] Jia, A.L., Yan, H.J., Guo, J.L., *et al.* (2014) Characteristics and Experiences of the Development of Various Giant Gas Fields All over the World. *Natural Gas Industry*, **34**, 33-46.

[11] He, D.B., Yan, H.J., Yang, C.C., *et al.* (2022) Gas Reservoir Characteristics and Technical Countermeasures for Development in the Fourth Member of Dengying Formation in Anyue Gas Field. *Acta Petrolei Sinica*, **43**, 977-988.

[12] Tang, Z.Y. and Kong, J.X. (1984) Structural Characteristics of Sinian Reservoirs in Weiyuan Gas Field, Sichuan. *Acta Petrolei Sinica*, **5**, 43-54.

[13] Wen, H.C. (1986) Gas-Water Relation in Weiyuan Gas Field. *Natural Gas Industry*, **6**, 14-19.

[14] Liu, E. (1985) Characteristics of Production Performance and an Idea of the Intensive Water Withdrawal in Gas Wells of Sinian Gas Pool, Weiyuan Gas Field. *Natural Gas Industry*, **5**, 41-46.

[15] Li, C.L. (2005) Fundamentals of Reservoir Engineering. Petroleum Industry Press, Beijing.

[16] Jia, A.L. and Cheng, L.H. (2010) The Technique of Digital Detailed Reservoir Characterization. *Petroleum Exploration and Development*, **37**, 709-715. https://doi.org/10.1016/S1876-3804(11)60005-0

[17] Li, X.Z., Guo, Z.H., Wan, Y.J., *et al.* (2017) Geological Characteristics and Development Strategies for Cambrian Longwangmiao Formation Gas Reservoir in Anyue Gas Field, Sichuan Basin, SW China. *Petroleum Exploration and Development*, **44**, 428-436. https://doi.org/10.1016/S1876-3804(17)30049-6

[18] Jia, A.L., Yan, H.J., Guo, J.L., *et al.* (2013) Development Characteristics for Different Types of Carbonate Gas Reservoirs. *Acta Petrolei Sinica*, **34**, 914-923.

[19] Ma, X.H., Yang, Y., Wen, L., *et al.* (2019) Distribution and Exploration Direction of Medium-and Large-Sized Marine Carbonate Gas Fields in Sichuan Basin, SW China. *Petroleum Exploration and Development*, **46**, 1-15. https://doi.org/10.1016/S1876-3804(19)30001-1

[20] Xie, J. (2020) Innovation and Practice of the Key Technologies for the Efficient Development of the Supergiant Anyue Gas Field. *Natural Gas Industry*, **40**, 1-10.

[21] He, D.B., Wang, L.J., Ji, G., *et al.* (2012) Well Spacing Optimization for Sulige Tight Sand Gas Field, NW China. *Petroleum Exploration and Development*, **39**, 491-497. https://doi.org/10.1016/S1876-3804(12)60066-4

[22] He, D.B., Jia, A.L., Ji, G., *et al.* (2013) Well Type and Pattern Optimization Technology for Large Scale Tight Sand Gas, Sulige Gas Field. *Petroleum Exploration and Development*, **40**, 84-95. https://doi.org/10.1016/S1876-3804(13)60008-7

[23] Lei, Q., Guan, B.S., Cai, B., *et al.* (2019) Technological Progress and Prospects of Reservoir Stimulation. *Petroleum Exploration and Development*, **46**, 605-613. https://doi.org/10.1016/S1876-3804(19)60040-6

[24] Wang, J.P., Zhang, C.W., Li, J.Y., *et al.* (2021) Tight Sandstone Gas Reservoirs in the Sulige Gas Field: Development Understandings and Stable-Production Proposals. *Natural Gas Industry*, **41**, 100-110

[25] Li, T., Li, Q., Hu, Y., *et al.* (2021) Quantitative Characterization of Irregular Micro-Fracture Network and Its Effect on the Permeability of Porous Media. *Petroleum Exploration and Development*, **48**, 430-441. https://doi.org/10.1016/S1876-3804(21)60034-4

[26] Shen, P.P., Yuan, S.Y., Han, D., *et al.* (2001) Strategy Study and Potentiality Evaluation of EOR for Onshore Oil Fields in China. *Acta Petrolei Sinica*, **22**, 45-48.

[27] Yuan, S.Y., Wang, Q., Li, J.S., *et al.* (2021) EOR Technological Innovation Keeps China's Crude Oil Production Stable on Longterm Basis. *Petroleum Science and Technology Forum*, **40**, 24-32.

[28] Yuan, S.Y., Hu, Y.L. and Luo, K. (2005) State of the Art, Challengesand Countermeasures of Natural Gas Development in China. *Petroleum Exploration and Development*, **32**, 1-6.

[29] Sun, L.D., Zou, C.N., Jia, A.L., *et al.* (2019) Development Characteristics and Orientation of Tight Oil and Gas in China. *Petroleum Exploration and Development*, **46**, 1073-1087. https://doi.org/10.1016/S1876-3804(19)60264-8