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Research on the Interlayer Interference Law of Multi-layer Combined Mining in Low-permeability Gas Reservoirs

Zhaoyuan Li

Xi`an Shiyou University, Xi'an 710000, China

Abstract

This paper focuses on the interlayer interference problem in multi-layer combined production of low-permeability gas reservoirs and studies the productivity laws of different lithologic combinations through physical simulation experiments. Three sets of single-layer and two sets of double-layer combined mining experiments were carried out on the sandstone cores of Qian 5 and He 4 and the 8+9# coal seam, and the gas production dynamics were systematically monitored. The results show that in the combined production system, the high-permeability layer significantly suppresses the medium and low-permeability layers, presenting the characteristics of "off-peak gas production" and production lag. The low-permeability layer was most disturbed. The gas production rates of the fourth layer of the double-layer combined mining middle box and the coal seam decreased by 14.02% and 32.27% respectively. The overall production capacity of the system has suffered a coordinated loss. The cumulative gas production of double-layer combined mining has decreased by 7.59% to 22.56% compared with the theoretical value of single mining. Mechanism analysis indicates that the high permeability layer dominates the bottom hole flow pressure system, resulting in insufficient effective production pressure difference in the medium and low permeability layers. The research results provide an important theoretical basis for the optimization of combined production in low-permeability gas reservoirs.

Keywords

Low Permeability Gas Reservoir; Coal Bed Gas; Commingling Production; Interlayer Interference.

1. Introduction

Natural gas, as a low-carbon and environmentally friendly high-quality energy source, plays a crucial role in the transformation of China's energy structure and the construction of ecological civilization [1]. With the continuous growth of the demand for clean energy in the economy and society, the consumption scale of natural gas has been expanding continuously, and its proportion in primary energy consumption has significantly increased. This not only effectively alleviates the environmental pressure caused by the excessive consumption of traditional coal resources, but also provides a key path for the control of air pollution and the realization of the carbon neutrality goal [2,3]. However, China's natural gas supply and demand pattern still faces severe challenges. Since 2018, its dependence on foreign sources has exceeded 40%, and energy security risks have become increasingly prominent [4]. Against this backdrop, intensifying the exploration and development of domestic unconventional natural gas resources has become a strategic choice to ensure national energy security [5]. Among them, low-permeability sandstone gas and coalbed methane, as important unconventional natural gas resources, have the characteristics of wide distribution and large reserves. However, their reservoirs generally have the typical features of low porosity and low permeability, making their exploitation rather difficult [6,7]. As a key means to enhance the development efficiency of low-permeability gas reservoirs, multi-layer combined mining technology can significantly

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reduce development costs by simultaneously exploiting multiple production layers in a single well [8]. However, its application effect is deeply restricted by the inter-layer interference phenomenon, that is, the mutual inhibition and dynamic response of production caused by the physical property differences among layers during the combined mining process [9]. Therefore, in-depth exploration of the formation mechanism and dynamic laws of interlayer disturbances during multi-layer co-production is of urgent theoretical and practical significance for achieving efficient development of such typical low-permeability gas reservoirs [10].

This study takes the low-permeability gas reservoirs in the Linxing Central area of the Ordos Basin as the research object, focusing on the combined mining interference problems of multiple production layers such as the Shiqianfeng Formation, Shihezi Formation and coal seams. By conducting systematic indoor physical simulation experiments, a combined production experimental scheme covering different permeability gradations, lithological combinations and stratigraphic configurations was constructed to reproduce the dynamic changes in production during the actual gas reservoir pressure attenuation process. The research aims to clarify the yield decline characteristics of different strata under single and combined mining conditions, reveal the initiation mechanism, manifestation mode and variation law of interlayer interference in the double-layer combined mining process, and further clarify the control effect of permeability difference, reservoir combination mode and production pressure difference on interference intensity [11]. The research results can not only provide a scientific basis for the optimal combination and working system design of the combined production layer in the central area of Linxing gas reservoir, but also establish theoretical support and practical models for the efficient development of similar low-permeability unconventional gas reservoirs in China. This is of great value for promoting the large-scale development and utilization of unconventional natural gas resources in China and enhancing the domestic energy self-supply capacity.

2. Experimental Section

2.1. Experimental Principle

To explore the interlayer interference laws during the multi-layer combined production process of low-permeability gas reservoirs, this study established a multi-layer combined production experimental system based on physical simulation methods. The experiment selected representative core samples from the Shiqianfeng Formation (Qian 5), Shihezi Formation (He 4), and coal seam (8+9#) of the Linxing Middle Block gas field of China United Coalbed Methane Co., LTD. Jinxi Branch, and filled them in combination according to their actual permeability grade differences to simulate the heterogeneous characteristics of the reservoir. The ISCO pump is used to maintain a constant initial formation pressure, and pressure reduction production is carried out at the set temperature. The actual production pressure drop process is simulated by stepwise adjustment of the back pressure. During the experiment, a computer data acquisition system was used to monitor and record the dynamic changes of gas flow and pressure at the outlet end of each layer in real time. By comparing and analyzing the instantaneous gas production, cumulative gas production and pressure drop characteristics of each layer under single sampling and combined sampling conditions, the degree of interference between gas layers, changes in gas production contribution and dynamic balance laws under different permeability combinations were revealed. So as to clarify the main controlling factors of inter-layer interference and the mechanism of changes in combined mining capacity.

2.2. Experimental Facility

This experiment adopts the multi-layer combined recovery physical flow simulation experimental system manufactured by Nantong Huaxing Petroleum Instrument Co., LTD. The

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ISCO pump model is 260D metering pump produced by Teledyne Isco Company of the United States, with a pressure range of 0-51.7MPa, and the continuous flow velocity range of the displacement pump is 0.001-80mL/min. The mass flowmeter is of the D07 series produced by Beijing Qixing Huachuang Electronics Co., LTD., with a maximum pressure resistance of 20MPa. The flow totalizer is provided by Beijing Qixing Huachuang Flowmeter Co., LTD. The model of the equipment is D08-8CM. The pressure recording instrument is a paperless recorder produced by Ningbo Keshun Instrument & Meter Co., LTD., with the model number KSB20A0R. The process of the experimental setup is shown in Figure 1.

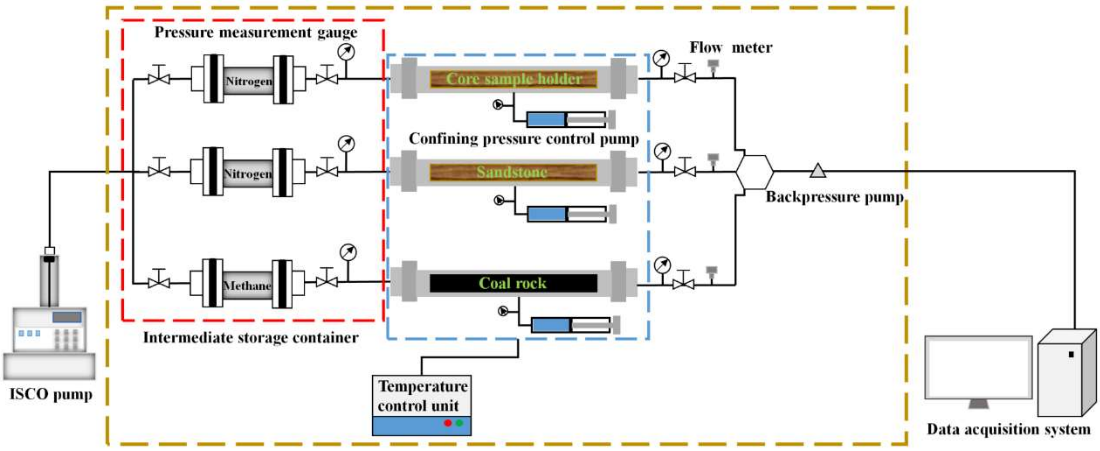

Figure 1. Flowchart of the gas reservoir combined production experimental setup

2.3. Experimental Material

All the core samples used in this experiment are cylindrical, with a uniform specification of 2.5 cm in diameter and 6 cm in length. The sample composition includes 15 pieces of sandstone from the Shiqianfeng Formation (Qian 5), 10 pieces of sandstone from the Shihezi Formation (He 4), and 15 pieces of coal-rock from the 8+9# coal seam. The core permeability ranged from 0.0101 mD to 0.7911 mD, with an average value of 0.3302 mD. The porosity varies from 1.20% to 11.29%, with an average of 6.54%, demonstrating strong reservoir heterogeneity. The purity of the gases (nitrogen and methane) used in the experiment was both 99.99%.

2.4. Experimental Procedure

(1) Build a simulation system for the multi-layer combined production of natural gas, confirm that the experimental equipment has good sealing performance, and check the airtightness of all high-pressure pipelines, joints and valves connected to the experimental equipment.

(2) Drill 20 core plunger samples with a diameter of 2.5cm and a length of 6cm in a concentrated manner on the full-diameter core, and measure the gas permeability of all the core plunger samples.

(3) 20 core plunger samples were successively and orderly loaded into the long core holder to fabricate the Shiqianfeng group, Shihezi group and coal seam simulated gas layer respectively. The total length of the filled cores was between 100cm and 110cm. After filling, confining pressure was applied to the set pressure to test the permeability of the long cores (i.e., reservoir permeability).

(4) Close the outlet of the core holder, and introduce the saturated gas (N2/CH4) into the core from the inlet of the holder. Control the internal pressure of the intermediate container through the ISCO pump. Stop the saturation when both ends of the core holder reach 15MPa and stabilize for more than 8 hours.

(5) Set the experimental temperature at 45℃, open the outlet valves of each simulated gas layer, and simultaneously open the valves of the combined sampling manifold to simulate combined

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sampling production. Record the gas flow and pressure data at the outlet in real time through the computer data acquisition control system.

(6) Continuously simulate the production of the gas reservoir. The initial pressure is 15MPa, and it gradually decreases in steps at intervals of 3MPa according to the changes in production time. The minimum back pressure is set at 3MPa (simulating the back pressure in the actual production process). The experiment is concluded and the system is shut down until the outlet pressure drops to the deprecation pressure (the outlet pressure is approximately 10% of the initial flow pressure). Take out multiple core samples from the simulated gas layer, check the integrity of the cores, and continue to use them in the next set of experiments.

(7) According to the experimental plan, multi-layer combined sampling experiments were conducted, totaling 6 groups, including 4 groups of single-layer production simulation experiments and 2 groups of double-layer combined sampling simulation experiments. First, conduct single-layer production simulation experiments as the standard group, and then carry out multi-layer combined sampling experiments and compare them with the standards.

2.5. Experimental Design

Four groups of single-layer single-sampling experiments and two groups of double-layer combined sampling experiments were designed based on the differences in permeability. The specific experimental designs are shown in Table 1. When conducting combined mining experiments with different permeability levels, it is ensured that the reservoir pressure and water saturation of each layer remain unchanged, and only the core permeability of each layer is altered. The instantaneous gas production and cumulative gas production of each group of experiments are recorded to explore the combined mining patterns between low-permeability sandstone gas layers and between low-permeability sandstone gas layers and low-permeability coal-rock gas layers.

Table 1. Design of Multi-layer Combined Sampling Experimental Scheme

Experimental Group	Type	Combination principle	Stratigraphic Layer	system pressure /MPa (formation pressure)	Permeability /mD (Reservoir permeability)	Lithology
1	Single-layer experiment	Single-layer control group	Shiqianfeng Formation(P3s5)	15	0.6470	Sandstone
2	Single-layer experiment	Single-layer control group	Shihezi Formation(He4)	15	0.2120	Sandstone
3	Single-layer experiment	Single-layer control group	coal seam(8+9#)	15	0.1061	Coal rock
4	Dual-Layer Combined Extraction	Dual-Layer Combined Recovery Mechanism for Tight Gas and Coalbed Methane	Shihezi Formation (He4)	15	0.2120	Sandstone
			coal seam(8+9#)	15	0.1061	Coal rock
5	Dual-Layer Combined Extraction	Dual-Layer Combined Recovery Mechanism for Tight Gas	Shihezi Formation(He4)	15	0.2120	Sandstone
			Shiqianfeng Formation(P3s5)	15	0.6470	Sandstone

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3. Experimental Results and Discussion

3.1. Single-Layer Single-Sampling Experiment

3.1.1. Experiment on the Variation Law of Output

According to the experimental design shown in Table 2, in this section, single-layer single-sampling experiments were carried out respectively for the three layers of No. 5, Box 4, and 8+9#. Each group of experiments was conducted under the conditions of consistent reservoir pressure and water saturation, with the main difference lying in the different reservoir permeability. By using the multi-layer combined mining physical flow simulation experiment system, the instantaneous gas production and cumulative gas production data of each layer were monitored and recorded respectively, and the dynamic variation law of the production of single-layer single mining under different permeability conditions was systematically analyzed.

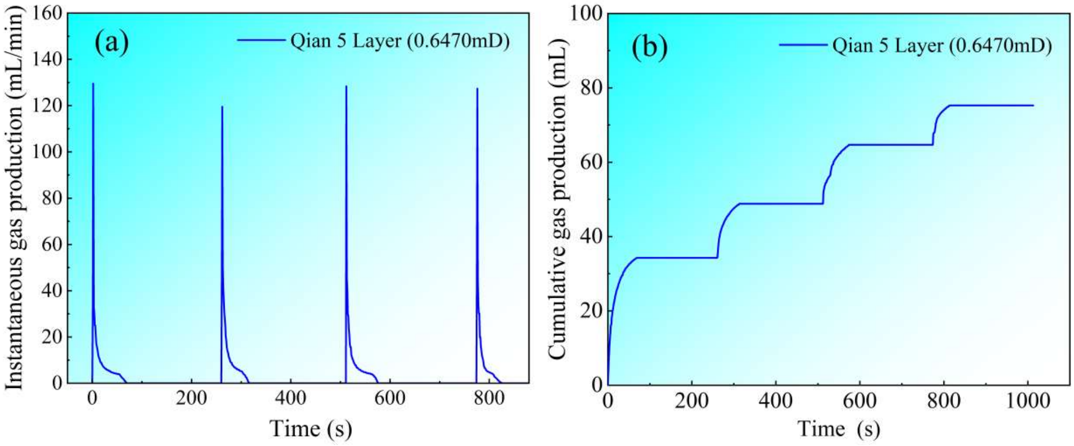

Figure 2. shows the variation in the single harvest yield of Qian 5 layers

Figure 2 presents the dynamic variation characteristics of the instantaneous gas production rate and the cumulative gas production during the four-stage pressure reduction gas production process in the single gas production of the thousand-fifth layer. The initial pressure of the reservoir was set at 15 MPa in the experiment, and the back pressure decreased step by step with a gradient of 3 MPa until the abandoned pressure of 3 MPa was reached. As can be seen from Figure 2 (a), each time the back pressure drops, an instantaneous gas production peak is triggered, which occurs respectively at the 3rd second, 260 seconds, 510 seconds and 780 seconds after the start of the experiment. The corresponding peak gas production rates were 129.51 mL/min, 119.51 mL/min, 128.32 mL/min and 127.34 mL/min respectively, and the average peak was 126.17 mL/min. During the non-peak stage, the gas production rate rapidly decays and remains at a relatively low level. The sections in the figure where the gas production rate is zero or the cumulative gas production remains unchanged correspond to the well shutdown stage, which is mainly used for system pressure regulation to prepare for the next gas production stage. Figure 2 (b) shows that the cumulative gas production increases in a typical stepwise manner with the alternating process of well opening and well closing. When the gas extraction time reaches 825 seconds, the system pressure drops to the waste pressure, the gas production process ends, and the final cumulative gas production is 75.27 mL. From the perspective of the overall extraction process, at the beginning of each round of pressure reduction, there is a rapid increase in cumulative gas production, and then it enters a relatively stable stage, forming an alternating evolution pattern of "growth - stability". As the mining process progresses, the gas production increments at each stage decrease successively, reflecting the continuous attenuation characteristics of formation energy.

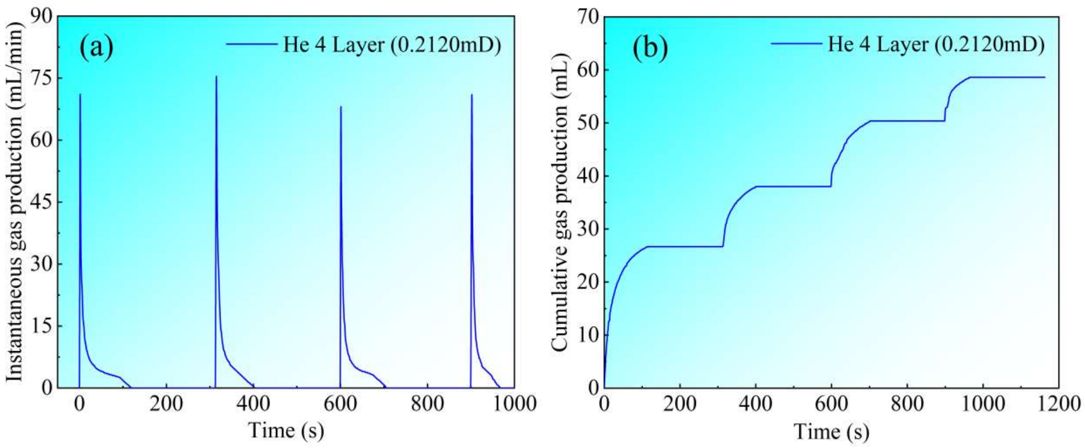

Figure 3. shows the variation in the single harvest yield of He 4 layers

Figure 3 presents the dynamic variation characteristics of the instantaneous gas production rate and cumulative gas production during the four-stage pressure reduction gas production process in the single sampling of box 4 layer. The experimental process is basically the same as that of the thousand-5 layer experiment. As can be seen from Figure 3 (a), at 2 seconds, 315 seconds, 600 seconds and 900 seconds after the start of the experiment, the corresponding peak gas production rates were 70.52 mL/min, 75.43 mL/min, 67.51 mL/min and 71.47 mL/min respectively, and the average peak was 71.23mL/min. Compared with Layer 5, the peak instantaneous gas production of Layer 4 has further decreased, reflecting the relatively weak gas production capacity of this reservoir. During the non-peak stage, the gas production rate rapidly decays and remains at a relatively low level. Figure 3 (b) shows that the cumulative gas production increases in a typical stepwise manner with the alternating process of well opening and well closing. When the gas extraction time reached 966 seconds, the system pressure dropped to the waste pressure, and the gas production process ended. The final cumulative gas production was 58.61mL.

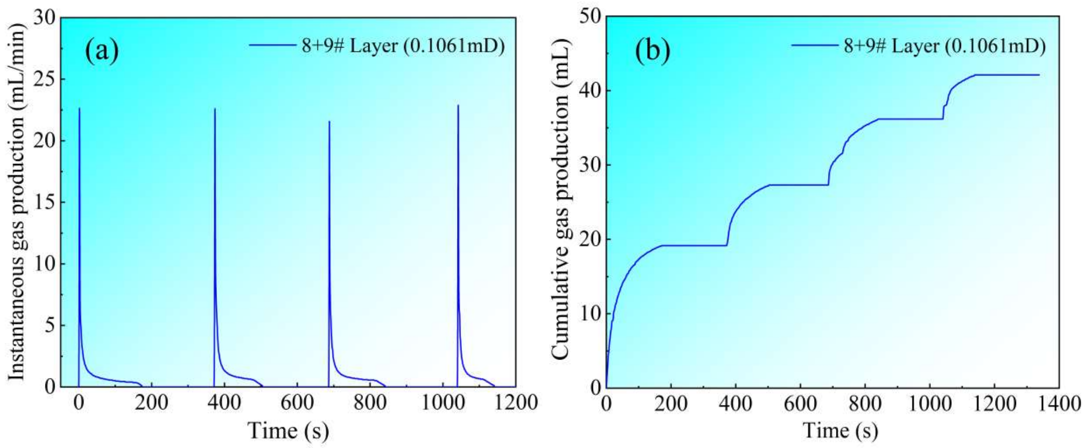

Figure 4. shows the variation in single mining output of the 8+9# coal seam

Figure 4 presents the dynamic variation characteristics of the instantaneous gas production rate and cumulative gas production during the four-stage pressure reduction gas extraction process of single mining in the 8+9# coal seam. The experimental process is basically the same as that of the thousand-5 layer experiment. As can be seen from Figure 4 (a), at 2 seconds, 375 seconds, 690 seconds and 1040 seconds after the start of the experiment, the corresponding peak gas production rates were 22.56 mL/min, 22.68 mL/min, 22.05 mL/min and 23.09

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mL/min respectively, and the average peak was 22.59mL/min. Compared with the sandstone in the 5-layer and 4-layer boxes, the peak instantaneous gas production of the coal-rock in the 4-layer box has further decreased, reflecting the very weak gas production capacity of the coal seam. During the non-peak stage, the gas production rate rapidly decays and remains at a relatively low level. Figure 4 (b) shows that the cumulative gas production increases in a typical stepwise manner with the alternating process of well opening and well closing. When the gas extraction time reaches 1140 seconds, the system pressure drops to the waste pressure, and the gas production process ends. The final cumulative gas production is 42.10mL.

In summary, through conducting single-layer single-mining experiments on three layers, namely the sandstone layers of Qian 5 and He 4 and the coal seam layer of 8+9#, the gas production dynamics of each layer during the stepwise pressure reduction process were systematically analyzed. The results show that all levels present a typical response pattern of "instantaneous gas production peak - rapid attenuation" and a "stepwise growth" rule of cumulative gas production. As the mining proceeds, the gas production increment at each stage decreases step by step, reflecting the continuous attenuation of formation energy. Through comparison, it was found that there were significant differences in the gas production capacity of the reservoirs. The Qian 5 layer performed the best (with an average peak gas production rate of 126.17 mL/min and a cumulative gas production of 75.27 mL), while the box 4 layer was relatively weak. The gas production capacity of the 8+9# coal seam was the weakest (with an average peak of only 22.59 mL/min). It fully reveals the significant differences in production dynamics of reservoirs with different permeability rates.

3.1.2. Analysis of the Mechanism of Yield Variation in Single-layer Single Harvesting

Based on the single-layer single-harvest yield variation experiment, the mechanism analysis of the following experimental process can be obtained.

(1) The core mechanism of yield variation in single-layer single-harvesting stems from the stepwise pressure reduction operation. Each stepwise drop in back pressure generates an instantaneous high pressure difference near the wellbore, greatly enhancing the driving energy acting on the reservoir. This pressure disturbance rapidly disrupts the original equilibrium state of the formation, effectively overcoming the capillary resistance and seepage resistance caused by gas initiation, thereby stimulating gas desorption and forming a high-speed cross-flow channel, resulting in a characteristic peak in the instantaneous gas production rate. After the peak, with the rapid gas extraction in the near-well zone and the initial reconstruction of the pressure field, the pressure difference rapidly decreases, and the gas flow is dominated by slow diffusion in the matrix or replenishment from more distant areas, resulting in a sharp decline in the gas production rate.

(2) The "stepwise" growth pattern of cumulative gas production is a direct manifestation of the cyclical cycle of "well opening for production" and "well closing for recovery". At the beginning of each round of pressure reduction, the free gas that has been utilized around the well is efficiently extracted, corresponding to the steep ascending section of the cumulative curve. When this part of the gas is nearly exhausted and the gas replenishment rate within the formation cannot maintain a high-speed flow, the production enters a plateau period. Although the subsequent well shutdown stage did not contribute to production, it provided a crucial window for the recovery of formation pressure and the rebalancing of gas from the matrix to fractures, and prepared a new movable gas source for the next round of pressure reduction mining. This cyclical mechanism of "consumption-recovery" is the intrinsic cause of the stepped growth pattern.

(3) As the mining process progresses, the overall trend of gradually decreasing gas production increments at each stage profoundly reveals the continuous attenuation of formation energy. In the initial stage of mining, the free gas that is easy to flow around the well is mainly utilized,

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which is abundant in energy and has a high output. Each subsequent round of mining requires disturbance to a more distant reservoir area, prolongs the gas flow path, and increases seepage resistance. Meanwhile, the average pressure level of the formation has systematically decreased due to continuous mining, resulting in a gradual narrowing of the effective production pressure difference that can be formed with each pressure drop. Ultimately, when the system pressure drops to the waste pressure, the production pressure difference is no longer sufficient to drive the effective output of gas, marking the end of the economic exploitation life of the reservoir. This attenuation process intuitively reflects the limited nature of the movable fluid and driving energy within the reservoir.

3.2. Double-layer Combined Sampling Experiment

3.2.1. Experiment on the Variation Law of Output

According to the experimental design in Table 1, this section conducted two sets of double-layer combined sampling experiments on Qian 5 and Box 4, as well as Box 4 and 8+9#. Each group of experiments was conducted under the conditions of consistent reservoir pressure and water saturation. The main difference lies in the different reservoir permeability between the combined mining layers. By using the multi-layer combined mining physical flow simulation experiment system, the instantaneous gas production and cumulative gas production data of each layer were monitored and recorded respectively. The gas production characteristics and inter-layer interference laws under different lithological combinations and mining modes were systematically analyzed.

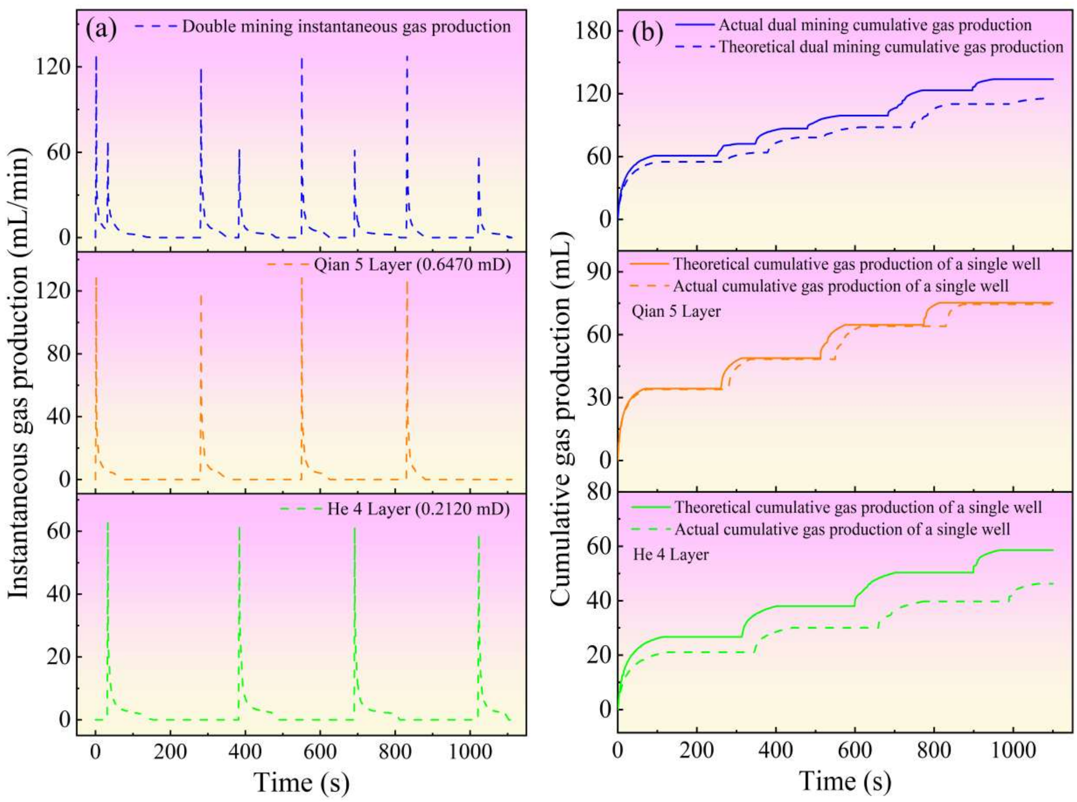

Figure 5. The changes in the combined production of qian 5 and box 4

This study systematically analyzed the yield dynamics and interlayer interference effects during the combined harvesting process by conducting double-layer combined harvesting experiments of 5-layer and 4-layer boxes. The initial pressure of the reservoir was set at 15

MPa in the experiment, and the back pressure decreased step by step from 3 MPa to the abandoned pressure of 3 MPa.

Figure 5 (a) shows that, compared with the single extraction condition (see Figures 2 and 3), the instantaneous gas production rate and cumulative gas production at both levels in the combined extraction system have decreased to varying degrees. Among them, the average instantaneous gas production rate of box 4 layer (relatively low-permeability layer) decreased from 71.23 mL/min at the time of single sampling to 61.24 mL/min, with a reduction rate of 14.02%. The average gas production rate of the Qianwu layer (relative to the high-permeability layer) decreased from 126.17 mL/min to 125.06 mL/min, with a reduction of only 0.88%, indicating that the high-permeability layer has a significant inhibitory effect on the production capacity of the low-permeability layer. Further observation revealed that during the same pressure reduction stage, the peak gas production of the 4th floor of the box lagged significantly behind that of the 5th floor, resulting in a "staggered gas production" phenomenon. As the mining proceeds, the time difference between the occurrence of the two peaks within the same stage gradually increases, reflecting the continuous strengthening of the interlayer interference effect over time. Figure 5 (b) shows the evolution process of cumulative gas production under combined production conditions. The cumulative gas production increases in a complex stepwise manner with the well opening and closing cycles. The final cumulative gas production of the combined production system was 115.98 mL, significantly lower than the sum of the theoretical cumulative production of the two layers of single production (149.78 mL), with a reduction rate of 22.56%. In addition, there is a significant production lag in both layers of the combined harvesting system, and the degree of lag has been continuously intensifying over time. Although the final cumulative gas production of Layer Qian 5 under both single mining and combined mining conditions is basically the same, it also shows a significant production lag during the combined mining process, further confirming that as mining continues, the inter-layer interference effect tends to intensify.

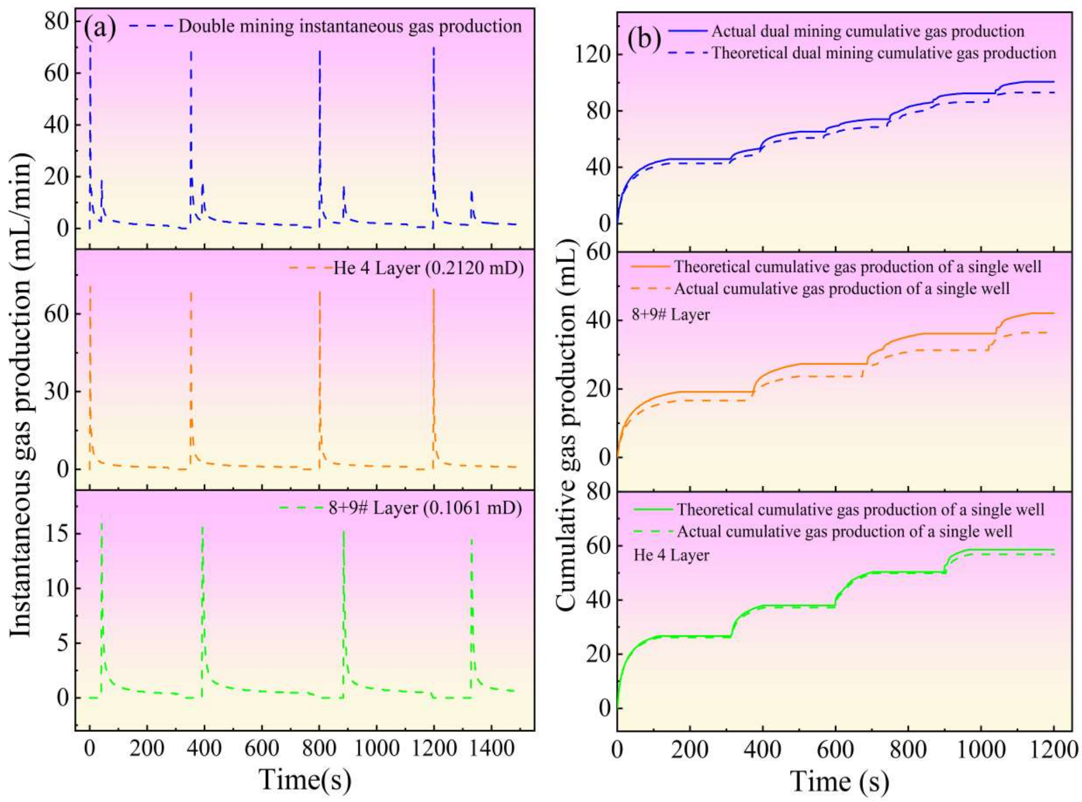

Figure 6. The changes in the combined production of 8+9# and box 4

Through the double-layer combined mining experiments of Box 4 layer and 8+9# coal seam, the production dynamics and interlayer interference effects during the combined mining process were systematically analyzed. Figure 6 (a) shows that, compared with the single extraction condition (see Figures 3 and 4), the instantaneous gas production rate and cumulative gas production at both levels in the combined extraction system have decreased to varying degrees. Among them, the average instantaneous gas production rate of the 8+9# coal seam (relatively low-permeability layer) decreased from 22.59 mL/min during single mining to 15.30 mL/min, with a reduction rate of 32.27%. The average instantaneous gas production rate of box 4 layer (relative to the hyperpermeability layer) decreased from 71.23 mL/min at the time of single sampling to 69.95 mL/min, with a reduction of only 1.79%, indicating that the hyperpermeability layer has a significant inhibitory effect on the production capacity of the hypopermeability layer. Further observation revealed that during the same pressure reduction stage, the peak gas production of the 8+9# coal seam lagged significantly behind that of the box 4 layer, resulting in a "staggered gas production" phenomenon. As the mining proceeds, the time difference between the occurrence of the two peaks within the same stage gradually increases, reflecting the continuous strengthening of the interlayer interference effect over time. Figure 6 (b) shows the evolution process of cumulative gas production under combined production conditions. The cumulative gas production increases in a complex stepwise manner with the well opening and closing cycles. The final cumulative gas production of the combined production system was 93.07mL, which was lower than the sum of the theoretical cumulative production of the two layers of single production (100.71 mL), resulting in a reduction of 7.59%. In addition, there is a significant production lag in both layers of the combined harvesting system, and the degree of lag has been continuously intensifying over time.

In summary, through conducting two sets of double-layer combined mining experiments, namely, the Qian 5 layer and the Box 4 layer, and the Box 4 layer and the 8+9# coal seam, the gas production patterns and interlayer interference characteristics under different lithological combinations have been systematically revealed. The results show that in the combined production system, the high-permeability layer has a significant energy production suppression effect on the low-permeability layer. The average gas production rate of the low-permeability layer decreases by 14.02% and 32.27% respectively, and a distinct "off-peak gas production" phenomenon occurs. As the mining progresses, the interlayer interference continues to intensify. The cumulative gas production of the combined mining system decreases by 22.56% and 7.59% respectively compared with the theoretical value of single mining. Moreover, each layer shows an intensified production lag phenomenon with the extension of mining time, reflecting the significant impact of interlayer interference on production capacity during the combined mining process.

3.2.2. Analysis of Inter-layer Interference Mechanism in Double-layer Combined Mining

Based on the physical model experiment results of the combined mining of the Qian 5 layer and the box 4 layer, as well as the combined mining of the box 4 and the 8+9# coal seam, the analysis and summary of the universal interference mechanism between the double-layer combined mining are as follows.

(1) In the combined production system, the high-permeability layer and the low-permeability layer form a unified pressure outlet at the wellbore. Due to the low flow resistance of the hyperpermeable layer, it will preferentially and in large quantities produce gas under the same production pressure difference, resulting in the bottom hole pressure being rapidly dominated and maintained at a relatively low level. This results in insufficient effective production pressure difference applied to the low-permeability layer, making it difficult to overcome its relatively high start-up pressure. As a result, the capacity release of the low-permeability layer

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is severely suppressed, creating a "sucking" or "suppressing" effect of the high-permeability layer on the low-permeability layer.

(2) The "off-peak gas production" phenomenon observed in the experiment is a direct manifestation of interlayer interference in the temporal dimension. At the beginning of each round of pressure reduction, the hyperpermeable layer reaches the peak gas production first due to its excellent flow diversion capacity. However, the low-permeability layer requires a longer time to establish sufficient pressure drop funnels, and thus the peak gas production is delayed. As the mining proceeds, the formation energy continues to decline, and the time required for the low-permeability layer to reach its peak is further prolonged. The time difference between the gas production peaks of the two layers becomes increasingly large, the dynamic asynchrony intensifies, and the interference also increases accordingly.

(3) The ultimate result of inter-layer interference is a decline in the overall system capacity, that is, "1+1<2". The final cumulative gas production of combined mining is significantly lower than the sum of the individual mining production of each layer. This is not merely a simple arithmetic superposition loss of production, but rather stems from the incompatibility between high and low permeability layers in terms of production systems, pressure fields, and energy replenishment. This incompatibility disrupts the optimal working system when each layer system operates independently, resulting in the inability to effectively utilize the reserves of some low-permeability layers and causing losses in collaborative production capacity.

Double-layer combined mining is essentially a complex dynamic process of "pressure competition - dynamic balance - collaborative production" among various layers. To achieve successful combined production, it is necessary to first recognize the objective inevitability of interlayer interference, and then create reasonable production pressure differences for each layer (especially the low-permeability layer) by optimizing the production system (such as controlling the initial production, adopting intermittent well opening strategies, etc.), so as to ensure that all layers can be effectively utilized, and ultimately maximize the production and recovery rate throughout the well's life cycle. For the combined mining of coal seams, it is even more necessary to fully consider their desorption particularity and reserve sufficient production time.

4. Summary

(1) Through systematic physical simulation experiments, it was clearly identified that there are significant interlayer interference phenomena in multi-layer co-production of low-permeability gas reservoirs, specifically manifested as "off-peak gas production", production lag and coordinated production capacity loss. The high permeability layer dominates the bottom hole pressure system, severely suppressing the release of energy from the medium and low permeability layers.

(2) The research reveals that the essence of interlayer interference is the result of "pressure competition - dynamic imbalance". In the combined mining system, the high-permeability layer prioritizes the establishment of pressure drop funnels, resulting in insufficient effective production pressure difference in the low-permeability layer and making it difficult to release production capacity. As mining progresses, the interference effect shows a dynamic strengthening trend. The reconstruction of the pressure field in multi-layer combined mining becomes more complex, further increasing the difficulty of mobilizing medium and low permeability layers. Especially in coal-bearing systems, the differences in reservoir physical properties and gas desorption characteristics make the interference more prominent.

(3) It is suggested that in the actual selection and development design of the combined mining layer system, the permeability grade difference between high and low permeability layers should be controlled as a priority, and reservoirs with similar physical properties should be

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given priority. For the already combined production Wells, effective production pressure differences can be created for the medium and low permeability layers by optimizing the working system (such as controlling the initial production, implementing staged fracturing or intermittent production). In the combined mining of coal-bearing strata, the coupling characteristics of gas desorption and seepage should be fully considered, and the time for well closure and recovery should be appropriately extended to enhance the overall utilization rate of reserves.

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