

Article

Performance Evaluation of Multistage Fractured Horizontal Wells in Tight Gas Reservoirs at Block M, Ordos Basin

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Abstract: Block M of the Ordos Basin is a typical low-permeability tight sandstone gas accumulation. To develop these reservoirs, various horizontal well fracturing technologies, such as hydra-jet fracturing, open-hole packer multistage fracturing, and perf-and-plug multistage fracturing, have been implemented in practice, showing greatly varying performance. In this paper, six fracturing technologies adopted in Block M are reviewed in terms of principle, applicability, advantages, and disadvantages, and their field application effects are compared from the technical and economic perspectives. Furthermore, the main factors affecting the productivity of fractured horizontal wells are determined using the entropy method, the causes for the difference in application effects of the fracturing technologies are analyzed, and a comprehensive productivity impact index (CPII) in good correlation with the single-well production of fractured horizontal wells is constructed. This article provides a simple and applicable method for predicting the performance of multi-frac horizontal wells that takes multiple factors into account. The results can be used to select completion methods and optimize fracturing parameters in similar reservoirs.



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Keywords: Ordos Basin; low-permeability tight sandstone gas reservoir; horizontal well; multistage fracturing; comprehensive productivity impact index

1. Introduction

Low-permeability tight sandstone gas reservoirs have high potential due to their wide distribution and large reserves. However, they usually have no or low natural flow rate that meets economic boundaries due to poor physical properties. Horizontal drilling and hydraulic fracturing are two technologies widely used to improve the ultimate recovery of these reservoirs by maximizing reservoir contact [1,2]. In the past few decades, with the widespread application of horizontal wells in unconventional reserves, especially shales and other tight rock formations, the level of multi-frac technology has also been continuously improved. A series of horizontal completion methods have been formed on the basis of hydra-jet, open-hole multistage system (OHMS), and plug and perf (P-n-P), including coiled tubing (CT) hydra-jet, fixed-string hydra-jet, open-hole (OH) packer and ball-activated sliding sleeve, OH packer and infinite sliding sleeve, cementing sliding sleeve, and quick-drill or dissolvable bridge plug [3,4]. Field tests verified that multistage fracturing in these wells has been proven to be a key technique for the efficient development of these resources [5–7]. However, what are the advantages and disadvantages of each process? Which method yields better gas production? What factors affect the performance of multistage fractured horizontal wells?

Multistage fracturing has been used to increase the production rate of shale gas since about 2000 in the United States. Scholars have worked extensively to compare different completion methods to determine which approach achieves a higher output,

mainly from two aspects: comparisons derived from field studies and comparisons based on analytical models.

Many methods such as historical production data, sonic anisotropy and radioactive tracer logs, or resistivity and acoustic imaging can be used to estimate the fracturing effect in field research. For example, East et al. [8] presented a comparison of different completion technologies through microseismic fracture mapping. Evidence from mapping of two wells in the Barnett Shale illustrates that horizontal completions were favorably stimulated by a hydra-jet/water-frac procedure with light sand and large volume. There is no doubt that microseismic monitoring and logging could be effective means to assess the effectiveness of fracturing, but they are costly and require extra on-site work. In contrast, comparisons based on historical data are a much more efficient approach. Publications have compared multiple indicators including initial and long-term production rate, ultimate recovery, and ROI.

Some scholars focused on the application of a certain process in oil and gas reservoirs. Mcdaniel et al. [9] reviewed applications of hydra-jet perforating in the years 2003–2009, particularly their practice on horizontal and highly deviated wells, and the research showed that hydra-jet perforating is widely used in horizontal wells, and that this technique is extremely superior in hard and very hard formations if high nozzle pressures are attained. Xiude et al. [10] proposed a hydra-jet fracturing technology with bottom packer on coiled tubing, and they verified its successful application in low-permeability gas reservoirs in the Sichuan Basin, China. Xue [11] and Jiang et al. [12] studied and demonstrated the advantages of hydra-jet fracturing technology, and they described its good performance in low-permeability hydrocarbon fields in China. Li et al. [13] reviewed the experimental, field, and numerical simulation studies of hydro-frac of unconventional reservoirs. Qin et al. [14] adopted a new OH horizontal well sliding sleeve multistage fracturing tool according to the geological conditions, fracture treatment, well trajectory, and diameter changes of the open-hole horizontal wells with long horizontal sections in the Daniudi gas field and Honghe oilfield, which was then satisfactorily applied in more than 20 horizontal wells in the Ordos Basin. Parshin et al. [15] demonstrated the successful application of the coiled tubing multistage hydraulic fracturing technology in the AS3 reservoir of Vinogradova Oilfield, which significantly improved the production performance of wells.

On the other hand, some scholars were more interested in a comparison between completion methods and fracturing processes. The most common topic was a performance comparison between OHMS and P-n-P, the two most common and widely used technologies; the former is often regarded as a representative of an open-hole approach, and the latter often represents cemented completion. Samuelson et al. [2] compared the applications of the two methods in the Cleveland tight gas sand formation of the Texas panhandle founded on 3 months of cumulative gas production. Lohoefer et al. [16] conducted a long-term comparison of production (cumulative gas production in 3 years) between the two completions in Barnett shale of Newark Field. Edwards et al. [17] compared the average 1 year cumulative gas production of 30 wells; six of the wells were completed with OHMS and the others with P-n-P, in the center of the Granite Wash tight sand reservoir located in western Oklahoma and the northern Texas Panhandle. The results of these three studies were consistent, all showing that wells completed with OHMS performed better. Wilson et al. [18] compared the daily gas production rates of 15 wells of two tight gas districts in the Lower Montney formation situated in southeast of Dawson Creek, British Columbia. The observation showed that the average performance of OHMS in these two areas was better than P-n-P completions; however, when it came to a single well, the results were not in the same direction. Furthermore, Augustine, Theppornprapakorn, and Vasudevan compared the output of OHMS and P-n-P analytical methods. Augustine [19] analyzed the difference using a 2D reservoir model. The study concluded that the biggest difference in production would occur when the reservoir permeability is in the range of millidarcy to microdarcy, while the production penalty in the range of microdarcy and nanodarcy is negligible. This range of permeability means that cementing has a greater

impact on the production of fractured horizontal wells in tight gas reservoirs than in shales. Theppornprapakorn [20] constructed a 3D gas reservoir model with a single transverse fracture based on the assumption of steady-state production and no formation damage. Results of the CFD simulation were consistent with Augustine's conclusion, i.e., OHMS outproduced P-n-P, but the difference between the two was much smaller than in previous studies. Vasudevan [21] assessed the gas yield of horizontal wells with both transverse and longitudinal fracture in a relatively high-permeability reservoir using CFD simulations. This study obtained the same results as earlier discussions.

Another hot topic is the comparison of various fracturing processes and their applications. Li et al. [22] compared the field plays of open-hole preset external string packer multistage fracturing, casing cementing multistage fracturing, and OH packer and CT with BOT packer multistage fracturing in the Daniudi gas field, showing that the last method was the best performer. Thomson et al. [23] analyzed four different horizontal completion systems for the Montney tight gas formation in NE British Columbia, namely, packer isolation and frac sleeves, P-n-P, hydrajet perforating on CT with sand plug isolation, and CT deployed bridge plugs and tubing conveyed perforating; they inferred that fracture stimulation is a powerful approach to raise the productivity of horizontal wells in this area. Gas rate per interval suggested that wells with different completion procedures yielded almost similar rates. Mcdaniel et al. [24] studied the cost, completion risk, and ROI of six hydraulic frac multistage isolation methods in horizontal wells, including hydra-jet, ball-activated sliding sleeve, and bridge plug, and they observed a strong relationship between higher initial rates and larger volumes of proppant being placed, longer laterals, and more stages in Haynesville shale completions. Yet, the reservoir quality varies from well to well in many low- to ultralow-permeability formations, making it very hard to evaluate if a certain completion process practically brings about more hydrocarbons. Stanojcic et al. [25] reviewed the advantages and disadvantages of the CT, jointed-pipe, sleeve, and perf-and-plug techniques, as well as their applications, suggesting that nearly 20 pinpoint fracturing technologies were available, and they recommended fracturing treatments depending on well types and formation conditions. Xing et al. [26] studied the cased-hole mechanical packer, OH hydra-jet, and OH packer completion technologies, and they developed the key technology of horizontal well multistage fracturing for the Daniudi gas field. Kennedy et al. [27] found little difference in the initial production rate, regardless of the completion process used, according to field studies carried out by some operators in tight sand and shale gas. Research conducted by Burton [28] confirmed three completion techniques as the most effective and efficient in these types of formations, namely, P-n-P, ball-activated completions, and coiled tubing-activated completions. Each completion method has its advantages and limitations, and there is no single solution for every application in unconventional reservoirs. Salah et al. [29] comparatively analyzed three fracturing technologies, i.e., cemented P-n-P, cemented shiftable sliding sleeves with dissolvable isolation drop ball, and abrasive jetting perforation and annular pumping (AJPAP) with sand plug diversion, in terms of principle, advantages and disadvantages, field application, and effectiveness, and they concluded that there is no fit-for-all fracturing treatment; instead, the fracturing process should be designed comprehensively from economic and technical aspects. Subsequently, Prudskiy et al. [30] demonstrated the application effect of horizontal well multistage hydraulic fracturing technology in the Sakhalin Shelf oilfield in contrast to traditional horizontal well completion methods, while Li et al. [31] compared the characteristics and application of P-n-P with multi-cluster perforation with early applied fracturing technology and OH hydra-jet multistage fracturing with fixed string in the Sulige gas field. Both studies coincidentally indicated that the latter techniques significantly improved the productivity of horizontal wells. Some other publications focused on factors influencing the output of multi-fractured horizontal wells. Since late 2008, multi-fractured horizontal wells have been distinctly successful in the Cardium Formation, Western Canadian Sedimentary Basin. Omatsone et al., [32] studied the performance of 120 multistage fractured horizontals; the study was quite thorough, as it looked at detailed reservoir parameters, fracture pa-

rameters, and well performance. Results concluded that the early performance of the wells was related to net pay thickness and horizontal well length. Gilbert and Barea noted that a complicating factor for determining the drainage area of multi-fractured horizontals is the rate at which interference occurs between adjacent fracture stages. Their study suggested that more fracture stages do not always result in an improvement in ultimate recovery. There were over 2500 horizontal wells drilled in Bakken/Three Forks oil play, Montana, North Dakota, and Saskatchewan from 2000 to 2009. Rankin et al. [33] reviewed the development philosophy and described the evolution of the completion strategies of these oil plays, recommending that ultimate recovery increments can be ascribed to an improvement in the completion design because of the similar reservoir quality in the study area. Taylor et al. [34] suggested that initial production rates might be a quick and simple guide to relative long-term well performance, but making critical economic decisions developed on initial production rates alone can be misleading; it is, therefore, essential to take reservoir characterization and well completion design into account to optimize ultimate recovery. The study also suggested that the fracture size and stage space had an impact on the rates. Hamm [35] studied and compared the results of horizontal multistage development, in various Western Canada plays. Type curves indicated that initial rates did not necessarily mean more ultimate recoveries; production rate differences between Manitoba Bakken and North Dakota were thought to be as a result of differences in permeability and reservoir pressure, while the differences between newer and older wells were greatly affected by well interference. Al-Ghazal [36] analyzed the practical application data of the multistage fracturing of horizontal wells in a Saudi Arabia tight gas field and revealed that borehole trajectory, reservoir parameters, and completion design are important factors affecting single-well productivity. Alekseev [37] divided the factors affecting the productivity of horizontal wells into three categories, reservoir quality, drilling quality, and completion quality, pointing out that the fracturing technologies differ significantly in parameters and processes; thus, their stimulation effects vary greatly from well to well under the combined influence of reservoir and drilling factors. Chodzicki's [38] results from over 120 wells in the Spearfish low-perm sandstone/siltstone formation, Southwest Manitoba, showed great production results from the application of horizontal well and multistage fracturing techniques, but individual fractured horizontal wells also yield variable results, making it difficult to correlate any strong trends that related initial production rates and estimated ultimate reserves to fracture size, number of stages, or total proppant.

These studies remarkably promoted the innovation of completion methods and processes, as well as enabled the horizontal well fracturing to be more efficient, intelligent, and infinite. However, although many scholars have adopted different indicators to compare the effect of different fracturing process horizontal wells based on field production data, there is no agreement on either indicators or performance. Some researchers concluded that one completion practice is better than another, while others held that there is no notable disparity with different completion processes in the production period. The results of comparisons that utilized analytical methods appeared to reach a consensus, i.e., open-hole completions exhibit better performance than cemented completions. However, the conclusion was obtained by assuming equal fracture geometry and absences of natural fracture. This clearly shows that the model has many limitations when applied in practice.

At the same time, various studies on multi-stage fracturing horizontal wells indicated that some wells performed better for various reasons. Several authors tried to analyze the interactions between hydrocarbon output and various parameters, such as net pay thickness, horizontal well length, reservoir pressure permeability, and completion design, but no obvious relationships were revealed. Some suggested these were related to rock and reservoir properties, while others suggested they were related to drilling and completion quality. It appears that there was no one quantitative evaluation method that could be applied to predict the well performance because of the multiple effect of geological heterogeneities, reservoir quality variations, and engineering complexity.

Therefore, it is necessary to carefully review various horizontal well fracturing technologies, compare their application effects in the same block, and deeply analyze the reasons resulting in difference well performance to identify quantitative description methods for fractured horizontal well production.

This paper takes 24 fractured horizontal wells in the S interval, Block M, the Ordos Basin, as examples. Block M, which is adjacent to the Sulige, Zizhou, Changbei, and Daniudi gas fields, is a typical gas accumulation with low porosity, low permeability, and low abundance. The main reservoirs were developed by the horizontal well plus multistage fracturing in the whole horizontal section. This block is highly representative for reservoir conditions or development strategy. Because of the short time in commercial development, the multistage fracturing technology of horizontal wells is mainly selected with reference to the practices in similar adjacent gas fields. So far, six horizontal well fracturing techniques have been attempted, including hydra-jet multistage fracturing, OH packer fracturing, and perf-and-plug multistage fracturing. It is found that wells with different completion methods vary significantly in gas production. In this paper, the six technologies are reviewed in terms of principle, applicability, advantages, and disadvantages, and their application effects are compared. Furthermore, the causes of yield difference of these technologies are analyzed, the main factors affecting the average gas rate of fractured horizontal wells are quantitatively studied, and a comprehensive productivity impact index (CPII) in good correlation with the 1 year average gas rate is constructed. This article provides a simple and applicable method for predicting the performance of multi-frac horizontal wells that takes multiple factors into account. The results can be used to select completion methods and optimize fracturing parameters in similar reservoirs.

2. Well Completion Methods

2.1. Common Multistage Fracturing Technologies

2.1.1. CT with BOT Packer Hydra-Jet Multistage Fracturing

Hydra-jet multistage fracturing is a basic technology of horizontal well stimulation. Generally, there is no need to adopt a mechanical seal method; instead, one can rely on the highly concentrated and strong focus of dynamic fluid force [9]. It is a method that combines hydraulic sandblasting perforation, fracturing, and interval isolation in one technique according to the Bernoulli principle. In the fracturing process, small flow channels are formed in the reservoir by hydraulic sandblasting perforation [39–41], and then the pressure in the annulus is increased while the flow channels are pressurized by the injection of high-pressure water jets. Once the pressure in the flow channels exceeds the formation fracture pressure, the formation is fractured instantly to realize hydra-jet fracturing. In hydra-jet fracturing, continuous fluid injection into the annulus is needed to help realize the propagation of fractures, and its pressure control is the key to realize effective perforation and dynamic isolation [42], as shown in Figure 1.

This technology adopts hydra-jet directional perforation, which can accurately lower the jetting tool to the designed position and exactly create fractures, without using mechanical packing tools. It also has the advantages of lower operation risk, shorter working cycle, and lower cost. It is appropriate for a wide range of completion processes, including open-hole, casing perforation, and screen pipe. The wide-ranging and successful use of this procedure in the field reveals its popularity and successful application [11].

However, for formations with high in situ stress, high fracture pressure, and high rock confining pressure, this technology may cause problems such as insufficient sandblasting penetration depth, difficult fracture initiation, and poor isolation effect between intervals; hence, the application of this technology in deep formations is limited.

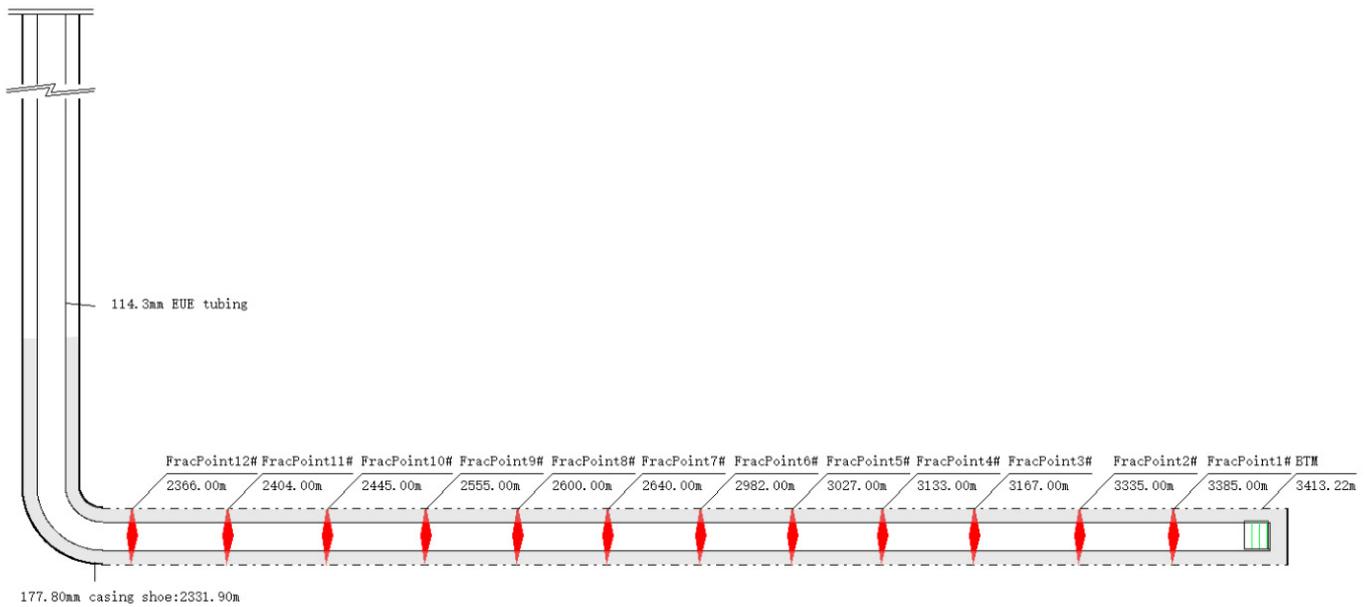


Figure 1. Schematic of coiled tubing with bottom packer hydra-jet multistage fracturing.

2.1.2. Fixed-String Hydra-Jet Multistage Fracturing

The fixed-string hydra-jet multistage fracturing technology introduces the ball-activated sliding sleeves used in packer multilayer fracturing into conventional hydra-jet fracturing treatment. It adopts multiple sets of jet gun groups, together with supporting sliding sleeves, and it can realize sandblasting perforation and fracturing through dropping balls, without moving the jet string. The sliding sleeve-type hydra-jet tool is run in advance, and the sliding sleeves at corresponding intervals are opened step by step during fracturing. Following the principle of the multistage opening of the hydra-jetting tool, it can be ensured that only the predetermined intervals are fractured. After the fracturing stimulation of the predetermined interval is completed, the plugging balls can be cast in hole to block the flow channels of the interval and activate the upper sliding sleeve to realize the stimulation of the upper interval. By repeating this process, the multistage fracturing stimulation of the whole horizontal well can be completed [43], as shown in Figure 2.

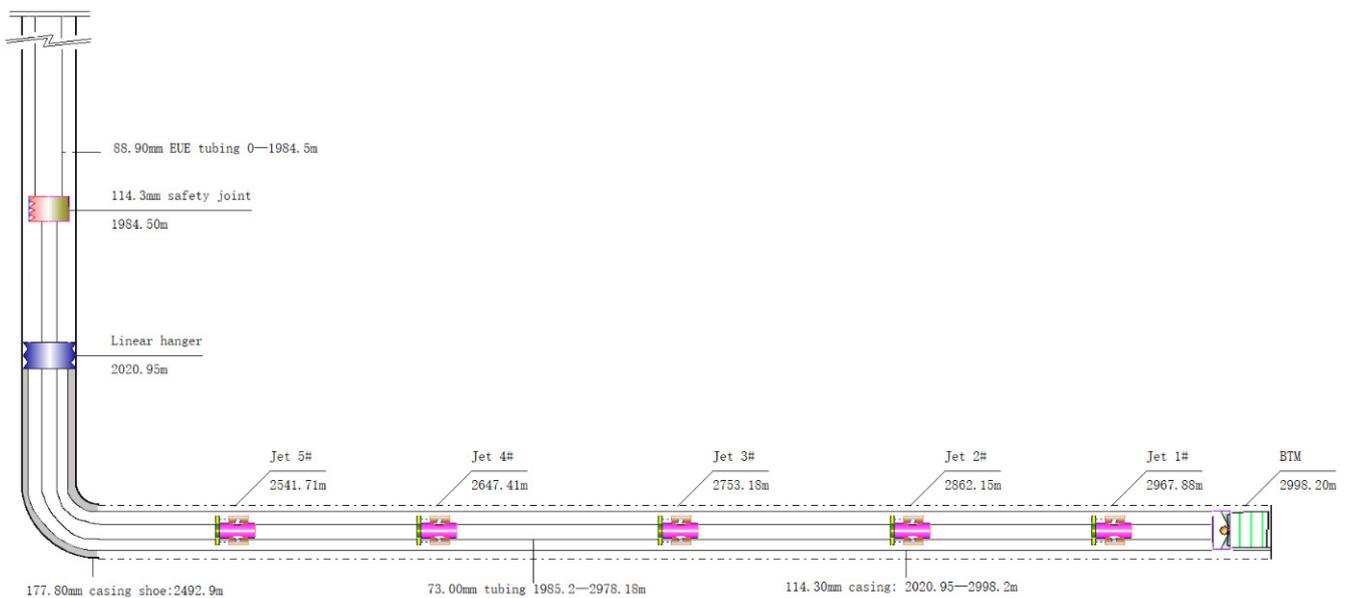


Figure 2. Schematic of fixed-string hydra-jet multistage fracturing.

This technology combines the advantages of hydra-jet technology and sliding sleeve multilayer fracturing, i.e., under the condition of not moving the pipe string, multistage fracturing can be continuously carried out in one trip without using packers, suggesting a high operation efficiency. In addition, by using the fracturing pipe string, the positive circulation and backwashing channels can be established. This technology has the advantages of simple process, low cost, fast production, and easy retrieval of the pipe string, and it subsequently allows repeated fracturing stimulation. It overcomes the disadvantages of conventional hydra-jetting operation, such as the need for snubbing units and moving the pipe string, long operation period, the reservoir damage caused by well killing, and the low displacement limited by coiled tubing. Therefore, this technology is suitable for stimulation in deep high-pressure reservoirs. However, its applicability is poor under the condition of complex borehole trajectory, and the number of fracturing stages needs to be improved [44].

2.1.3. OH Packer and Ball-Activated Sliding Sleeve Multistage Fracturing

Multistage fracturing with OH packer in horizontal wells is a technology to realize selective isolation and staged fracturing stimulation of horizontal wells in only one trip. Essentially, the open-hole packer is used to separate the horizontal section into multiple stages, and then balls with small size difference are dropped stage by stage to open the sliding sleeves at each stage to realize multistage fracturing [45–47], as shown in Figure 3.

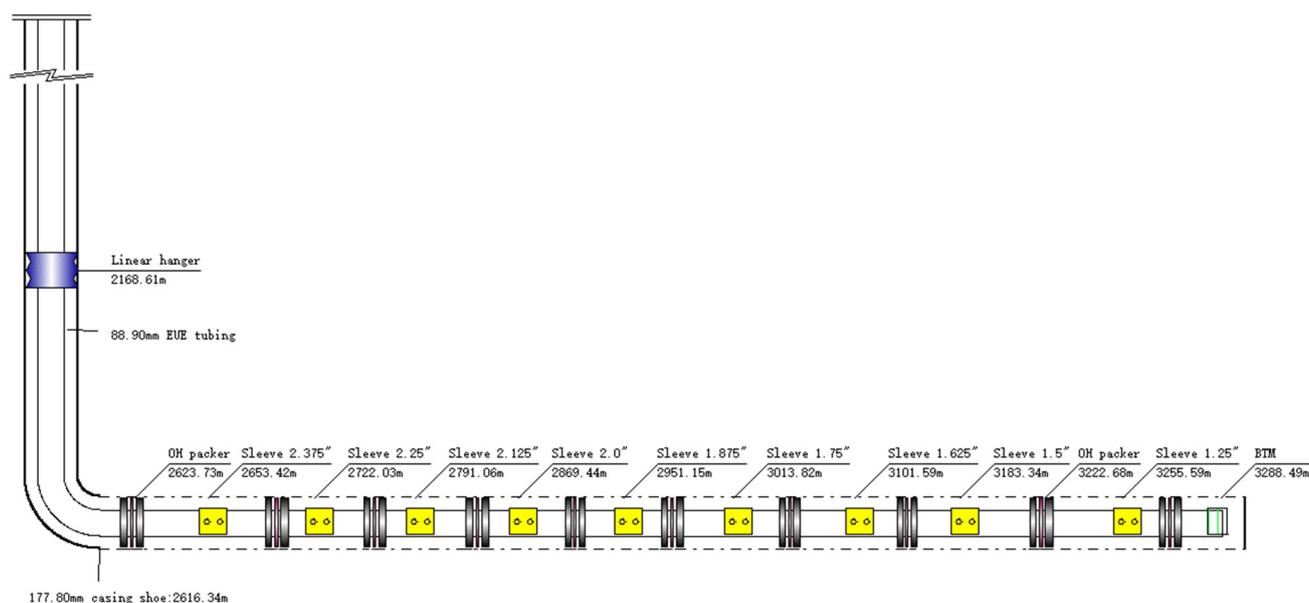


Figure 3. Schematic of open-hole packer multistage fracturing completion string.

Multistage fracturing with OH packer in horizontal wells can realize multistage fixed-point fracturing stimulation in one trip, saving significant completion time and money. It is advantageous for its fewer downhole tools, simple process, and high safety and efficiency, without the necessity of cementing and perforation in the horizontal section, which can reduce time and cost and increase the return on investment. However, it requires packers with high performance, and the completion string below the suspension packer cannot be retrieved; furthermore, due to the graduated ball seat sizes for each additional zone, each ball seat generates its own backpressure in the system, thereby limiting the number of fracturing stages [48]. During the process, the balls must be dropped in sequence from small to large and cannot be operated flexibly, making the operation difficult and risky for a completion string and ball seat of sliding sleeves that are small in inner diameter. Therefore, the technology is not suitable for post-fracturing production tests or other oil and gas wells requiring repeated fracturing [49].

2.1.4. OH Packer and Infinite Sliding Sleeve Multistage Fracturing

In infinite sliding sleeve multistage fracturing, stages are essentially isolated with OH packer or cement sheath, and then the infinite sliding sleeves installed on the casing or tubing string at pay zones are activated by the bottomhole assembly (BHA) conveyed by CT to establish the flow channel. The sliding sleeves, as a part of the casing, are lowered by the drilling rig and landed at the predetermined fracturing depth, and the position of the sliding sleeves corresponds to the position of the fracturing intervals.

OH packer and infinite sliding sleeve multistage fracturing is achieved by installing open-hole packers and infinite sliding sleeves on the tubing string, and the intervals are separated by activating and setting open-hole packers, as shown in Figure 4.

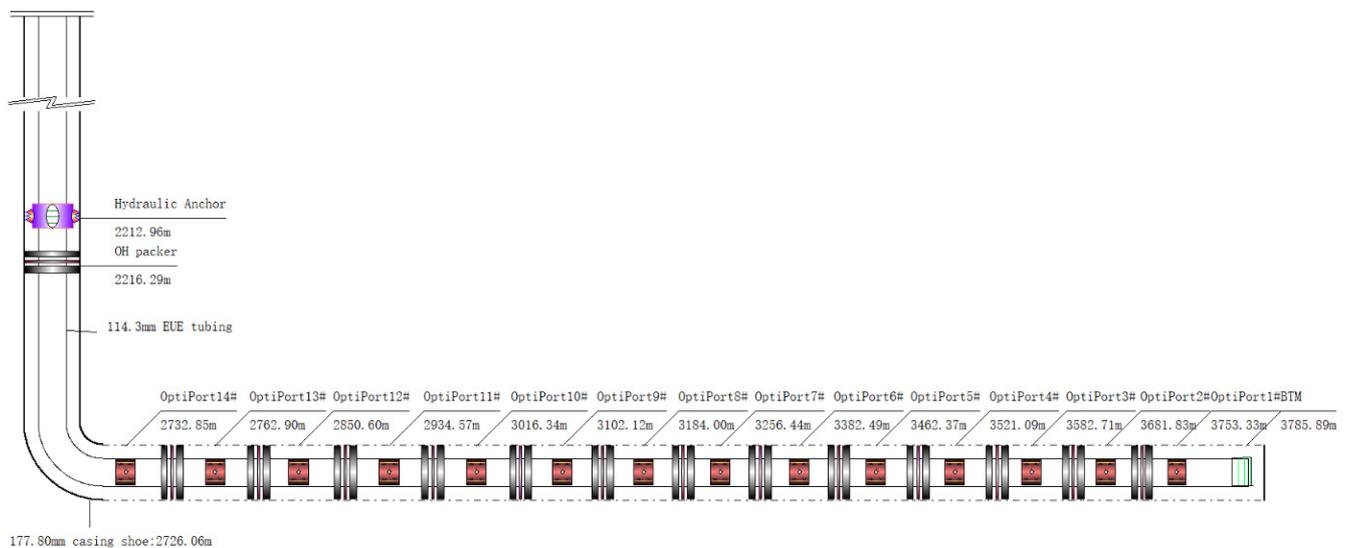


Figure 4. Schematic of open-hole packer and infinite sliding sleeve multistage fracturing completion string.

The number of stages in infinite sliding sleeve multistage fracturing is not limited by the process [48,50] by adopting same size balls and ball-seats for all zones. This technique can considerably lessen frictional forces and facilitates a more effective operation, in addition to realizing an inside diameter (ID) extremely close to the host tubular string; therefore, a much lower surface fracturing pressure can be used [48]. Due to the use of CT, it is convenient and easy to flow back after fracturing. Moreover, CT can be used to monitor the bottomhole pressure in real time, which is conducive to the timely detection of the risk of sand plugging. A sandblasting perforator is also integrated in the switch tool of the sliding sleeves, which can be used as a preventive measure; that is, once the formation cannot be fractured, the sandblasting perforation can be used as a remedial measure, and the displacement fluid at the interval is the preflush in the next interval, which reduces the use of fracturing fluid. However, this technology requires high isolation performance of the packers in the string, and it may suffer a risk that the production casing cannot be run to the design position, resulting in misalignment of the fracturing sliding sleeves with the corresponding fracturing intervals.

2.1.5. Infinite Cementing Sliding Sleeve Multistage Fracturing

Infinite cementing sliding sleeve multistage fracturing is another form of infinite sliding sleeve multi-frac technology, and its principle, process, and parameters are basically the same as OH packer and infinite sliding sleeve multistage fracturing [51,52]. For this technology, infinite sliding sleeves are installed and run with the casing string to complete cementing operation. It differs from the OH packer and infinite sliding sleeve multistage fracturing in that the intervals are isolated by consolidated cement before multistage fracturing is carried out, as shown in Figure 5.

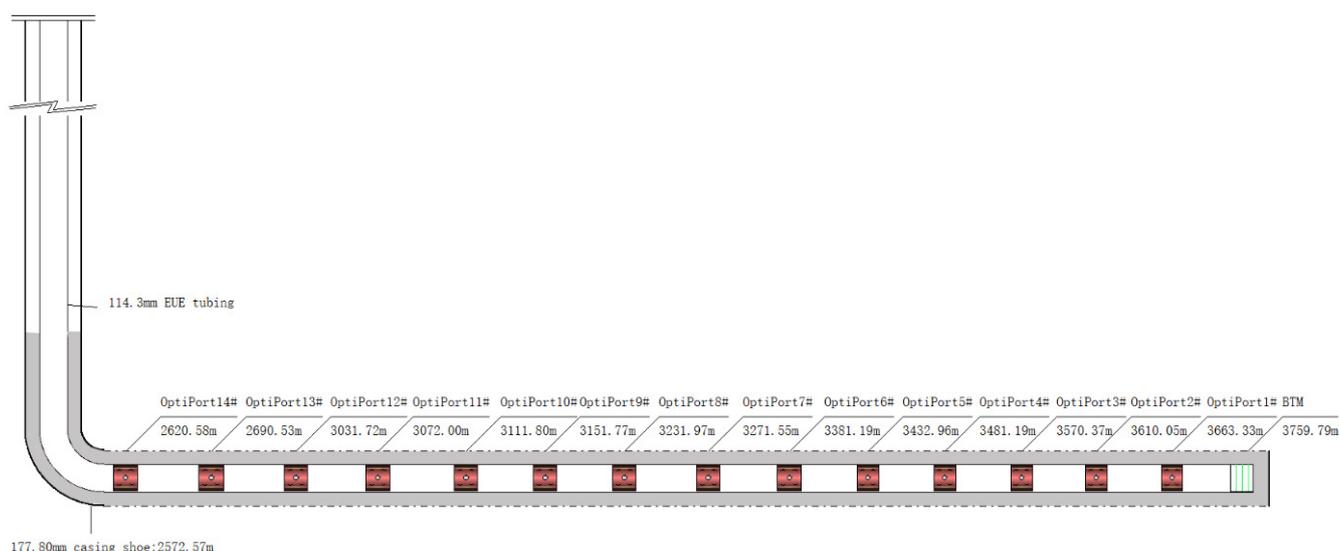


Figure 5. Schematic of infinite sliding sleeve multistage fracturing cementing.

2.1.6. Perf-and-Plug Multistage Fracturing

Perf-and-Plug is the most widely used strategy for multistage fracturing in unconventional reservoirs. It is regarded as a fully developed approach and is usually employed in cemented casing or liner completion horizontal wells [20]. CT conveyed perforation is performed, and then fracturing is realized by pumping fluid through the casing. After the fracturing operation in the interval, the bridge plug tool string with a perforation gun is pumped to the designated isolation position of the horizontal section by means of liquid injection, and the perf-and-plug operation is realized through cables. Then, the fracturing operation in the next interval can be initiated. The tool assembly is run in the wellbore stage by stage, and the fracturing operation is implemented accordingly. After the stimulation of the entire horizontal section is completed, the well is put into production from all pay zones together [53], as shown in Figure 6.

Due to the different isolation methods and pipe string structure, perf-and-plug multistage fracturing is advantageous to some extent. First, it is not necessary to run the tool in advance along with the casing, and bridge plugs are used to reliably isolate the intervals. Second, fixed-point fracturing is realized through perforation, with accurate fracture placement. Third, the bridge plugs are generally drillable or soluble, leaving a full borehole for subsequent operation and production. Compared with other technologies, this technology can realize multi-cluster fracturing in one stage, achieving large displacement, large-scale fracturing, and high operating efficiency [54–56]. Despite the simplicity of plug-and-perf completion operations, producers are faced with a few challenges, including unproductive clusters and poor perf cluster efficiency, excess fluid volumes and over-displacement, time-consuming operations, operational risk, and high costs [57].

2.2. Comparison of Technologies

All the abovementioned multistage fracturing technologies for horizontal wells can achieve the purpose of reservoir stimulation and production enhancement, but each technology has its applicability, advantages, and disadvantages. Table 1 compares these technologies, in which infinite cementing sliding sleeve multistage fracturing and OH packer and infinite sliding sleeve multistage fracturing are combined into infinite sliding sleeve multistage fracturing technology, since they are basically identical in principle, process, and parameters.

Table 1. Applicability, advantages, and disadvantages of horizontal well multistage fracturing technologies.

Technology	CT with BOT Packer Hydra-Jet	Fixed-String Hydra-Jet	OH Packer and Ball-Activated Sliding Sleeve	Infinite Sliding Sleeve (Infinite Cementing Sleeve and OH Packer and Infinite Sliding Sleeve)	Perf-and-Plug
Applicability	Various horizontal wells, such as open holes and cased holes.	Various horizontal wells, such as open holes and cased holes. The drift diameter of the fracturing string is small, which can effectively meet the production of gas wells with a certain quantity of water produced.	Open-hole horizontal wells with relatively regular boreholes. The drift diameter of the fracturing string is small, which can effectively meet the production of gas wells with a certain quantity of water produced.	Cemented or open-hole horizontal wells. After fracturing, full bore tubing or casing is used for production, which is more suitable for gas wells with high production.	Cased horizontal wells. After fracturing, full bore tubing or casing is used for production, which is more suitable for gas wells with high production.
Advantages	<ol style="list-style-type: none"> Isolation is realized automatically, without mechanical isolation tools, suggesting low tool risk. It is not limited by completion technique. Circulation can be established, and backwashing channels are available. Directional perforation is realized by hydra-jetting, and fractures are created accurately. 	<ol style="list-style-type: none"> Isolation is realized automatically, without mechanical isolation tools, suggesting low tool risk. Multistage fracturing can be carried out in one trip, which can shorten the operation time and mitigate reservoir damage. Circulation can be established, and backwashing channels are available. The pipe string is easy to retrieve, and repeated fracturing can be carried out at a later stage. The fracturing string has a small drift diameter and a strong liquid-carrying capacity after fracturing. 	<ol style="list-style-type: none"> Intervals are isolated by open-hole packers, the operation is simple and convenient, and fracturing completion is done safely and efficiently in one trip. No cementing or perforation is conducted in the horizontal section, thus saving time and cost. Multistage fracturing completion is realized. The fracturing string has a small drift diameter and a strong liquid-carrying capacity after fracturing, which can effectively meet the production of gas wells with a certain quantity of water produced. 	<ol style="list-style-type: none"> Fracturing completion is done safely and efficiently in one trip. The number of stages is not limited by the process, and multistage fracturing completion can be achieved satisfactorily. No perforation is required, saving time and cost. Sand plugging can be detected in advance, and large-scale fracturing can be realized. Coiled tubing is used, making flowback easier. The fracturing and production string is adopted with large diameter, which is convenient for subsequent treatment. Any sand plugging can be removed immediately by circulation. 	<ol style="list-style-type: none"> Intervals are isolated reliably. The number of stages is not limited by the process, and multistage fracturing completion can be achieved satisfactorily. Coiled tubing is used, making flowback easier. The string has a large diameter, which is convenient for subsequent treatment. Fixed-point fracture initiation is realized by perforation, and fracture placement and fracturing position are accurate. Large displacement, large fluid volume, and multi-cluster perforating volume fracturing can be realized. Any sand plugging can be removed immediately by circulation.

Table 1. Cont.

Technology	CT with BOT Packer Hydra-Jet	Fixed-String Hydra-Jet	OH Packer and Ball-Activated Sliding Sleeve	Infinite Sliding Sleeve (Infinite Cementing Sleeve and OH Packer and Infinite Sliding Sleeve)	Perf-and-Plug
Disadvantages	<ol style="list-style-type: none"> 1. The string will be moved, operation time is long, and damage to the reservoir may be caused by well killing. 2. A wellhead with snubbing units is required, or the wellhead working pressure needs to be high. 3. Simple fractures are created, and the scale of fracturing is limited. 4. Application in deep formations is limited. 	<ol style="list-style-type: none"> 1. High requirements for borehole trajectory, etc. 2. Simple fractures are created, and the scale of fracturing is limited. It cannot create complex fractures. 	<ol style="list-style-type: none"> 1. High requirements for open-hole packer and well trajectory. 2. To prevent sand plugging, the fracturing scale is small, and there are few emergency plans for sand plugging. 3. The number of fracturing stages is limited by borehole size. 4. The displacement is limited by the opening differential pressure of the ball seat. 	<ol style="list-style-type: none"> 1. There is a risk that the production casing cannot be run to the design position, and the fracturing sliding sleeves cannot be aligned with the corresponding fracturing section. 2. Coiled tubing is used, and there are high requirements for the performance of the tool string and packers. 	<ol style="list-style-type: none"> 1. It is not suitable for open holes. 2. Multiple trips of coiled tubing lead to high operation cost. 3. Unproductive clusters and poor perf cluster efficiency. 4. Excess fluid volumes and over-displacement. 5. Time-consuming. 6. Operational risk.

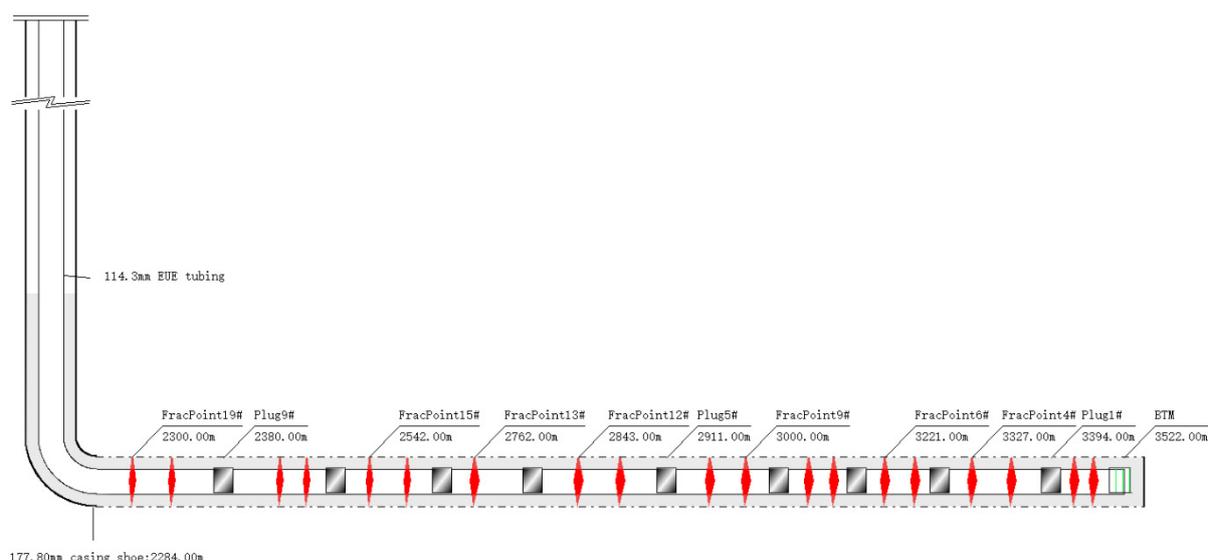


Figure 6. Schematic of perf-and-plug multistage fracturing completion string.

3. Application

3.1. Block Profile

Block M, located in the transitional zone between the Yi-Shaan slope and Western Shanxi flexural fold belt in the Ordos Basin, is a wide and gentle regional west-dipping monocline, with simple structure and undeveloped faults. It is a constant-volume elastic-drive tight gas accumulation controlled by lithology and physical properties under the local tectonic setting. The block covers an area of 1524.34 km², with proven reserves of 127.57 billion cubic meters. The main pay zones are S2, S1, and H8, with a superimposed gas-bearing area of 929 km² and an average reserve abundance of 137 million m³/km². The horizontal wells in this block have no natural productivity and require fracturing to obtain commercial gas flow. The block is a typical low-permeability tight sandstone gas reservoir.

Block M was put into production in March 2014, predominantly by horizontal wells (contributing more than 90% of the total output). Trial production has been carried out in H8, S1, and BX, while horizontal wells are mainly used to develop S2. The S2 reservoir has a good continuity, connectivity, and stable distribution. The buried depth is 2330 m, the average formation pressure is 20.53 MPa, the reservoir temperature is 67.6 °C, the reservoir thickness is 5–25 m, and the average effective thickness is 9.9 m. The porosity is 3.0–12.4%, with an average of 6.8% and a median range of 4–10%. The permeability ranges from 0.1 to 1.2 × 10^{−3} μm², with an average of 0.47 × 10^{−3} μm². The clay is mainly composed of kaolinite/illite (K/I), with a high content of kaolinite. The microseismic results show that the fractures mainly strike between 75° and 90°. The interpretation results of the dipole array acoustic logging infer that the direction of the maximum principal stress of the formation is nearly NE–SW, which is basically consistent with the microseismic results. According to logging calculation, the Young's modulus is 2.0–2.8 × 10⁴ MPa, the Poisson's ratio is 0.15–0.22, and the fracture pressure gradient and closure pressure gradient are 0.018–0.022 MPa/m.

Block M is adjacent to the Sulige and Zizhou gas fields in the Ordos Basin. It is highly representative for reservoir conditions or development mode. Table 2 compares the parameters between Block M and adjacent blocks.

Table 2. Comparison of parameters between Block M and adjacent blocks in Ordos Basin.

Item	Block M	Yulin Gas Field	Zizhou Gas Field	Sulige Gas Field	Shenmu Gas Field
Trap type	Lithologic/ stratigraphic	Lithologic/ stratigraphic	Lithologic/ stratigraphic	Lithologic/ stratigraphic	Lithologic/ stratigraphic
Structural location	Transition zone between the Western Shanxi flexural fold belt and the Yi-Shaan slope	Yi-Shaan slope	Yi-Shaan slope	Yi-Shaan slope	Yi-Shaan slope
Structural characteristics	West-dipping monocline	West-dipping monocline	West-dipping monocline	West-dipping monocline	West-dipping monocline
Stratum name	Shanxi Formation	Shanxi Formation	Shanxi Formation	Shanxi Formation, Shihezi Formation	Shanxi Formation, Taiyuan Formation
Sedimentary environment	Delta facies	Fluvial facies	Delta facies	Fluvial/delta facies	Fluvial/delta facies
Rock type	Quartz and lithic quartz sandstone	Quartz and lithic quartz sandstone	Quartz and lithic quartz sandstone	Quartz and lithic quartz sandstone	Quartz and lithic quartz sandstone
Effective thickness (m)	9.9	12.3	7.2	7.5	22.4
Porosity (%)	6.8	6.2	6.7	6.9	6.5
Permeability ($10^{-3} \mu\text{m}^2$)	0.47	4.8	1.1	0.52	0.51
Gas saturation (%)	68.5	78.1	70.1	53.2	54.5
Mid-reservoir depth (m)	2330	2950	2700	3000	2900
Formation static pressure (MPa)	20.53	27.5	23.7	30.1	22.1

3.2. Application Effect

Six multistage fracturing technologies were attempted, namely, CT with bottom packer hydra-jet, fixed-string hydra-jet, OH packer and ball-activated sliding sleeve, OH packer and infinite sliding sleeve, infinite cementing sliding sleeve, and perf-and-plug.

The fractured horizontal wells studied in this paper were all located in the enrichment zone of S2 in Block M, as shown in Figure 7, with similar physical properties and fluid properties. Table 3 shows the parameters of the 24 wells that have been producing for more than 1 year without engineering failures.

As seen from Table 3, the net fracturing fluid volume injected was 1896.0–8698.0 m³, the displacement was 2.5–7.5 m³/min, the number of fracturing stages was 5–16, and the total sand addition was 188.5–960.3 m³, suggesting greatly variable ranges for different horizontal wells. It can be inferred that the parameters were similar for the same fracturing technology, but different among fracturing processes. As shown in Table 4, the scales of perf-and-plug multistage fracturing and infinite sliding sleeve multistage fracturing (infinite cementing sleeve and OH packer and infinite sliding sleeve) were large, while the displacement, total sand addition, and total fracturing fluid volume injected of fixed-string hydra-jet multistage fracturing were significantly lower than those of other technologies.

On the basis of the historical production data and the single-well completion fracturing cost, the production performances of fractured horizontal wells were preliminarily compared to explore whether fracturing technologies significantly enhanced the well production.

3.2.1. Production Comparison

The annual average daily gas production (annual cumulative gas production divided by production days) was used to measure the production of each fractured horizontal well, as shown in Figure 8.

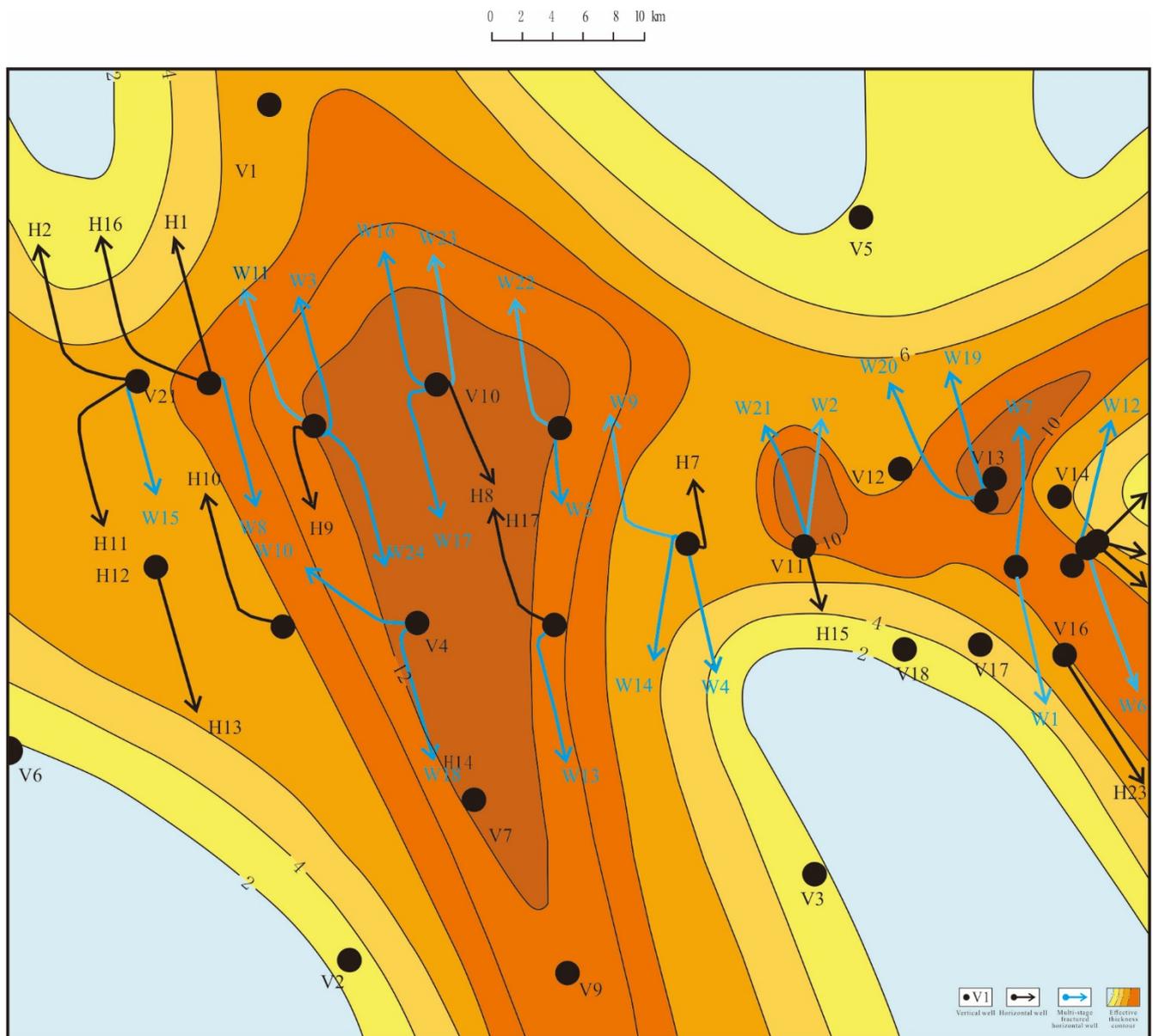


Figure 7. Effective thickness contour and well location map of the enrichment area, S2 formation, Block M.

Table 3. Parameters of multistage fractured horizontal wells.

No.	Well	Multistage Fracturing Technology	OD of Production Casing (mm)	Number of Fracturing Stages	Net Fracturing Fluid Volume Injected (m ³)	Displacement (m ³ /min)	Total Sand Addition (m ³)	Average Sand Ratio (%)	Cumulative Liquid Production (m ³)	Flowback Rate (%)
1	W1	CT with BOT packer Hydra-jet	114.30	13	5839.5	3.5–4.2	619.8	16.6	1753.0	30.0
2	W2	CT with BOT packer Hydra-jet	114.30	11	6435.0	3.3–3.9	587.1	18.4	1818.0	30.0
3	W3	CT with BOT packer Hydra-jet	114.30	12	3768.4	2.5–3.9	508.5	21.1	887.5	23.0
4	W4	Fixed-string Hydra-jet	88.90	7	2932.6	2.4–2.6	360.6	16.3	1021.5	34.8
5	W5	Fixed-string Hydra-jet	88.90	5	1896.0	2.4–2.6	188.5	16.0	454.0	23.9
6	W6	OH packer and ball-activated sliding sleeve	88.90	6	3539.5	3.4–5.0	387.7	15.2	2020.0	56.0

Table 3. Cont.

No.	Well	Multistage Fracturing Technology	OD of Production Casing (mm)	Number of Fracturing Stages	Net Fracturing Fluid Volume Injected (m ³)	Displacement (m ³ /min)	Total Sand Addition (m ³)	Average Sand Ratio (%)	Cumulative Liquid Production (m ³)	Flowback Rate (%)
7	W7	OH packer and ball-activated sliding sleeve	88.90	9	3810.7	3.5–5.5	478.6	16.5	2090.0	53.0
8	W8	OH packer and ball-activated sliding sleeve	88.90	11	4725.1	4.6–6.0	543.0	19.7	918.0	19.4
9	W9	OH packer and ball-activated sliding sleeve	88.90	10	3257.7	4.6–5.7	436.2	18.2	460.6	14.0
10	W10	OH packer and ball-activated sliding sleeve	88.90	9	3249.0	5.0–5.7	407.7	17.5	1401.3	43.0
11	W11	OH packer and ball-activated sliding sleeve	88.90	12	5129.5	5.0–5.8	603.3	18.6	1480.0	29.0
12	W12	OH packer and ball-activated sliding sleeve	88.90	8	4775.9	4.5–5.6	578.4	17.9	1127.0	23.6
13	W13	OH packer and ball-activated sliding sleeve	88.90	10	3872.4	4.5–5.5	324.4	15.4	310.0	8.0
14	W14	OH packer and infinite sliding sleeve	114.30	14	5997.1	3.4–3.9	713.6	20.5	2040.0	33.0
15	W15	OH packer and infinite sliding sleeve	114.30	13	5825.8	3.2–4.0	680.2	18.5	1661.0	28.0
16	W16	OH packer and infinite sliding sleeve	114.30	16	7261.8	3.0–3.9	960.3	22.1	995.0	13.0
17	W17	OH packer and infinite sliding sleeve	114.30	13	5872.6	2.7–3.8	830.0	21.4	1518.0	26.0
18	W18	OH packer and infinite sliding sleeve	114.30	12	5139.3	3.4–3.9	766.0	22.6	1130.0	22.0
19	W19	Infinite cementing sliding sleeve	114.30	15	5897.5	3.4–3.9	434.6	18.6	1264.0	20.0
20	W20	Infinite cementing sliding sleeve	114.30	15	5209.5	3.9–4.2	510.3	19.4	1127.0	21.0
21	W21	Infinite cementing sliding sleeve	114.30	16	5409.4	3.0–5.0	383.2	18.4	1818.0	33.0
22	W22	Perf-and-plug	114.30	10	7154.0	4.0–7.0	765.5	18.8	1458.0	21.0
23	W23	Perf-and-plug	114.30	10	6377.9	3.0–7.0	798.8	19.0	1732.0	27.0
24	W24	Perf-and-plug	114.30	12	8698.0	3.5–7.5	730.2	19.5	800.0	9.2

Table 4. Parameters of horizontal well multistage fracturing technologies.

Multistage Fracturing Technology	Number of Producing Wells	OD of Production Casing (mm)	Number of Fracturing Stages	Net Fracturing Fluid Volume Injected (m ³)	Displacement (m ³ /min)	Total Sand Addition (m ³)	Average Sand Ratio (%)	Liquid Production (m ³)
CT with BOT packer hydra-jet	3	114.30	12	5347.6	3.6	571.8	18.7	1486.2
Fixed-string hydra-jet	2	88.90	6	2414.3	2.5	274.6	16.2	737.8
OH packer and ball-activated sliding sleeve	8	88.90	9	4045.0	5.0	469.9	17.4	1225.9
OH packer and infinite sliding sleeve	5	114.30	14	6019.3	3.5	790.0	21.0	1468.8
Infinite cementing sliding sleeve	3	114.30	15	5505.5	3.9	442.7	18.8	1403.0
Perf-and-plug	3	114.30	11	7410.0	5.3	764.8	19.1	1330.0

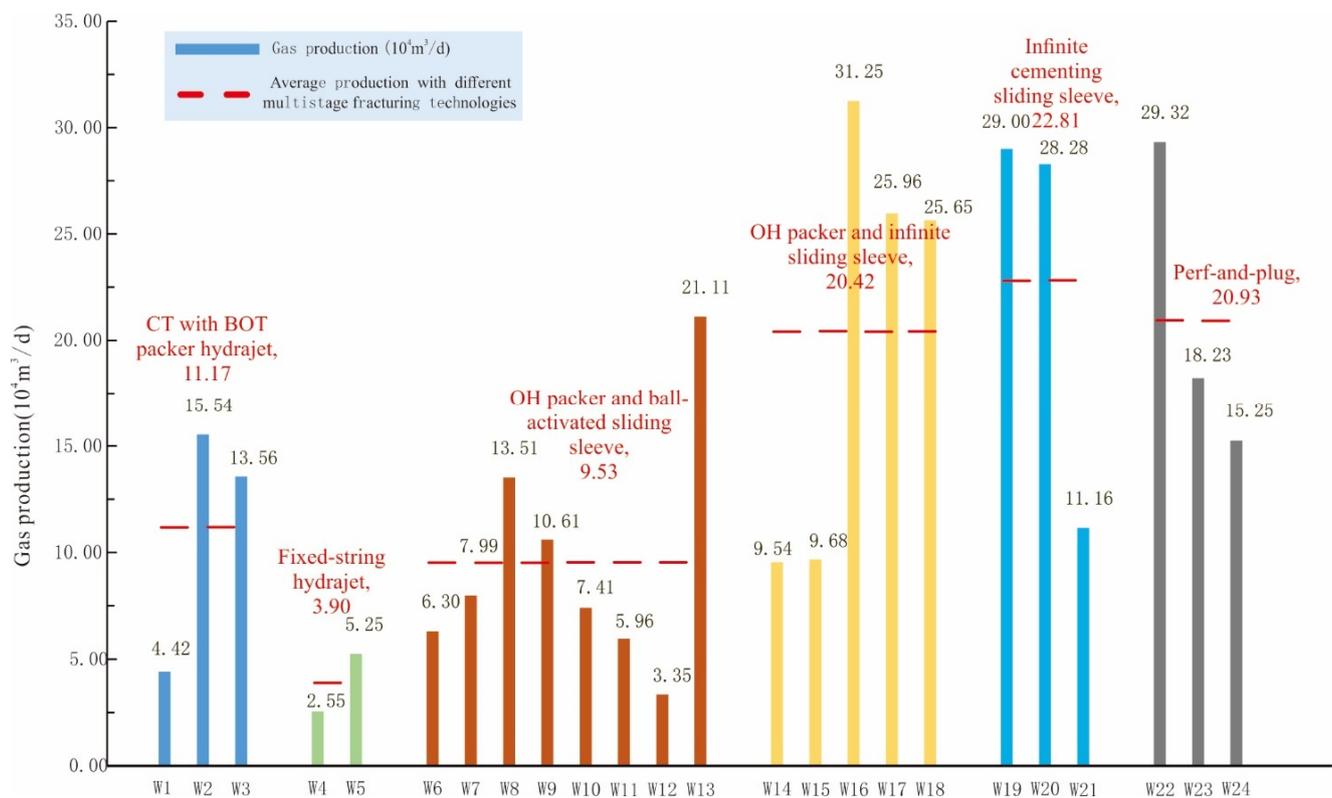


Figure 8. Production of horizontal wells with different multistage fracturing technologies.

It can be seen intuitively from Figure 8 that the annual average daily gas production was $2.55\text{--}31.25 \times 10^4 \text{ m}^3$, and it was significantly different from well to well. When neglecting the influence of geological reservoir parameters of horizontal wells, infinite cementing sliding sleeve multistage fracturing exhibited the best performance, followed by perf-and-plug multistage fracturing and OH packer and infinite sliding sleeve multistage fracturing, while CT with BOT packer hydra-jet multistage fracturing and fixed-string hydra-jet multistage fracturing demonstrated relatively poor effects.

3.2.2. Economic Benefits

To evaluate the economics of each fracturing technology, the average payback periods for fracturing technologies were calculated according to the actual completion fracturing costs and cumulative gas productions of wells. The results are shown in Figure 9.

It can be seen from Figure 9 that the payback periods of perf-and-plug, infinite cementing sliding sleeve, and OH packer and infinite sliding sleeve multistage fracturing were similar, about 30–35 days, while the payback periods of CT with BOT packer hydra-jet and fixed-string Hydra-jet multistage fracturing were longer, about 74–97 days.

In summary, the multistage fracturing technologies of horizontal wells significantly affected the production and benefits of wells. When neglecting the influence of geological reservoir parameters of horizontal wells, from the aspects of production increase and return on investment, it can be concluded that the infinite sliding sleeve multistage fracturing (cemented and OH) and perf-and-plug had good application effects, while fixed-string hydra-jet multistage fracturing had the worst performance.

Preliminary analysis of the production data revealed that, as stated in most previous studies, there were indeed large differences in the production of horizontal wells completed with different methods. However, the impact of open hole or cementing completion on the performance in this area was much smaller than expected, suggesting that production may be influenced by factors other than completion method.

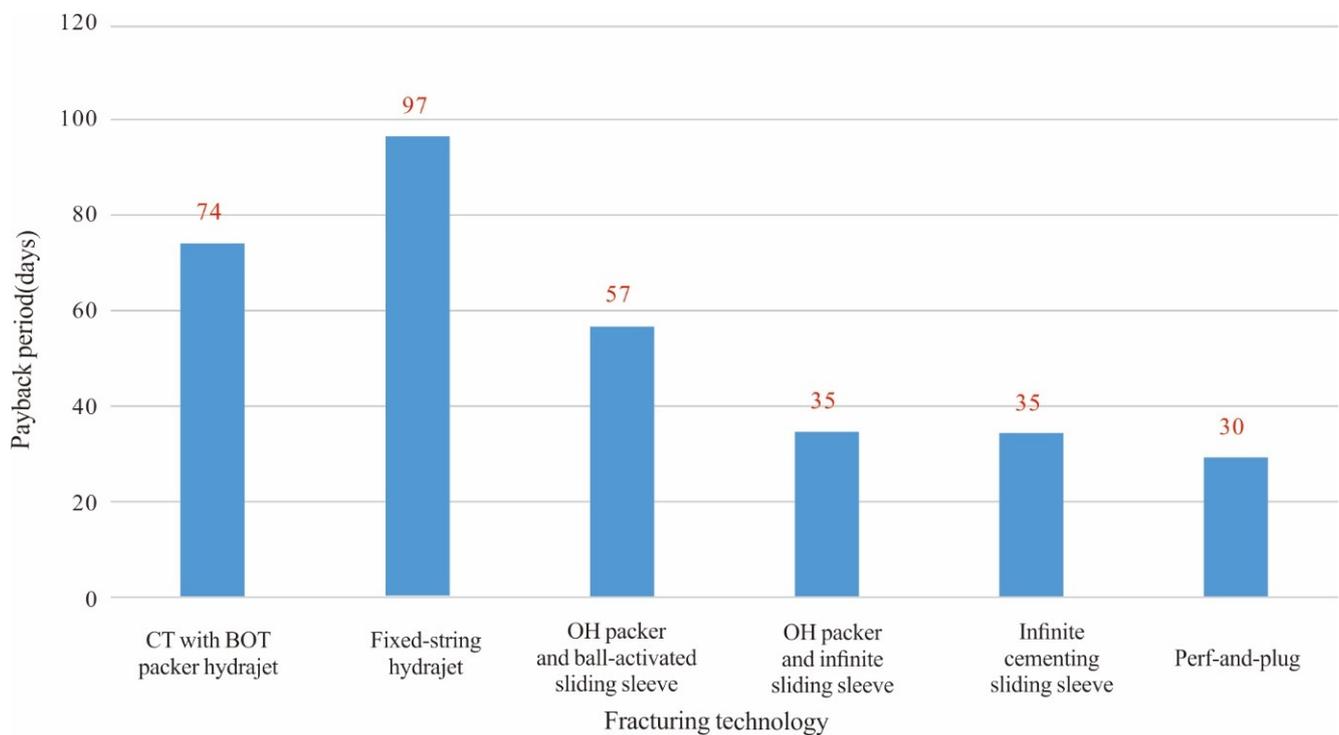


Figure 9. Payback periods for horizontal well multistage fracturing technologies.

4. Analysis of Reasons for Performance Difference

The reliability of the above conclusions needed to be further demonstrated, since they were derived from comparative analysis without consideration of the geological reservoir conditions of wells. It can be seen from Figure 8 that the same fracturing technology exhibited significantly different performance from well to well. Taking W19, W20, and W21 as examples, given the same fracturing technology and similar parameters, the production performance of W21 was much worse than that of W19 and W20. This indicates that the well production is comprehensively influenced by factors other than fracturing technology.

4.1. Main Factors Controlling the Productivity of Fractured Horizontal Wells

The gas flow regime of fractured horizontal wells is complex–turbulent flow occurring near the wellbore, which is also known as a non-Darcy flow. Due to the presence of fractures, the coupling effects between fractures and the wellbore result in a very complicated seepage. Therefore, the productivity of fractured horizontal wells is always difficult to calculate. In this paper, the most typical horizontal well productivity calculation formula, Joshi’s formula, was implemented [58]. Firstly, the steady-state productivity formula of horizontal wells in homogeneous and isotropic reservoirs was derived according to the potential energy theory. Then, to consider the influence of the eccentricity of actual horizontal wells and the anisotropy of reservoirs, the modified Joshi’s formula was established as Equation (1):

$$J_h = \frac{0.543K_h h \Delta P / (B_0 \mu)}{\ln \left[\frac{a + \sqrt{a^2 - (L/2)^2}}{L/2} + \frac{\beta h}{L} \ln \left[\frac{(\frac{\beta h}{2})^2 + (\beta \delta)^2}{\frac{\beta h r_w}{2}} \right] \right]} \quad (1)$$

where K_h is the permeability of horizontal section ($10^{-3} \mu\text{m}^2$), h is the oil zone thickness (m), ΔP is the production pressure difference (MPa), B_0 is the oil volume factor (m^3/m^3), μ is the oil viscosity (mPa·s), L is the horizontal section length (m), a is the half length of the elliptical major axis, defined as $a = 0.5L \left[0.5 + \sqrt{0.25 + \left(\frac{2r_{eh}}{L} \right)^4} \right]^{0.5}$ (m), r_{eh} is the quasi-circular driving radius (m), β is the reservoir anisotropy coefficient, defined as $\beta = \sqrt{K_h/K_v}$, δ is the eccentricity of the horizontal wellbore (m), and r_w is the borehole radius (m).

According to Equation (1), the productivity of horizontal wells is jointly controlled by many factors, such as the length of the horizontal section, oil zone thickness, drainage radius, production pressure difference, oil viscosity, and permeability, but there is often no good correlation between a single factor and productivity. For horizontal wells in low-permeability and tight sandstone gas reservoirs, which are generally treated by large-scale fracturing, the gas drainage radius and fluidity are significantly affected by completion technology and fracturing scale. Therefore, it is proposed to construct a comprehensive productivity impact index (CPII) to explore the relationship between the production of horizontal wells and the geological, engineering, and development factors [59–61].

This study dealt with 24 horizontal wells in S2 of Block M, which are basically similar in terms of original permeability, oil viscosity, and volume factor. To construct the CPII, a total of 11 indicative parameters (Table 5) were considered to meet Joshi's formula. Specifically, horizontal section length, encountering rate of net pay zone, reservoir thickness, nozzle size, bottomhole static pressure, and tubing pressure represent the geological and development factors, while the OD of production casing represents the borehole radius. Moreover, parameters such as the number of fracturing stages, displacement, and sand addition are used to characterize the effects of fracturing stimulation on drainage radius, induced fractures, and permeability.

The comprehensive productivity impact index (CPII) was constructed in three steps: (1) standardize the original data; (2) use the entropy method to calculate the weight of each indicator; (3) calculate the CPII from the comprehensive evaluation formula.

4.1.1. Data Processing

The range method was used for data standardization to ensure the uniformity of data. The standardization formula see Equations (2) and (3).

For positive indicators, use Equation (2).

$$Y_i(j) = \frac{X_i(j) - \min X_i(j)}{\max X_i(j) - \min X_i(j)} \quad (2)$$

For negative indicators, use Equation (3).

$$Y_i(j) = \frac{\max X_i(j) - X_i(j)}{\max X_i(j) - \min X_i(j)} \quad (3)$$

where j represents the well number, i represents the indicator layer, $X_i(j)$ represents the original value of indicator i of well j , and $Y_i(j)$ represents the standardized value of indicator i of well j . Since the interval of the standardized data is $[0, 1]$, the standardized data are possibly equal to 0. Considering that the logarithm is introduced into the subsequent calculation using the entropy method, the standardized data were shifted by 0.5 unit.

4.1.2. Determination of Weights

Weights can be determined using many methods. Gray correlation, principal component analysis (PCA), analytic hierarchy process (AHP), and expert scoring were mainly used in reservoir engineering studies, which, however, are too subjective, with the optimal values of some indicators difficult to define and the results nonobjective enough.

Table 5. Indicative parameters of CPII for horizontal wells.

Well	Geological Factors				Engineering Factors				Development Factors		
	Horizontal Section Length (m)	Encountering Rate of Net Pay Zone (%)	Reservoir Thickness (m)	OD. of Production Casing (mm)	Number of Fracturing Stages	Net Fracturing Fluid Volume Injected (m ³)	Displacement (m ³ /min)	Total Sand Addition (m ³)	Nozzle Size (mm)	Bottom Hole Static Pressure (MPa)	Initial Tubing Pressure (MPa)
W1	1173.0	65.0	4.5	114.3	13	5839.5	3.9	619.8	16	15.6	3.9
W2	1156.3	61.5	7.5	114.3	11	6435.0	3.6	587.1	10	20.0	11.1
W3	1175.1	35.3	9.5	114.3	12	3768.4	3.2	508.5	10	22.5	16.3
W4	933.0	73.7	4.0	88.90	7	2932.6	2.5	360.6	14	15.1	9.6
W5	652.0	73.2	10.0	88.90	5	1896.0	2.5	188.5	14	21.0	12.1
W6	1181.7	42.1	8.0	88.90	6	3539.5	4.2	387.7	10	18.5	5.9
W7	1188.9	42.8	8.0	88.90	9	3810.7	4.5	478.6	10	16.6	8.1
W8	1399.5	34.9	8.0	88.90	11	4725.1	5.3	543.0	10	16.9	10.5
W9	1349.2	60.0	8.0	88.90	10	3257.7	5.2	436.2	12	17.4	8.6
W10	1329.9	61.4	8.0	88.90	9	3249.0	5.4	407.7	10	17.5	6.8
W11	1336.5	58.2	8.0	88.90	12	5129.5	5.4	603.3	12	18.0	7.3
W12	1068.0	75.0	5.0	88.90	8	4775.9	5.1	578.4	12	16.2	2.3
W13	1200.0	90.0	12.0	88.90	10	3872.4	5.0	324.4	14	22.9	16.9
W14	1081.0	61.3	6.5	114.3	14	5997.1	3.7	713.6	14	19.1	9.5
W15	969.0	39.0	6.5	114.3	13	5825.8	3.6	680.2	14	21.1	8.9
W16	1245.6	80.0	11.0	114.3	16	7261.8	3.5	960.3	10	22.9	17.0
W17	1211.9	51.3	12.0	114.3	13	5872.6	3.3	830.0	16	23.2	16.8
W18	897.5	61.4	9.5	114.3	12	5139.3	3.7	766.0	16	22.7	17.3
W19	1192.4	64.6	8.0	114.3	15	5897.5	3.7	434.6	16	19.6	13.0
W20	1193.2	72.4	8.0	114.3	15	5209.5	4.1	510.3	10	20.9	13.1
W21	1222.5	50.2	8.0	114.3	16	5409.4	4.0	383.2	12	20.3	9.2
W22	1229.7	61.5	9.5	114.3	10	7154.0	5.5	765.5	16	22.5	17.8
W23	1200.7	58.9	10.0	114.3	10	6377.9	5.0	798.8	16	22.3	16.3
W24	834.0	67.9	11.0	114.3	12	8698.0	5.5	730.2	14	20.0	7.4

In this paper, the entropy method was adopted to determine the weight of each indicator. Entropy, a concept derived in thermodynamics, is used to measure the uncertainty of the system state. Information is a measure of the order degree of a system, while entropy is a measure of the disorder degree of a system, in information theory. The two are equal in absolute value but opposite in sign. Entropy is a measure of uncertainty. A smaller entropy denotes a lower disorder degree of information, less uncertainty, a larger utility value of information, and a larger weight of the indicator. The entropy method is an objective weighting approach because it only considers the discreteness of the data itself.

The entropy method is critical to determine the weights of indicators. The weight of each indicator can be calculated to provide a basis for comprehensive evaluation of indicators. The calculation process and formula are as follows:

- (1) On the basis of the above standardized data, calculate the proportion of indicator i using Equation (4).

$$Z_i(j) = \frac{Y_i(j)}{\sum_{i=1}^n Y_i(j)} \quad (4)$$

- (2) According to Equation (5), calculate the information entropy of each indicator.

$$E_i = - \frac{\sum_{i=1}^n \sum_{j=1}^m Z_i(j) \ln Z_i(j)}{\ln nm} \quad (5)$$

- (3) Determine the weight of indicator i of CPII using Equation (6).

$$W_i = \frac{1 - E_i}{\sum_{j=1}^m (1 - E_i)} \quad (6)$$

The original data of the 24 fractured horizontal wells shown in Table 4 were processed using the entropy method, and the weights of the indicators were determined, as shown in Table 6 and Figure 10.

Table 6. Weights of CPII indicators for fractured horizontal wells.

Level-1 Indicator	Level-2 Indicator	Level-3 Indicator	Weight of Level-3 Indicator
Comprehensive productivity impact index (CPII)	Geological factors	Horizontal section length, m	0.21
		Encountering rate of net pay zone, %	0.03
			Reservoir thickness, m
	Engineering factors	OD of production casing, mm	0.07
		Number of fracturing stages	0.12
		Net fracturing fluid volume injected, m ³	0.04
		Average displacement, m ³	0.12
		Total sand addition, m ³	0.06
	Development factors	Nozzle size, mm	0.01
		Bottomhole static pressure, MPa	0.11
		Initial tubing pressure, MPa	0.12

From Table 6 and Figure 10, it can be seen that the productivity of fractured horizontal wells is comprehensively controlled by multiple indicators of geological, development, and engineering factors. In terms of Level-3 indicators, horizontal section length, initial tubing pressure, displacement, number of fracturing stages, bottomhole static pressure, and reservoir thickness exhibited the largest weights.

This result is basically consistent with previous studies, which means it is reasonable to select impact indicators using a theoretical formula (Joshi's formula, See Equation (1)). Unlike the previous study, which was only a qualitative analysis of a few indicators, this study used entropy quantification to obtain the weights of each impact indicator.

Meanwhile, the method to calculate indicator weights is objective, making it easy to apply to other reservoirs

4.2. Cause Analysis for Performance Difference

In terms of engineering factors, displacement and the number of fracturing stages had the greatest weights. Previous studies showed that large displacements and fracturing stages can only be achieved by perf-and-plug and the new open-hole multistage hydraulic fracturing system [50]. The actual fracturing parameters of the six fracturing technologies of 24 wells in Block M indicated that displacement and number of fracturing stages were largely dependent on fracturing technology. Moreover, it can be seen from Figure 11 that the difference in well production was consistent with the difference in parameters of horizontal wells. This suggests that the fracturing technology largely determined the ranges of parameters, which in turn affected the fracturing performance and well production. Therefore, the key step for successful horizontal well fracturing is the selection of fracturing technology.

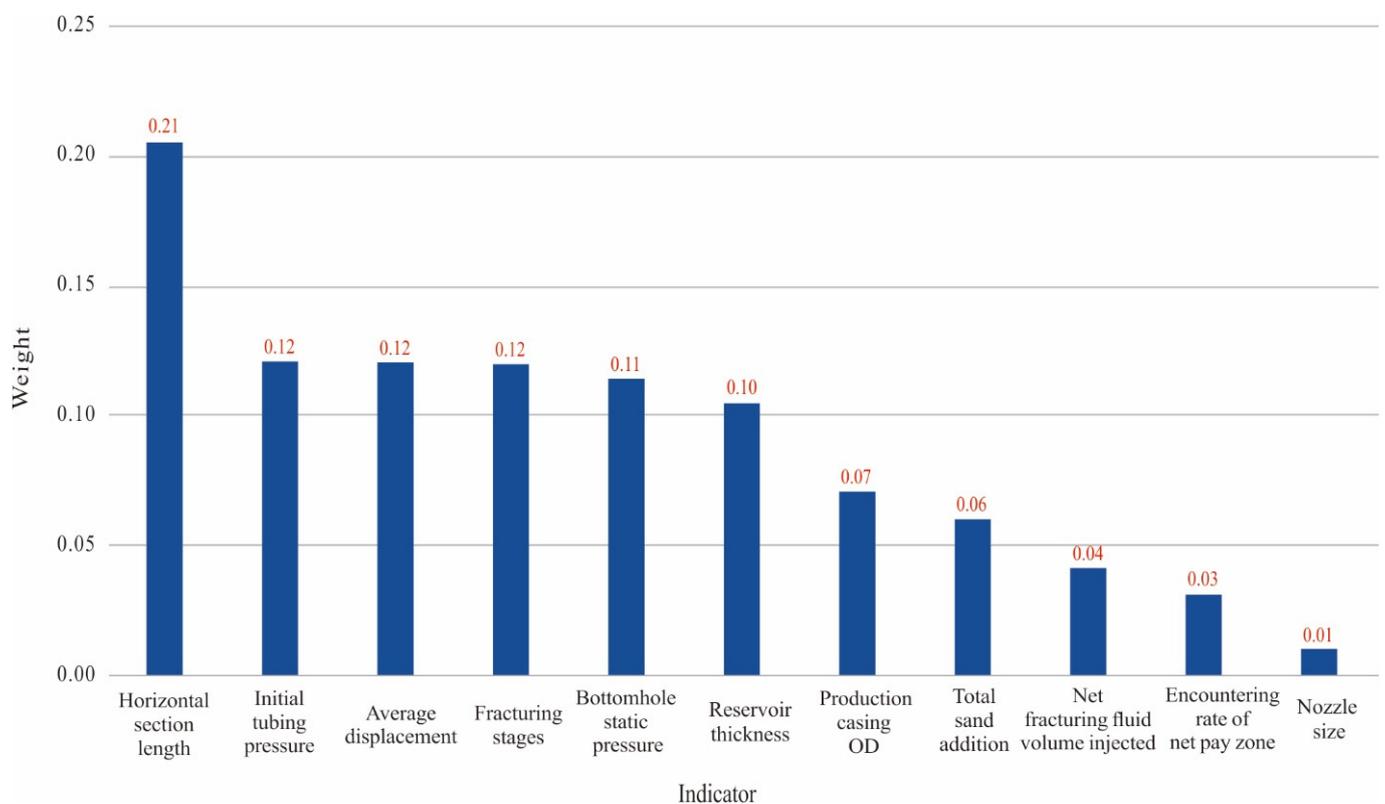


Figure 10. Weights of CPII indicators for fractured horizontal wells.

In terms of development factors, initial tubing pressure and bottomhole static pressure had the greatest weights. Reservoir pressure is an important factor affecting production, as mentioned by many scholars (Hamm and Struyk, Chaikine et al.). The production data of horizontal wells in this block also confirmed the significant impact of formation pressure. The section above described the difference in performance of the same fracturing technology among wells, such as W19, W20, and W21. According to statistics, the horizontal wells in this study were all located in the enrichment zone of S2, with similar bottomhole static pressure (15.07–23.16 MPa), but greatly variable initial tubing pressure (2.28–17.76 MPa). Typically, W19, W20, and W21 had similar horizontal section lengths and reservoir thicknesses, and they adopted the same fracturing technology, but their tubing pressures were quite different: only 9.22 MPa for W21, in contrast to about 13 MPa for W19 and W20. The production of W21 was also much lower than that of W19 and W20. Similarly, due to the influence of tubing pressure, the production performance of W24

(tubing pressure of 7.43 MPa) was far lower than that of W22 and W23 (tubing pressure of 16.31–17.76 MPa), as shown in Table 5. These cases demonstrated the reliability of the computation results of the entropy method, revealing pressure as an important factor that significantly affects the well production.

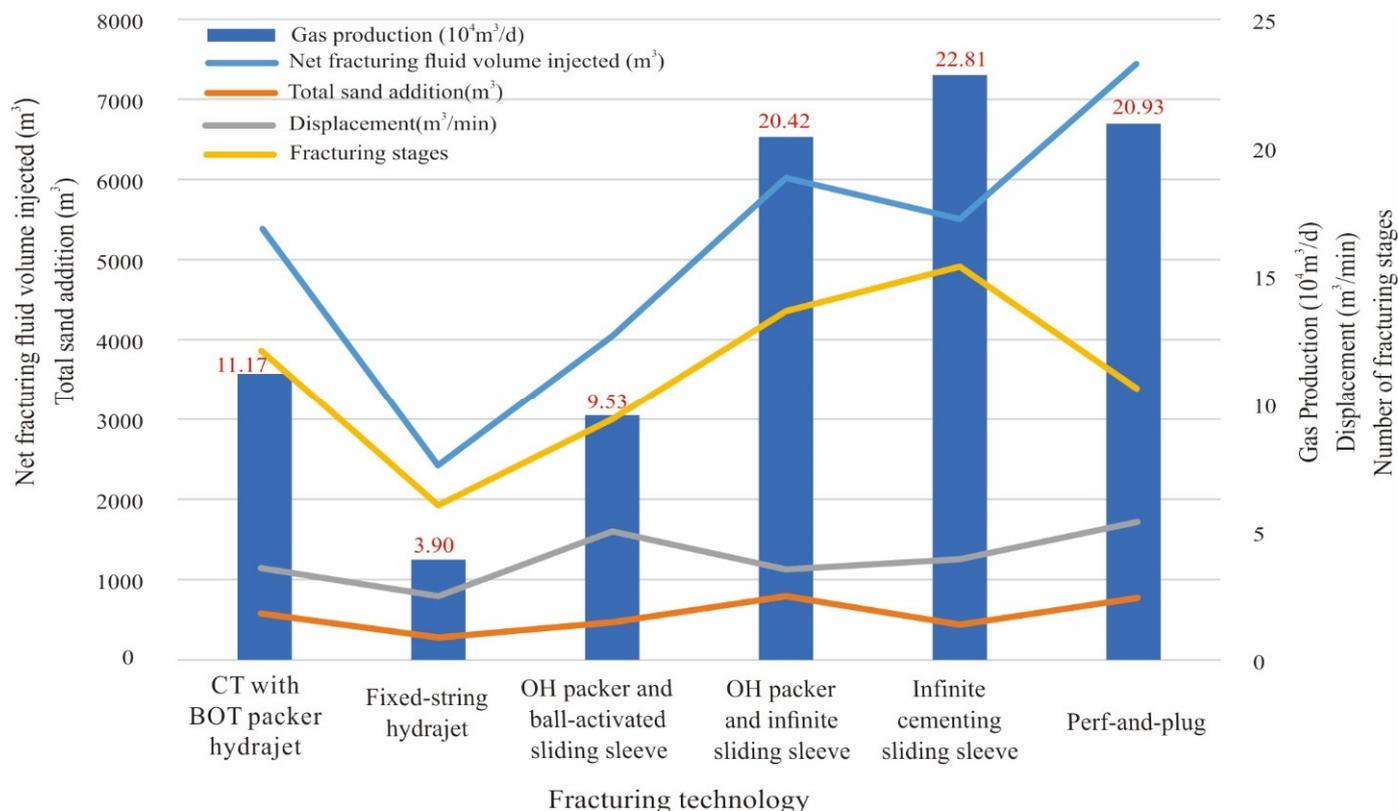


Figure 11. Well production and parameters according to multistage fracturing technologies.

In terms of geological factors, horizontal section length and reservoir thickness had the greatest weights. Analytical results noted that wells in different areas seemed to benefit from a longer overall length and reservoir thickness (Omatson, Galas, et al.). In Block M, most of the wells had basically similar horizontal section length, ranging from 652 m to 1399 m. However, the reservoir thickness varied greatly, ranging from 4 to 4–12 m. For W4 and W5, given the similarity of other parameters, the reservoir thickness was only 4 m in W4 and 10 m in W5, resulting in lower production of W4 than W5. Meanwhile, fixed-string hydra-jet multistage fracturing was adopted in both wells, with horizontal section lengths of 652 m and 933 m, respectively, which were relatively small in this block. It was, thus, inferred that the actual performance of fixed-string hydra-jet multistage fracturing should be better than the recorded data of the above two wells, although it is less applicable to Block M than other technologies, due to the limitation of displacement and number of fracturing stages.

Furthermore, field data confirmed that the well production is more affected by a comprehensive influence of multiple factors; the productivity index ratio is a function of variables including reservoir permeability, reservoir thickness, fracture half-length, fracture spacing along the horizontal, and completion method [19]. For example, the production difference between W1 and W2/W3 was greatly dependent on tubing pressure and reservoir thickness. The production of W1 (tubing pressure of 3.9 MPa, reservoir thickness of 4.5 m) was lower than that of W2 and W3 (tubing pressure of 11.1–16.3 MPa, reservoir thickness of 7.5–9.5 m). The production of W14 and W15 (tubing pressure of 8.9–9.5 MPa, reservoir thickness of 6.5 m) was lower than that of W16, W17, and W18 (tubing pressure of 16.3–17.8 MPa, reservoir thickness of 11–9.5 m). Similarly, due to the relatively small

horizontal section length (834 m) and low initial tubing pressure (7.4 MPa), W24 revealed lower production when using the perf-and-plug multistage fracturing technology, which was considered highly applicable to this block, than other wells adopting the same fracturing technology. In contrast, W13 had a large horizontal section length (1200 m) and high initial tubing pressure (16.9 MPa), but it achieved higher production than other wells, ranking among the top three fractured wells in terms of overall performance, although it adopted the open-hole packer and ball-activated sliding sleeve multistage fracturing, which features a small scale. This also proves from another aspect that the impact of fracturing technology on horizontal well production is restricted by the geological reservoir conditions of horizontal wells.

4.3. Comparison of Application Effects of Fracturing Technologies

The above analysis suggests that the conclusion drawn in Section 3.2 only by the classification of fracturing technologies but ignoring the influence of other factors is not accurate. To identify the influence of fracturing technologies on horizontal well production and their applicability in Block M, some Class I horizontal wells with similar horizontal section length, reservoir thickness, and pressure but adopting different fracturing technologies were selected for comparison, as shown in Table 7 and Figure 12.

From Table 7 and Figure 12, it can be seen that, for Class I horizontal wells, infinite sliding sleeve multistage fracturing exhibited the best performance, followed by perf-and-plug and traditional open-hole packer multistage fracturing, while CT with BOT packer hydra-jet showed poor performance. The performance of fixed-string hydra-jet technology needs to be further evaluated due to the lack of samples. This conclusion is basically in line with historical studies; that is, completion methods do have a significant impact on production. However, this study suggests a much smaller difference between open-hole and cemented completions than illustrated in previous articles. As mentioned above, the productivity of horizontal wells in this area was comprehensive affected by multiple factors, especially length of horizontal section, fracturing construction parameters, and reservoir pressure.

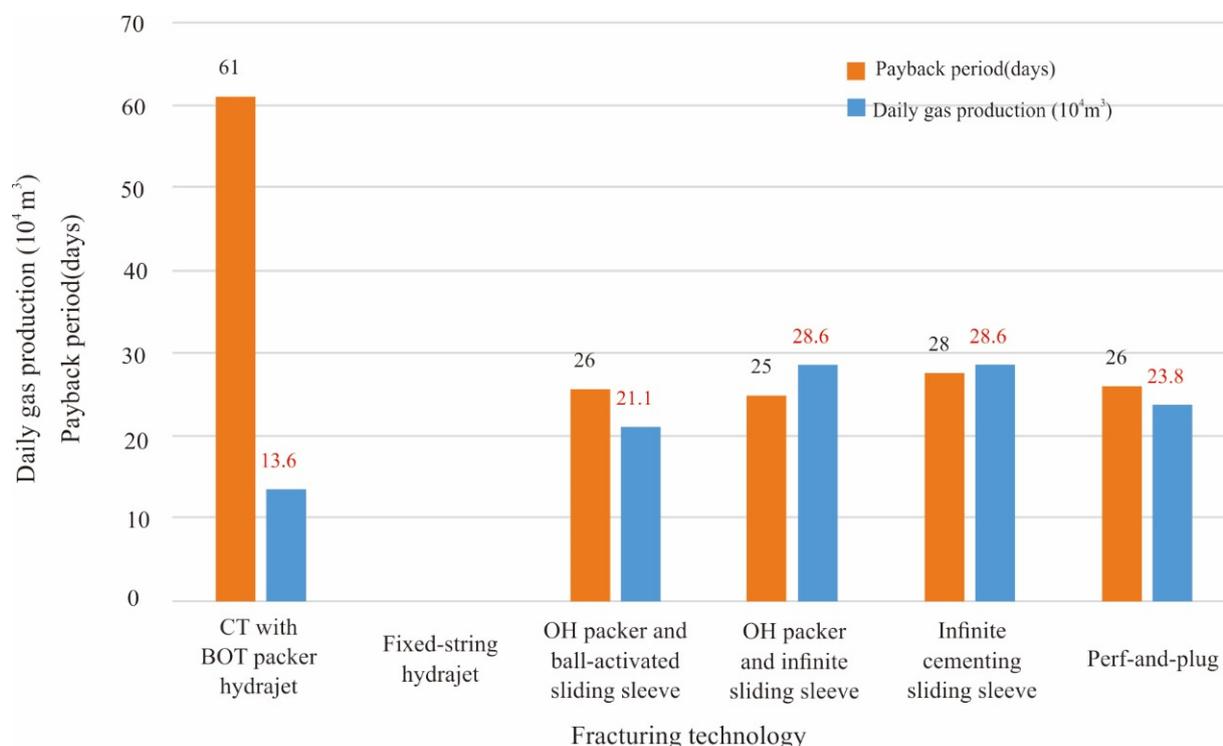


Figure 12. Production and payback period of Class I horizontal wells by multistage fracturing technology.

Table 7. Parameters and production of Class I horizontal wells in Block M.

Well	Horizontal Section Length (m)	Reservoir Thickness (m)	OD. of Production Casing (mm)	Multistage Fracturing Technology	Number of Fracturing Stages	Net Fracturing Fluid Volume Injected (m ³)	Displacement (m ³ /min)	Total Sand Addition (m ³)	Bottomhole Static Pressure (MPa)	Initial Tubing Pressure, (MPa)	Production (10 ⁴ m ³ /day)
W3	1175	9.5	114.3	CT with BOT packer Hydra-jet	12	3768.4	2.5–3.9	508.5	22.5	16.3	13.6
W13	1200	12.0	88.90	OH packer and ball-activated sliding sleeve	10	3872.4	4.5–5.5	324.4	22.9	16.9	21.1
W16	1246	11.0	114.3	OH packer and infinite sliding sleeve	16	7261.8	3.0–3.9	960.3	22.9	17.0	31.2
W17	1212	12.0	114.3	OH packer and infinite sliding sleeve	13	5872.6	2.7–3.8	830.0	23.2	16.8	26.0
W19	1192	8.0	114.3	Infinite cementing sliding sleeve	15	5897.5	3.4–3.9	434.6	19.6	13.0	29.0
W20	1193	8.0	114.3	Infinite cementing sliding sleeve	15	5209.5	3.9–4.2	510.3	20.9	13.1	28.3
W22	1230	9.5	114.3	Perf-and-plug	10	7154.0	4.0–7.0	765.5	22.5	17.8	29.3
W23	1201	10.0	114.3	Perf-and-plug	10	6377.9	3.0–7.0	798.8	22.3	16.3	18.2

5. Comprehensive Productivity Impact Index (CPII)

The results demonstrated that horizontal well production was affected by a combination of factors, but there is no method available to characterize this comprehensive index. In this paper, in order to explore the comprehensive impact of indicators on the production of horizontal wells, on the basis of the factors weights calculated above, a comprehensive productivity impact index (CPII) was constructed in Equation (7).

$$W_{ij} = \sum_{i=1}^n Y_i(j)W_i \quad (7)$$

The correlation between the production of the fractured horizontal well and CPII is plotted in Figure 13.

It can be seen from Figure 13 that the CPII constructed has a good positive correlation with the well production. Without considering the economic and technical constraints, a greater CPII denotes greater production of the fractured horizontal well. For a newly drilled horizontal well, where horizontal section length, reservoir thickness, and initial tubing pressure are given, the only way to improve well production is to optimize the fracturing technology. According to Figure 13 and the weight ranking of the three-level indicators mentioned above, it can be seen that the well production of horizontal wells can be increased as much as possible by increasing the number of fracturing stages and displacement. This also further demonstrates the reason why the infinite sliding sleeve multistage fracturing and perf-and-plug multistage fracturing technologies with unlimited fracturing stages and larger fracturing scale have relatively better performance in Block M.

Meanwhile, according to the curve matching relation between well production and CPII in Figure 13, the production of fractured horizontal wells in Block M can be roughly predicted by using Equation (8), so as to provide reference for selection of fracturing technology and optimization of parameters for fracturing design of new horizontal wells for the purpose of better fracturing performance and higher economic benefit of wells.

$$Q = 0.1532e^{4.0449W_{ij}} \quad (8)$$

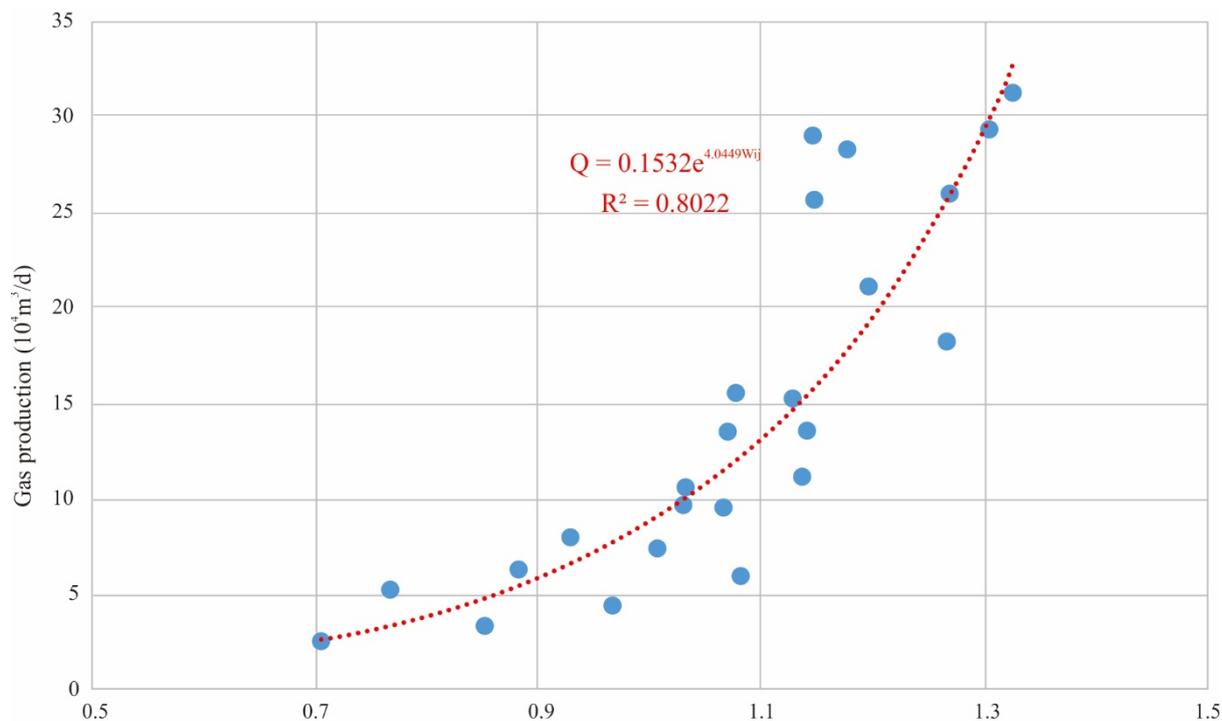


Figure 13. Well production vs. CPII.

6. Conclusions

The following conclusions can be drawn in this study:

- (1) All horizontal well multistage fracturing technologies can achieve the purpose of gas reservoir stimulation, production enhancement, and improved economics, but each technology has its own advantages, disadvantages, and applicability. Considering technical and economic benefits, infinite sliding sleeve multistage fracturing and perf-and-plug multistage fracturing are preferred for Class I wells in Block M and horizontal wells in similar gas reservoirs.
- (2) The comprehensive productivity impact index (CPII) constructed in this paper shows a good positive correlation with the production of fractured horizontal wells. Without considering the economic and technical constraints, a greater CPII, denotes greater well production. This relation can be used to predict the production of newly drilled horizontal wells and guide fracturing design and optimization of fracturing parameters.
- (3) For Block M, from the perspective of Level-2 indicators, the production of fractured horizontal wells is comprehensively controlled by geological, engineering, and development factors. From the perspective of Level-3 indicators, horizontal section length, initial tubing pressure, displacement, number of fracturing stages, bottom hole static pressure, and reservoir thickness are the main indicators with the largest weights influencing the production of fractured horizontal wells.
- (4) Horizontal well fracturing technology should be selected with consideration of the geological reservoir parameters of horizontal wells, as well as the fracturing design and parameters to be optimized according to specific well conditions. For newly drilled horizontal wells, where the geological reservoir conditions are given, selection of fracturing technology and optimization of parameters are critical for production enhancement, because the fracturing technology largely determines the range of parameters, which further affects the fracturing performance and well production.
- (5) The study method in this paper, that is, determining the main factors dominating the production of horizontal wells and constructing the comprehensive productivity impact index (CPII) on the basis of the data from Block M, is universal and can be easily applied to other similar reservoirs.

7. Research Limitations

This paper may be deficient in several aspects. The horizontal wells involved in this study were all located in the reserve enrichment zone of S2 in Block M, with similar reservoir physical properties and fluid properties; hence, the influence of reservoir physical properties and fluid properties was ignored when constructing the CPII. Meanwhile, the effect of inter-well interference was ignored in this paper because of the short production time of Block M. It is recommended to consider these indicators when using the proposed method to analyze the performance of fracturing technologies in similar reservoirs. Secondly, some viewpoints in this paper need to be further quantitatively demonstrated using more samples. For instance, the fixed-string hydra-jet multistage fracturing technology is undoubtedly less applicable in this block due to the limitation of displacement and number of fracturing stages, but its performance needs further quantification, since the two horizontal wells involved in the analysis were affected by horizontal section length, tubing pressure, and type of fracturing technology. Moreover, the applicability of fracturing technologies in Class I horizontal wells was verified in this paper, while the applicability in Class II and Class III horizontal wells needs to be further confirmed with more samples.

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