A study of the mechanism of nonuniform production rate in shale gas based on nonradioactive gas tracer technology

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Abstract
The performance of horizontal wells in shale gas is controlled by multiple factors, and there is a difference in gas production rate between different fracturing stages. However, the mechanism of the nonuniform gas production rate is still not clear. In this paper, a typical shale gas well in the Longmaxi formation was selected to conduct the performance evaluation based on the nonradioactive gas tracer technology. The gas production profile was obtained, and the production feature of each stage was analyzed. On this basis, the production differences between fracturing stages were compared in four aspects: reservoir physical properties, distribution of natural fracture, parameters of fracturing operation, and technology of temporary plugging re-orientation. The effect of various factors on the contribution of each stage was analyzed. And then, the mechanism of the nonuniform gas production rate was clarified. Finally, relevance analysis was performed to determine the main controlling factors, and a mathematical model for characterizing the nonuniform gas production rate feature was established by adopting the nonlinear regression method. This study provides a reliable basis for optimal fracturing designing and reasonable production planning.

KEYWORDS
multivariate nonlinear regression, nonradioactive gas tracer, nonuniform gas production rate, shale gas

1 | INTRODUCTION

In recent years, the development of unconventional oil and gas reservoirs, such as shale gas and shale oil, has attracted more and more attention. According to EIA’s forecast, natural gas production growth in the future will mainly depend on shale gas.¹² Shale gas features ultra-low permeability,³,⁴ multifractured horizontal well (MFHW) which is the most effective technique is commonly used to achieve economic and effective development.⁵,⁶ The productivity of horizontal well is controlled by multiple factors after fracturing, and the production of different fracturing stages show differences.⁷ It is critical to research the mechanism of nonuniform gas production rate in shale gas, which can deepen understanding of the formation and optimize development policies.

The key to studying the mechanism of the nonuniform gas production rate of the MFHW is to determine the gas production profile. There are two methods to determine the gas production profile, which are the indirect method and the direct method, respectively. The indirect method, such as unsteady well testing...
and reservoir numerical simulation, usually evaluates the performance of each fracturing stage by fitting the production data. He et al. established a semi-analytical well test model for the MFHW considering the impact of nonuniform production rate in fractures. The location of low production stages was diagnosed by fitting the bottom hole pressure. Qin et al. also proposed a semi-analytical model to estimate nonuniform production rate distribution for the tight oil reservoir. The advantage of the indirect method is that it is economical and fast. However, the multiplicity of the model and the high dependence on the data limit the accuracy of the result. The direct method mainly includes the production logging test (PLT) and the tracer test. Although PLT can obtain the gas production profile, the difficulty of using producing logging tools has increased due to the complicated well trajectory and structure of the MFHW in shale gas. Therefore, it is difficult to put the tools into the target position and the accuracy of results is limited. The tracer test technology overcomes the shortcomings of the PLT, which can obtain the gas production profile directly instead of putting the instrument into the well and has low engineering risk. The tracer technology was widely used in oil and gas field development. Brigham et al. first carried out tracer quantitative analysis in the homogeneous five-point well network. He has introduced the prediction method of tracer production time and peak concentration, which laid a theoretical foundation for the use of tracer test in oil fields. Cooke also made a significant contribution to the application of tracers. He established a method and theory for studying the residual oil in the reservoir using chromatographic theory. Subsequently, tracer technology was widely used to determine reservoir parameters, connectivity between wells, and CO₂ migration and storage in oil and gas reservoirs. In recent years, the tracer technology has been widely used in the diagnosis of hydraulic fracturing effects. King and Leonard evaluated the flowback process by comprehensively using fluid and proppant tracer test, micro-seismic, records of pumping, production logging, and production data. Catlett et al. used hydrocarbon tracer technology to obtain oil production for each fracturing stage, and the reason for low production was analyzed combined seismic data. Goswick and LaRue used oil soluble tracers to evaluate the stimulation efficiency along the lateral. Tian et al. proposed that the chemical tracer can be used to analyze the stimulated reservoir volume (SRV) under two-phase flow conditions. Tian et al. also used the chemical tracer flowback data to study the distribution of fracturing fluid for an individual fracturing stage. Based on gas tracer technology, Miao et al. analyzed the characteristics of the gas production profile of the MFHWs in shale gas.

Although scholars have carried out a lot of work, there is still a lack of systematic research on the mechanism of nonuniform gas production rate. Besides, previous studies mainly focus on qualitative evaluation, and there is a lack of mathematical model which can be used for rapid quantitative evaluation. In this paper, a performance evaluation was conduct on a typical shale gas well in the Longmaxi formation by using nonradioactive gas tracer technology. The gas production profile was determined, and the effect of reservoir physical properties, distribution of natural fracture, parameters of fracturing operation, and technology of temporary plugging re-orientation on the gas production rate were analyzed. Then, the mechanism of the nonuniform gas production rate was brought to light. Finally, the main controlling factors were defined by using the relevance analysis method, and a mathematical model for performance evaluation was established based on the nonlinear regression method.

2 | NONRADIOACTIVE GAS TRACER TECHNOLOGY

Considering the needs of gas testing and environmental protection, the nonradioactive gas tracer technology was adopted to obtain the gas production profile which tracers by injecting specific gas tracers into specific areas down-hole. In the fracturing process, tracers are injected into each fracture stage along with the fracturing fluid. Then, the unique tracer of each stage is carried along with the produced fluid. Finally, the produced fluid is sampled at the wellhead and the amount of each tracer is analyzed by a chromatograph to obtain the production proportion of each stage, as shown in Figure 1.

The nonradioactive gas tracer used in the field test is a perfluorocarbon compound which has a solubility of less than 0.001 g in the water at 50-150°C. Besides, it is a substance that does not exist in nature and is nontoxic, nonradioactive, and inert. Therefore, the nonradioactive gas tracer does not chemically react with any substance. Besides, the tracer is physically compatible with natural gas and has traceability.

The steps for testing the gas production profile using the nonradioactive gas tracer are as follows:
1. Tracers are selected according to the number of the fracture stage and are different for each stage.
2. The amount of tracer is determined in combination with formation pressure, lithology conditions, and production.
3. Different types of tracers are added to the fracturing fluid of different fracturing stages and then injected into the formation along with the fracturing fluid.
4. Gas samples are collected at the beginning of gas production after fracturing. The concentration of tracers is analyzed by gas chromatography.
5. The chromatographic integrated area is compared to a standard curve to obtain a concentration versus time curve for a tracer in the mixed fluid.
6. The contribution of each stage can be obtained by further matching the total production of the well.

3 | BACKGROUND AND FIELD TEST

Well X of the Longmaxi formation in the Sichuan Basin was selected for researching. Well X was deployed in Long $I_1$, and Long $I_2$ sublayers (Figure 2), and both Long $I_1$ and Long $I_2$ are Type I reservoirs. The lateral length of the well X is 1380.46 m. To improve the complexity of the fracture and enlarge the SRV, multicluster fracture with tight cutting was adopted. Within the depth of 4353.0-5733.46 m, the well X was divided into 25 stages for fracturing, with an average length of 55.2 m and a total perforation cluster number of 75. The result of log interpretation shows that the natural fracture develops in 11 stages, which are stage 7, stages 10-12, and stages 16-22, respectively. The well is deep, which poses a greater risk to coiled tubing operation. Therefore, the soluble bridge plug was selected for fracturing. Slip water was selected as fracturing fluid. Proppant consisted of 70/140 mesh quartz sand and 40/70 mesh ceramsite. Quartz sand was used to support micro-fractures, and ceramsite was used to support artificial fractures. It is difficult to form a complex fracture network due to the relatively large horizontal stress difference (17.8 MPa). Therefore, temporary plugging re-orientation technology was adopted to 12 stages (7, 10-11, 14-20, 22, and 25) according to the micro-seismic monitoring and operation conditions. The temporary plugging agent was added after the injection of 60 t proppant and 1100 m$^3$ liquid. There are four types of temporary plugging agent, as shown in Table 1. The total injection mass of temporary plugging agent in stage 7 and 15 was 300 kg, and that in the other stages was 200 kg.

Nonradioactive gas tracer technology was used to evaluate the performance of well X. Twenty-five gas-soluble tracers were selected to calibrate 25 fracturing stages. In the process of fracturing, tracers were injected with fracturing fluid at each stage. Gas sampling began when gas begins to appear at wellhead during the backflow period. Ten gas samples were collected from February 25 to May 30, 2019, according to the sampling frequency of 1 time/5 day. After sampling, these 10 samples were tested and analyzed in the laboratory. Finally, the gas production proportion of each fracturing stage was obtained, as shown in Figure 3.
4 | WELL PERFORMANCE EVALUATION

The dynamic performance curves of well X are shown in Figure 4. The gas production rate of each stage can be obtained combined with the results of the tracer test. The gas production rate of each stage shows obvious differences as shown in Figure 5. In the early period, the gas production rate increased rapidly, but there were some fluctuations. The gas production rate gradually stabilized until the 7-mm coke was used from March 4 to 8. However, the formation pressure dropped rapidly. As of March 11, the pressure has decreased from about 55 MPa to about 33 MPa, and the gas production rate has also decreased to $2 \times 10^4$ m$^3$/d. The well was shut-in to restore formation pressure from March 12 to May 17. Therefore, 8 samples were taken before shut-in and 2 after shut-in. To test the effect of well shut-in, the well was opened from 18:00 on April 5 to 18:00 on April 6. However, there is a negligible impact on the result of the tracer test due to the short well opening time.

The comparison of the gas production rate for each fracturing stage of well X is shown in Figure 6. The average gas production rate of three days from March 5 to 8, which was relatively stable, was used as a reference to classify the gas production rate of each period, as shown in Table 2. As can be seen, the number of fracturing stages with a gas production rate ranging from 0.5 to $1 \times 10^4$ m$^3$/d is the largest, which accounts for 56% of the total stage number. The gas production rate of these stages accounts for 49.6% of the total gas production rate. Although the number of stages with a gas production rate greater than $1 \times 10^4$ m$^3$/d is only 32%, its gas production rate also accounts for 45.3% of the total gas production rate, which is a great contribution. The gas production rate of only three stages is less than $0.5 \times 10^4$ m$^3$/d, which only accounts for 5.1%.

The comparison of gas production proportion for each fracturing stage was shown in Figure 7. The gas production proportion in the 7th, 8th, 10th, 11th, 14th, and 15th stages are relatively high and are all more than 5%. The gas production proportion of the front half of the horizontal wellbore shows a downward trend, with a rapid decline in the middle and late periods of stage 24 and 25. However, the gas production proportion of the latter half of the horizontal wellbore shows an upward trend, and the gas production proportion of stages 3, 4, and 7 increased obviously in the middle and late periods.

The average gas production proportion is shown in Figure 8. The stages with a gas production proportion greater than 4% are concentrated in the middle of the Long I1 sublayer, with a depth range from 4645 m to 5478 m. And the fracturing stage is from the 6th to the 20th stage (stage B). The average gas production proportion of stage B is 4.95%, which contributes the most to the production. However, the average gas production proportion

**FIGURE 4** Dynamic performance of well X

**FIGURE 5** Gas production rate of each fracturing stage
of stages 1-5 (stage A) and stages 21-23 (stage C) of the Long I$_1$ sublayer is only 2.74% and 2.77%. The average gas production proportion of stages 24 and 25 (stage D) in the Long I$_2$ sublayer is the lowest, which is only 2%. The results of logging interpretation show that the Long I$_1$ sublayer is a Type II reservoirs, and the Wufeng formation is Type II ~ III reservoirs. The reservoir physical properties of the Long I$_2$ sublayer and the Wufeng formation are worse than that of Long I$_1$ sublayer. Hence, the production of stages A, C, and D is significantly lower than stage B.

5 | THE MECHANISM OF NONUNIFORM GAS PRODUCTION RATE

To clarify the reasons for the differences in the production of each stage, detailed comparative analyses were carried out from four aspects: reservoir physical properties, distribution of natural fracture, parameters of fracturing operation, and technology of temporary plugging re-orientation.

5.1 | Reservoir physical properties

The relationship between reservoir physical properties and the average gas production proportion is shown in Figure 9. There is a positive correlation between effective porosity and gas production proportion, but it is not significant. The correlation mainly depends on the proportion of organic pore. The correlation between TOC and gas production proportion is good, so is GR. TOC is a key factor to measure the enrichment capacity of shale gas, which determines the gas content. The larger the value of TOC, the larger the gas content. The value of GR is closely related to the content of organic matter. This

![Figure 6](image)

**Figure 6** Comparison of gas production rate for each fracturing stage

| Gas production rate classification | Sublayer | Total number | Stage number | Gas production proportion |
|-----------------------------------|----------|--------------|--------------|--------------------------|
| $≥1 \times 10^4$ m$^3$/d           | Long I$_1$ | 8            | 7-11, 14-15, 19 | 45.3%                   |
| $0.5 \times 10^4$ ~ $1 \times 10^4$ m$^3$/d | Long I$_1$+2 | 14          | 1, 3-6, 12-13, 16-18, 20-22, 25 | 49.6%                   |
| $<0.5 \times 10^4$ m$^3$/d         | Long I$_1$+2 | 3            | 2, 23-24     | 5.1%                    |

![Figure 7](image)

**Figure 7** Comparison of gas production proportion for each fracturing stage
is because the organic matter has strong adsorption of radioactive elements, and the larger the value of GR, the higher the content of organic matter of the shale. The average value of TOC and GR of stage B is 5.23% and 200.61, which is significantly higher than stage A (TOC: 3.7%, GR: 147.6) and stage C (TOC: 3.22%, GR: 160.2). Hence, stages with a larger value of TOC and GR usually have a larger gas production proportion.

5.2 Distribution of natural fracture

Natural fractures play an important role in shale gas. Stages 7, 10-12, and 16-22, where the natural fractures are developed, are all distributed in the sublayer of Long I1. The average gas production proportion of these stages is 4.6%, while the average gas production proportion of stages that natural fracture undeveloped is only 3.6%. On the one hand, natural fractures can effectively increase the migration channel and the accumulation space, which is conducive to the increase of free gas and the improvement of transportability. What is more, the existence of natural fractures can increase the specific surface of shale, which leads to a higher content of adsorbed gas. The average TOC and GR of natural fracture developed stages are 4.91% and 196.86, while those of natural fracture undeveloped stages are 4.21% and 170.19. On the other hand, the more natural fractures develop, the more easily complex fracture network will be formed. The SRV of each fracturing stage obtained by micro-seismic interpretation is shown in Figure 10. It can be easily obtained that the SRV of natural fracture developed stages and natural fracture undeveloped stages are $329.85 \times 10^4$ m$^3$ and $294.69 \times 10^4$ m$^3$, respectively. Obviously, the SRV of natural fracture developed stages is bigger.

5.3 Parameters of fracturing operation

The relationship between fracturing operation parameters and the average gas production proportion is shown in Figure 11. Total sand, total fluid volume, sand usage per meter, liquid usage per meter, maximum sand concentration, and average pumping rate are positive correlated with gas production proportion. The stages with larger sand and liquid consumption and larger pumping rate usually have a higher gas production proportion. However, average operation pressure in the sand-carrying period and pump shutdown pressure are negatively correlated with gas production proportion. The larger the average operation pressure and pump shutdown pressure, the worse the compressibility of the formation, which leads to a more difficult fracturing operation and a worse fracture network.

Further comparison of the relationship between the gas production proportion and the amount of 70/140 mesh quartz sand and 40/70 ceramsite was conducted. The relationship
between the amount of quartz sand and gas production proportion is not significant. However, there is a positive correlation between the amount of ceramsite and gas production proportion. In other words, the contribution of ceramsite to gas production rate is more significant than that of quartz sand. There are 6 stages that the amount of ceramsite is less than 60 t. 4 of the 6 stages belong to the Long $I_1$ sublayer and the other 2 belong to the Long $I_2$ sublayer. The average amount of ceramsite added in these 4 stages in the Long $I_1$ sublayer is 44.4 t, and the average gas production proportion is 3.4%. However, the average amount of ceramsite added to the other 19 stages is 75.2 t, and the average gas production proportion is 4.3%. The comparison shows that the average gas production proportion is reduced by 16.3% due to a 30.2 t reduction in ceramsite. The amount of ceramsite added to the Long $I_2$ sublayer is less than 60 t, and the
average gas production proportion is only 2.0%. Ceramsite is mainly used to support the artificial fracture, while quartz sand is mainly used to support micro-fractures. Hence, increasing the amount of ceramsite to ensure a higher conductivity of artificial fracture is more beneficial to increase production.

5.4 | Technology of temporary plugging re-orientation

The technology of temporary plugging re-orientation was adopted in 12 stages (7, 10-11, 14-20, 22, 25). The 11 stages of the Long I_1 sublayer adopted the temporary plugging re-orientation technology, and the average gas production proportion is 5.02%, while the average gas production proportion of the remaining 12 stages without using this technology is only 3.40%. In the Long I_2 sublayer, the average gas production proportion of stage 25 is 50% higher than that of stage 24. For the four types of temporary plugging agent, the average gas production proportion is 6.49%, 5.85%, 4.83%, and 4.41%, respectively. The average gas production proportion of the fracturing stage with 300 kg temporary plugging agent is significantly higher than that of the fracturing stage with only 200 kg temporary plugging agent. Besides, it is better to use a temporary plugging agent with a combination of 1-mm or 3-mm particles and powder.

6 | PERFORMANCE EVALUATION MODEL

6.1 | Main controlling factors

In summary, the nonuniform gas production rate mechanism is controlled by multiple factors. To determine the main controlling factors, quantitative analysis was carried out by calculating the Pearson correlation coefficient of each parameter. The parameters used in the calculation are shown in Appendix 1, and the calculation results are shown in Table 3. Parameters with a correlation coefficient greater than 0.2 were selected as the main controlling factors. The top two parameters are TOC and GR, which indicates that the material basis is the decisive factor of production. The 3rd to 9th parameters (expect for 5th parameter) are the fracturing technology and operation parameters, which also have a great impact on production. This indicates that the product can be improved by optimizing the fracturing technology and operation parameters. In addition, the correlation coefficient of natural cracks ranks 5th, which is significantly higher than some fracturing operation parameters. Therefore, deepening the understanding of the distribution of natural fractures in shale gas is also very helpful to enhance production.

| Parameters                                                  | Pearson’s correlation coefficient | Sort |
|-------------------------------------------------------------|----------------------------------|------|
| TOC                                                        | 0.8062                           | 1    |
| GR                                                         | 0.7538                           | 2    |
| Temporary plugging re-orientation                          | 0.5355                           | 3    |
| Total fluid volume                                         | 0.3979                           | 4    |
| Natural fracture                                           | 0.3499                           | 5    |
| Total sand                                                 | 0.3047                           | 6    |
| Average pumping rate                                       | 0.2851                           | 7    |
| Sand usage per meter                                       | 0.2750                           | 8    |
| Maximum sand concentration                                 | 0.2071                           | 9    |
| Liquid usage per meter                                     | 0.1968                           | 10   |
| Pump shutdown pressure                                     | -0.1965                          | 11   |
| Average operation pressure in the sand-carrying period     | -0.1697                          | 12   |

6.2 | Mathematical model

The multivariate nonlinear regression method was adopted to establish the performance evaluation model. First, the relationship between each independent variable and dependent variable needs to be determined separately. Then, the interaction between independent variables requires further consideration. Last, the multivariate nonlinear mathematical model can be obtained by superimposing these mathematical relationships. The expression of the model is:

$$Y = \sum_{i=1}^{n} a_i x_i + \sum_{i=1, i\neq j}^{n} b_{ij} x_i x_j + k$$  \hspace{1cm} (1)$$

where $Y$ represents dependent variable, $a_i$, $b_{ij}$ and $k$ represent regression coefficients, and $x_i$ and $x_j$ represent independent variables.

According to the results of the quantitative analysis, the above 9 parameters can be used to establish the regression model. However, the more the parameters of the model, the more complicated the model will be, which will reduce the efficiency of the model. Hence, the parameters need to be filtered to simplify the model. Obviously, some of these 9 parameters are interrelated. For instance, there is a positive correlation between total fluid volume and liquid usage per meter. That is to say, the bigger the total fluid volume is, the bigger the liquid usage per meter will be. Therefore, in view of the higher correlation of total fluid volume, liquid usage per meter may not be considered in the model. In fact, liquid usage per meter has been excluded in the quantitative analysis. Similarly, sand usage per meter and maximum sand
concentration also have a positive correlation with total sand. Hence, sand usage per meter and maximum sand concentration are excluded according to the magnitude of the correlation. Finally, the top 7 parameters were chosen to establish the evaluation model.

Assume that all parameters are linear with the average gas production proportion, then \( f(x_i) = x_i \). There are interactions between TOC, GR, and natural fracture, which need to be considered. Similarly, the interaction among total fluid volume, total sand, and average pumping rate also needs to be considered. Therefore, the regression model is

\[
Y = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 + a_7x_7 + b_1x_1x_2 + b_2x_1x_5 + b_3x_2x_5 + b_4x_4x_6 + b_5x_5x_7 + b_6x_6x_7 + k
\]

where \( x_1 \) represents TOC, \( x_2 \) represents GR, \( x_3 \) represents temporary plugging re-orientation, \( x_4 \) represents total fluid volume, \( x_5 \) represents natural fracture, \( x_6 \) represents total sand, and \( x_7 \) represents average pumping rate.

The nonlinear fitting function nlinfit in MATLAB was used to fit the relevant parameters based on the data in Appendix 1. The nonlinear model is

\[
Y = 1.4337x_1 - 0.0088x_2 + 0.7653x_3 - 0.0131x_4 + 0.7448x_5 + 0.7418x_6 + 0.6399x_7 - 0.0009x_1x_2 - 0.1681x_1x_3 - 0.001x_2x_5 - 0.000696x_4x_6 + 0.0013x_4x_7 - 0.0364x_6x_7 - 26.39
\]

The average gas production proportion calculated by the evaluation model was compared with the results of the tracer test, as shown in Figure 12. The scatter points are distributed on both sides of a straight line with a slope of 1, and the correlation coefficient is 0.873. This indicates that the calculated results of the evaluation model are consistent with the test results. Therefore, the evaluation model is reliable and can be used for quantitative performance evaluation of each fracturing stage in shale gas.

7 | CONCLUSION

Based on the nonradioactive gas tracer technology, the gas production profile of a typical shale gas well in the Longmaxi formation was obtained and the production feature of each stage was analyzed. By carrying out the analysis of influencing factors and the revenant analysis, the mechanism of nonuniform gas production rate was revealed and the main controlling factors were determined. The mechanism of nonuniform gas production rate is controlled by multiple factors, including the reservoir physical properties, distribution of natural fracture, fracturing technology, and operation parameters. Reservoir physical properties are the primary factors affecting the gas production rate, which provides an important material basis for the high production of shale gas wells. The production potential can be maximized by optimizing the fracturing process and the operation parameters. In addition, the effect of fracturing can be effectively improved by deepening the understanding of the distribution of natural fractures. On this basis, a mathematical model for performance evaluation was established, which lays a foundation for the optimal design of fracturing and reasonable production planning.

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REFERENCES
1. Xinhua MA, Jun XIE. The progress and prospects of shale gas exploration and development in southern Sichuan Basin, SW China. Petrol Explor Develop. 2018;45(1):172-182.
2. Zhang L, Baochao S, Yulong Z, Zhaoli G. Review of micro seepage mechanisms in shale gas reservoirs. Int J Heat Mass Transf. 2019;139:144-179.
3. Huang S, Yao Y, Zhang S, Ji J, Ma R. A fractal model for oil transport in tight porous media. Transp Porous Media. 2018;121(3):725-739.
4. Wang L, He YM, Peng X, Deng H, Liu YC, Xu W. Pore structure characteristics of an ultradeep carbonate gas reservoir and their effects on gas storage and percolation capacities in the Deng IV Member, Gaoshiti-Moxi Area, Sichuan Basin, SW China. Mar Petrol Geol. 2020;111:44-65.
5. Huang S, Yao Y, Zhang S, Ji J, Ma R. Pressure transient analysis of multi-fractured horizontal wells in tight oil reservoirs with consideration of stress sensitivity. Arab J Geosci. 2018;11(11):285.
6. Huang S, Yao Y, Ma R, Wang J. Analytical model for pressure and rate analysis of multi-fractured horizontal wells in tight gas reservoirs. *J Petrol Explor Prod Technol.* 2019;9(1):383-396.

7. He Y, Cheng S, Qin J, et al. Analytical interference testing analysis of multi-segment horizontal well. *J Petrol Sci Eng.* 2018;171:919-927.

8. He Y, Cheng S, Li S, et al. A semi-analytical methodology to diagnose the locations of underperforming hydraulic fractures through pressure-transient analysis in tight gas reservoir. *SPE J.* 2017;22(03):924-939.

9. He Y, Cheng S, Qin J, et al. Interference testing model of multiply fractured horizontal well with multiple injection wells. *J Petrol Sci Eng.* 2019;176:1106-1120.

10. Qin J, Cheng S, He Y, et al. Estimation of non-uniform production rate distribution of multi-fractured horizontal well through pressure transient analysis: model and case study. In: *SPE Annual Technical Conference and Exhibition.* Society of Petroleum Engineers; 2017.

11. Qin J, Cheng S, He Y, et al. Decline curve analysis of fractured horizontal wells through segmented fracture model. *J Energy Res Technol.* 2019;141(1):012903.

12. Drylie S, Pechiney J, Villaseñeø R, et al. Determining the number of contributing fractures in shale gas wells with production analysis and proppant tracer diagnostics. In: *SPE Production and Operations Symposium.* Society of Petroleum Engineers; 2015.

13. Tayyib D, Al-Qasim A, Kokal S, et al. Overview of tracer applications in oil and gas industry. In: *SPE Kuwait Oil & Gas Show and Conference.* Society of Petroleum Engineers; 2019.

14. Brigham WE, Smith DH Jr. Prediction of tracer behavior in five-spot flow. In: *Conference on Production Research and Engineering.* Society of Petroleum Engineers; 1965.

15. Cooke CE Jr. *Method of determining fluid saturations in reservoirs: U.S. Patent 3,590,923;* 1971-7-6.

16. Tang JS, Harker B. Interwell tracer test to determine residual oil saturation in a gas-saturated reservoir. Part I: theory and design. *J Can Pet Technol.* 1991;30(03):76-85.

17. Tang JS, Harker B. Interwell tracer test to determine residual oil saturation in a gas-saturated reservoir. Part II: field applications. *J Can Pet Technol.* 1991;30(04):34-42.

18. Gillis JV, Radke CJ. A dual-gas tracer technique for determining trapped gas saturation during steady foam flow in porous media;1990.

19. Sinha R, Asakawa K, Pope GA, et al. Simulation of natural and partitioning interwell tracers to calculate saturation and swept volumes in oil reservoirs. In: *SPE/DOE Symposium on Improved Oil Recovery.* Society of Petroleum Engineers; 2004.

20. Al-Qasim A, Kokal S, Hartvig S, et al. Reservoir description insights from inter-well gas tracer test. In: *Abu Dhabi International Petroleum Exhibition & Conference.* Society of Petroleum Engineers; 2019.

21. Al-Qasim A, Kokal S, Hartvig S, et al. Reservoir description insights from inter-well gas tracer test. In: *Abu Dhabi International Petroleum Exhibition & Conference.* Society of Petroleum Engineers; 2019.

22. Ren B, Ren S, Zhang L, et al. Monitoring on CO2 migration in a tight oil reservoir during CCS-EOR in Jilin Oilfield China. *Energy.* 2016;98:108-121.

23. Ringrose PS, Mathieson AS, Wright IW, et al. The In Salah CO2 storage project: lessons learned and knowledge transfer. *Energy Proc.* 2013;37:6226-6236.

24. King GE, Leonard RS. Deciphering chemical tracer results in multi-fractured well backflow in shales: a framework for optimizing fracture design and application. In: *SPE Hydraulic Fracturing Technology Conference.* Society of Petroleum Engineers; 2011.

25. Catlett RD, Spencer JD, Lolon E, et al. Evaluation of two horizontal wells in the eagle ford using oil-based chemical tracer technology to optimize stimulation design. In: *SPE Hydraulic Fracturing Technology Conference.* Society of Petroleum Engineers; 2013.

26. Goswick RA, LaRue JL. Utilizing oil soluble tracers to understand stimulation efficiency along the lateral. In: *SPE Annual Technical Conference and Exhibition.* Society of Petroleum Engineers; 2014.

27. Tian W, Wu X, Shen T, Kalra S. Estimation of hydraulic fracture volume utilizing partitioning chemical tracer in shale gas formation. *J Nat Gas Sci Eng.* 2016;33:1069-1077.

28. Tian W, Darnley A, Mohle T, et al. Understanding frac fluid distribution of an individual frac stage from chemical tracer flowback data. In: *SPE Hydraulic Fracturing Technology Conference and Exhibition.* Society of Petroleum Engineers; 2019.

29. Miao Y, Zeng B, Zhou C, et al. Reservoir study for shale gas horizontal casing completion multi-stage frac using gas tracer technology. In: *SPE Symposium: Production Enhancement and Cost Optimisation.* Society of Petroleum Engineers; 2017.

30. Li S, Du Y. Model of concrete strength prediction based on multivariate nonlinear analysis. *Concrete.* 2016;317(03):44-46+55.

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APPENDIX 1

Parameters used in the quantitative analysis are shown in Table A1. In the natural fracture section, number 1 represents that the natural fracture was developed and number −1 represents that the natural fracture was undeveloped. Similarly, number 1 represents that the temporary plugging re-orientation technology was adopted, and number −1 represents the opposite in the temporary plugging re-orientation section.

TABLE A1  Detailed parameters for each fracturing stage

| Stages | TOC | GR API t | Total sand | Natural fracture | Temporary plugging re-orientation fracturing | Total fluid volume m³ | Sand usage per meter t/m | Sand usage per meter m³/m | Liquid usage per meter kg/m³ | Maximum sand concentration | Average pumping rate m³/min | Average operation pressure in the sand carrying period MPa | Pump shutdown pressure MPa | Gas production proportion % |
|--------|-----|----------|------------|-----------------|---------------------------------------------|-----------------------|--------------------------|--------------------------|-----------------------------|---------------------------|-----------------------------|--------------------------------|---------------------------|--------------------------|
| 1      | 3.6 | 149.3    | 101.5      | −1              | −1                                         | 2307.3                | 1.97                     | 41.7                     | 140                         | 14.5                      | 97.5                        | /                              | 2.3                        |
| 2      | 4   | 154.9    | 60.1       | −1              | −1                                         | 2323.5                | 1.18                     | 45.55                    | 100                         | 14.75                     | 105                         | 68.1                          | 1.4                        |
| 3      | 3.8 | 147.8    | 100.9      | −1              | −1                                         | 2286.7                | 1.98                     | 44.84                    | 120                         | 14.2                      | 100.5                       | 68.5                          | 3                          |
| 4      | 3.7 | 143.7    | 101.9      | −1              | −1                                         | 2311.8                | 2                       | 45.33                    | 140                         | 15.3                      | 92.5                        | 68.9                          | 3.8                        |
| 5      | 3.4 | 142.3    | 112        | −1              | −1                                         | 2276.7                | 2.2                      | 44.65                    | 160                         | 15.5                      | 92                          | 70.4                          | 3.2                        |
| 6      | 5.9 | 208.6    | 120.1      | −1              | −1                                         | 2248.4                | 2.35                     | 44.08                    | 160                         | 16.5                      | 92.5                        | 67.8                          | 4.4                        |
| 7      | 5.9 | 208.6    | 82.9       | 1               | 1                                          | 2331.9                | 1.51                     | 38.18                    | 140                         | 16.5                      | 96                          | /                              | 6.5                        |
| 8      | 5.9 | 233.9    | 81.3       | −1              | −1                                         | 2110.4                | 1.45                     | 37.68                    | 120                         | 16.5                      | 95                          | 73.6                          | 5.4                        |
| 9      | 4.2 | 178.2    | 80.2       | −1              | −1                                         | 2519.9                | 1.46                     | 45.82                    | 140                         | 16.5                      | 97.5                        | 68.7                          | 4.8                        |
| 10     | 6.2 | 235.2    | 74.4       | 1               | 1                                          | 2588.1                | 1.4                      | 48.83                    | 120                         | 15.5                      | 100                         | 65.7                          | 5.6                        |
| 11     | 6.4 | 236.8    | 102.2      | 1               | 1                                          | 2540.5                | 1.89                     | 47.06                    | 120                         | 16.5                      | 91.5                        | 65.5                          | 6.7                        |
| 12     | 5.7 | 200.1    | 90.2       | 1               | −1                                         | 2403.8                | 1.67                     | 44.52                    | 140                         | 17                        | 91.5                        | 66.4                          | 3.8                        |
| 13     | 6   | 225.1    | 115        | −1              | −1                                         | 2326.9                | 2.02                     | 40.82                    | 160                         | 16.75                     | 87.5                        | 66.4                          | 4.3                        |
| 14     | 5.6 | 195.1    | 112.85     | −1              | 1                                          | 2376.9                | 2.01                     | 42.43                    | 140                         | 17                        | 86.5                        | 65                            | 5.5                        |
| 15     | 5.2 | 184.9    | 113.7      | −1              | 1                                          | 2323.4                | 1.99                     | 40.75                    | 140                         | 17                        | 87.5                        | 64.3                          | 5.9                        |
| 16     | 4.4 | 178.9    | 120.2      | 1               | 1                                          | 2224.9                | 2.11                     | 39.02                    | 140                         | 17                        | 87                          | 66.6                          | 4.5                        |
| 17     | 4.4 | 181.5    | 110.2      | 1               | 1                                          | 2174.5                | 1.93                     | 38.14                    | 160                         | 17                        | 86                          | 64.7                          | 3.7                        |
| 18     | 4.2 | 184.5    | 114.1      | 1               | 1                                          | 2372.8                | 2                       | 41.61                    | 140                         | 17                        | 86.5                        | 65.1                          | 4.1                        |
| 19     | 4.1 | 167.5    | 100.1      | 1               | 1                                          | 2362.3                | 1.76                     | 41.44                    | 120                         | 16.5                      | 89                          | 68                            | 4.9                        |
| 20     | 4.3 | 190.2    | 101.6      | 1               | 1                                          | 2297.8                | 1.78                     | 40.3                     | 120                         | 16.5                      | 89.5                        | 65.3                          | 4.2                        |
| 21     | 3.8 | 183.9    | 80.1       | 1               | −1                                         | 2237.8                | 1.41                     | 39.25                    | 100                         | 16.5                      | 94.5                        | 66.3                          | 2.6                        |
| 22     | 4.6 | 198.3    | 104.5      | 1               | 1                                          | 2459.9                | 1.84                     | 43.16                    | 100                         | 16.35                     | 92.5                        | 69.7                          | 3.8                        |
| 23     | 2.9 | 156.6    | 79.4       | −1              | −1                                         | 2216.4                | 1.37                     | 38.21                    | 120                         | 17                        | 88                          | 70.6                          | 1.9                        |
| 24     | 2.4 | 126      | 85.2       | −1              | −1                                         | 2247.3                | 1.42                     | 37.45                    | 140                         | 17                        | 88.5                        | 66.7                          | 1.6                        |
| 25     | 2.4 | 136.2    | 80.9       | −1              | 1                                          | 2315                  | 1.35                     | 38.58                    | 110                         | 17                        | 91.5                        | 65.5                          | 2.4                        |